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Fibre Optic Sensing Techniques Based on Incoherent Optical Frequency Domain Reflectometry

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Fibre Optic Sensing Techniques Based on Incoherent Optical Frequency Domain Reflectometry

vorgelegt von Dipl.-Ing. Sascha Liehr

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Abstract

In this thesis, an alternative approach to the well-known optical time domain reflectometry (OTDR) technique is presented. A thorough analysis regarding distributed backscatter measurement in optical fibres is provided and its prospects for optical fibre sensing applications are demonstrated and discussed. The measurement approach is referred to as incoherent optical frequency domain reflectometry (I-OFDR): the frequency response of the fibre under test is measured and transferred into its time domain equivalent using inverse Fourier transform. This general technique has been studied and used for the measurement of nonlinear scattering effects in optical fibres. The requirements, limitations and prospects for general backscatter measurement, however, are different and have not been studied in detail prior to this work. Distributed sensing using Rayleigh scattering and reflective events in the fibre is first demonstrated using I-OFDR with remarkable measurement resolution. The incoherent detection technique allows for measuring singlemode fibres as well as multimode fibres.

The first part of this work deals with the theoretical analysis and optimized implementation of the frequency domain approach. Necessary signal processing and its impact on the time domain response are presented. Sources of deviation from the linearity of the I-OFDR system are identified and an optimized laboratory setup is introduced; the crucial impact of the source coherence is thoroughly discussed. Suitable system parameters for the I-OFDR approach are defined: the system dynamic range and sensitivity are determined. A technique to suppress the dynamic range-limiting signal originating from strong reflections in the fibre is suggested. It is demonstrated that the I-OFDR technique has advantages over OTDR in terms of implementation for high-resolution measurement, measurement accuracy and signal stability. These advantages and measurement possibilities specific to the frequency domain approach are utilized for spatially resolved sensing applications in the second part of this work:

A low optical loss polymer optical fibre (POF) is for the first time studied and analyzed for distributed strain sensing. The backscatter level dependence on strain in the fibre can be used to detect and locate strained fibre sections. Also, a correlation algorithm is proposed and demonstrated to measure length changes along the fibre with mm-resolution by correlating the typical backscatter signature of this fibre type. The fibre type is analyzed in detail regarding cross-sensitivities to temperature, relative humidity as well as mode propagation influences. The proposed sensing principles in combination with the high-resolution I-OFDR allow for promising distributed sensing applications. Special interest is expressed by the structural health monitoring (SHM) sector since the fibre can measure strain values exceeding 100 %.

Another sensing technique, specific to I-OFDR, is proposed for quasi-distributed and dynamic measurement of length changes and optical power changes at reflective events along the fibre. Precise calculation of the positions and reflected powers of multiple reflections can be conducted in parallel from the measurement of a few sampling points of the complex-valued frequency response. That allows for measuring with an increased repetition rate up to 2 kHz or at μ m-scale length changes resolution at lower measurement frequencies. The approach is demonstrated in the laboratory and in a field application by measuring the deformation of a masonry building on a seismic shaking table.

The I-OFDR exhibits competitive performance for general high-resolution backscatter measurement and the proposed optical fibre sensor principles may have promising prospects in the structural health monitoring (SHM) sector.

Zusammenfassung

Arbeit beschreibt alternativen Diese einen Ansatz zur weit verbreiteten optischen Zeitbereichsreflektometrie, engl.: optical time domain reflectometry (OTDR). Die inkohärente optische Frequenzbereichsreflektometrie, engl.: incoherent optical frequency domain reflectometry (I-OFDR), wird grundlegend analysiert und hinsichtlich ihrer Möglichkeiten zur kontinuierlich ortsaufgelösten (verteilten) Rückstreumessung in optischen Fasern sowie faseroptischen Sensoranwendungen betrachtet. Im Gegensatz zum OTDR Ansatz wird hier die Übertragungsfunktion der optischen Faser gemessen, die über die inverse Fouriertransformation mit der äquivalenten Zeitbereichsantwort verknüpft ist. Das grundsätzliche Verfahren hat gewisse Vorteile und wird bereits zur Messung nichtlinearer optischer Effekte in optischen Fasern genutzt. Die allgemeine Rückstreumesstechnik unterscheidet sich jedoch bezüglich Anforderungen und Einschränkungen und wurde bisher nicht genau untersucht. Verteilte faseroptische Sensoranwendungen mit bemerkenswerter Messauflösung basierend auf Rayleigh-Rückstreuung und Reflexionsstellen in optischen Fasern werden erstmals vorgestellt.

Im ersten Teil der Arbeit wird der Frequenzbereichsansatz theoretisch beschrieben. Notwendige Signalverarbeitung und deren Einfluss auf die Zeitbereichsantwort werden dargestellt. Abweichungen von der Linearität des I-OFDR Systems werden diskutiert und ein optimierter Messaufbau wird eingeführt; der entscheidende Einfluss der spektralen Eigenschaften der optischen Quelle wird im Detail betrachtet. Geeignete Parameter des I-OFDR Ansatzes, wie Dynamikbereich und Empfindlichkeit, werden definiert und für den Laboraufbau bestimmt. Ein möglicher Ansatz zur Unterdrückung starker Störsignale wird vorgestellt. Die Vorteile des I-OFDR Ansatzes gegenüber der OTDR Technik bezüglich der Umsetzung für hohe Ortsauflösungen sowie Messauflösung und Signalstabilität werden gezeigt. Diese Vorteile und dem Frequenzansatz eigene Messmöglichkeiten werden im zweiten Teil der Arbeit für ortsaufgelöste Sensoranwendungen demonstriert:

Eine dämpfungsarme polymeroptische Faser (POF) wird erstmals auf ihre Sensoreigenschaften untersucht und zur verteilten Dehnungsmessung verwendet. Die Abhängigkeit der Rückstreuleistung von der aufgebrachten Dehnung kann genutzt werden, um gedehnte Faserstrecken zu lokalisieren. Weiterhin wird ein Korrelationsalgorithmus eingeführt, der es ermöglicht ortsaufgelöst Längenänderungen entlang der Faser mit mm-Auflösung zu messen indem die starken Streuzentren in der Faser mit einer Referenzmessung korreliert werden. Untersuchungen auf Querempfindlichkeiten der Sensorfaser bezüglich Temperatur, relativer Feuchte und Modenausbreitung zeigen vernachlässigbare bzw. beherrschbare Abhängigkeiten. In Kombination mit dem hochauflösenden I-OFDR Ansatz ermöglichen die vorgestellten Sensorverfahren vielversprechende neue Messanwendungen. Spezielles Interesse besteht in Bereichen der Bauwerksüberwachung, da die Faser nahezu verlustfrei auf über 100 % gedehnt werden kann.

Ein weiteres Sensorverfahren, basierend auf dem Frequenzbereichsansatz zur dynamischen und quasi-verteilten Messung von Längenänderungen und Leistungsänderungen zwischen Reflexpunkten in der Faser wird präsentiert. Basierend auf der Messung weniger Frequenzpunkte der komplexen Frequenzantwort der Messfaser können mehrere Reflexe gleichzeitig und unabhängig voneinander bezüglich Position und reflektierter optischer Leistung ausgewertet werden. Messfrequenzen bis zu 2 kHz können erreicht werden und Längenänderungsauflösungen im µm-Bereich bei kleineren Messfrequenzen sind möglich. Das Messverfahren wird auf systematische Fehlereinflüsse untersucht und anhand von Demonstratormessungen validiert. Messungen der Deformation eines Gebäudes auf einem Erdbebenversuchsstand demonstrieren die Möglichkeit der Feldanwendung des Verfahrens.

Das vorgestellte I-OFDR Verfahren demonstriert konkurrenzfähige Messparameter für allgemeine und hochauflösende optische Rückstreumessungen und die vorgestellten faseroptischen Sensorprinzipien zeigen vielversprechende Perspektiven für Anwendungen z.B. in der Bauwerksüberwachung.

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1 Introduction

The monitoring of for example civil engineering structures, geotechnical structures and industrial components is becoming a more and more important issue. The maintenance and safe operation of existing structures as well as new regulations regarding structural health monitoring (SHM) of new buildings lead to an increasing demand on cost-efficient and reliable measurement systems. The emergence of optical fibre sensors and their recent commercial availability during the last years has put a new option on the table. Using an optical fibre as the sensor medium offers numerous distinct advantages over traditional sensing principles. Fibre optic sensors can be multiplexed, are immune to electromagnetic interference, non-conducting (Galvanic isolator), small in size, reliable, low-cost, lightweight, non-corrosive and can be used for remote sensing. They are uncritical in flammable or explosive environment and can endure high temperatures.

The most convincing advantage of fibre optic sensors is the possibility to measure for example strain or temperature continuously and spatially resolved along the whole length of the fibre. Such distributed fibre sensors could for example substitute a great number of standard electrical transducers and ensure uninterrupted monitoring of the entire structure. The benefit of distributed fibre sensors is therefore not only an increase of safety but also a commercial one since damages can be detected and repaired at an early stage, thus decreasing maintenance costs. Distributed fibre optic sensor solutions have become a more and more serious option, also in the rather conservative SHM field, simply because there are no equivalent technology options available. Several techniques for distributed measurement of strain and temperature in standard silica optical fibres have been proposed and are now commercially available. Most of these techniques are based on spatially resolved detection of optical backscattering and are increasingly used for the monitoring of extended structures such as bridges, tunnels, pipelines, boreholes, slopes, dams, or structural and industrial elements. These techniques commonly rely on the 'pulse echo technique' or optical time domain reflectometry (OTDR) to retrieve the spatial information from the fibre.

The aim of this thesis is, in short, to consider an alternative technique for distributed backscatter measurement and to investigate its prospects for optical fibre sensing.

1.1 Motivation

The work presented in this thesis is basically motivated by two domains of optical fibre sensing technology: the development of a fibre optic measurement technique on the one hand and the exploration of related novel sensing principles on the other hand.

• The first incentive is to thoroughly investigate the potential, the advantages and limitations of the incoherent optical frequency domain reflectometry (I-OFDR) as an alternative to the established optical backscatter measurement techniques. Most of the optical fibre sensor systems allowing continuously distributed measurement are based on the optical time domain reflectometry (OTDR) technique: short optical pulses are sent into one end of the fibre and the backscattered light is recorded as a function of time. Knowing the group refractive index of the fibre allows calculating the backscatter signature as a function of distance. Various intrinsic and extrinsic effects altering the backscatter signal of a fibre can therefore be detected and are used for distributed sensing.

The incoherent optical frequency domain reflectometry (I-OFDR) is equivalent to measuring the time domain response of an optical fibre using OTDR and is mathematically linked by the Fourier transform of the transfer function of the fibre under test (FUT). Measuring the complex frequency domain response of the FUT and conducting an inverse Fourier transform results in the impulse response, or time domain response, the equivalent to an OTDR measurement. Although seemingly delivering mathematically interchangeable solutions, the I-OFDR technique and the OTDR approach exhibit differences regarding technological implementation, signal generation, detection and processing as well as light propagation and interaction. The basic principle of I-OFDR has previously

been presented [1],[2], but its true potential has never seriously been investigated and considered for general backscatter measurement or fibre optic sensing applications.

The differences to OTDR and the fundamental prospects of the I-OFDR approach are investigated in detail in this work. A focus is on the analysis and optimization of the I-OFDR approach for general backscatter measurement in optical fibres and the investigation of the inherent advantages of the frequency domain approach for novel and alternative optical fibre sensor principles. A systematic analysis of the I-OFDR approach, its advantages and limitations and a state-of-the-art implementation is attempted. This topic is mainly presented in chapter 2.

The second motivation is thought from the sensor application point of view with the focus on structural health monitoring applications. The analysis of the mechanical advantages and backscatter effects for sensing applications in a new low-loss polymer optical fibre (POF) type in connection with I-OFDR is the target. This work is motivated by recent investigations on standard polymethyl(methacrylate) (PMMA) POF: applying strain to PMMA POF sections results in an increase of the local backscatter level as a function of strain and can be used for distributed strain measurement using OTDR as measurement technique [3], [4], [5], [6], [7]. This effect does not occur in silica fibres. The motivation of using POFs instead of silica fibres is the presence of this effect as well as their extraordinary high strain range of more than 40 % [5]. Extending the measurable strain range from about 1 % to 2 % for silica fibres to several tens of percent in POF allows for new sensing applications where very high strain is expected. Possible application scenarios are crack detection and localization and the monitoring of possible high-strain failures, for example in earthwork structures, where the deformation limits of silica fibres are exceeded. This fibre type is an excellent option for high strain measurement over short distances. Cross-sensitivities of the Rayleigh backscatter level to temperature and relative humidity interfere with the strain signal but can be used for temperature and relative humidity measurement [6],[8],[9]. Practical limitations using standard PMMA POF are their high attenuation and therefore limited sensor length to about 100 m as well as the strong dispersion in the high-NA (NA = 0.5) step-index fibres that strongly decreases the spatial resolution¹ of the measurement system with increasing fibre length.

The subject of this work is the *investigation and application of a new POF type for distributed sensing*. The availability of POF based on the fluoropolymer CYTOP promises significantly increased performance. The lower attenuation of this perfluorinated (PF) POF allows considerably extending the measurement length. The gradient-index (GI) structure of the fibre core reduces modal dispersion and ensures maximum spatial resolution along the whole fibre length. The characterization and investigation of this fibre type for application as a distributed strain sensor is intended. The compatibility of this fibre to standard multimode telecom components (50 µm core diameter and attenuation minimum around 1300 nm) is the motivation to design an I-OFDR laboratory setup compatible to this fibre type. The backscatter-strain interaction as well as the cross sensitivity dependencies of PF POF is investigated using I-OFDR. Distributed strain measurement in PF POF and a distributed length change measurement technique are proposed and demonstrated in chapter 4.

Another sensing principle that is uniquely based on the I-OFDR technique is presented in a separate chapter. This novel approach allows for *dynamic and simultaneous measurement of length changes and optical power changes* on multiple reflection points in an optical fibre. The measurement of just a few frequency points of the fibre frequency response and subsequent calculations of the distance and power changes for all reflection points allow for high measurement repetition rates and precise length change and optical power change measurement. The advantages of this technique are its easy implementation into an I-OFDR setup, the flexibility in

¹ When comparing resolution values throughout this thesis: 'higher resolution' or 'increased resolution' means lower actual resolution values (better sensor characteristics). This comparative definition is consistent with the terminology used in the majority of publications dealing with measurement and sensing.

gauge length from centimetres to kilometres and the possibility to use standard singlemode fibres (SMF) but also multimode fibres and POF. This dynamic evaluation approach is presented in chapter 5.

The initiated innovations presented in this work led to a new research project 'Digital OFDR'¹ with the fibrisTerre GmbH². The aim of the project is to lead the proposed sensing techniques and innovations presented in this thesis towards commercialization.

1.2 Optical fibre sensing - definition and terminology

1.2.1 Sensor classes

Optical fibre sensors have been a subject of research from the beginning of fibre optic technology but only started to become a serious alternative to traditional and established measurement techniques in specific fields during the last two decades. The commercial success has certainly arrived with the fibre Bragg grating (FBG) sensors [10] that enable precise and dynamic measurement of strain and temperature. Such fibre optic sensors that provide multiple sensing points or sensing regions along the fibre are commonly referred to as *quasi-distributed optical fibre sensors*. The definition and terminology used in this work is consistent with the majority of publications.

A large potential for optical fibre sensors lies in the possibility to conduct continuously and spatially resolved measurements along the whole length of the fibre. Such sensors are commonly referred to as *distributed optical fibre sensors*. The most important measurement parameters of continuously distributed sensors are strain, temperature and vibration. Examples for commercially successful distributed sensor systems are Brillouin scattering measurement systems for the measurement of strain and temperature and distributed temperature sensors based on Raman scattering.

Distributed or quasi-distributed sensor systems based on Rayleigh backscatter measurement are rather conceptual or employed for niche applications. Various principles have been proposed to measure for example strain [5],[7], temperature [11],[8], humidity [9], displacement [12], fibre curvature [8], refractive indices or other chemical parameters. Providing a universal and precise measurement system for the evaluation of these parameters is attempted in this work. More detailed information on optical fibre sensors in general and their classification can be found in topical summaries [13],[14],[15],[16].

1.2.2 Scattering in optical fibres

The prerequisite for continuously distributed sensing is the interaction of the light propagating in the fibre with the fibre medium. This causes a measurable change of the light's properties or power. The measurement of the properties of scattered light (e.g. power, phase, spectrum or polarization) is the basic principle of almost all spatially resolved sensing principles. One of the most important fibre properties is propagation loss. This is also a limiting factor concerning the maximum distance range of distributed optical fibre sensors. The major sources of loss in silica fibres and POFs are scattering loss, absorption loss or due to fibre bends. Scattering loss is generally the dominant loss mechanism in the favourable transmission windows of silica fibres (around 850 nm, 1300 nm and 1550 nm), PMMA POF (around 500 nm and 650 nm) and perfluorinated POF (around 850 nm, 1000 nm and 1300 nm). Scattering processes can be grouped into two groups: linear scattering processes such as Rayleigh scattering and nonlinear scattering processes that results in a frequency change of the scattered light. Both scattering processes contribute to different extend to propagation loss and backscattered power and can be analyzed for distributed sensing.

¹ Project 'Digital OFDR'; KMU-innovativ program of Bundesministerium für Bildung und Forschung (BMBF) under grant 16N12076.

² FibrisTerre GmbH is a BAM spin-off originating from the former working group "Distributed and Polymer Optical Fibre Sensors" with expertise in Brillouin-OFDR and digital hardware.

Nonlinear scattering

The two most important nonlinear scattering effects in optical fibres are *Raman scattering* and *Brillouin scattering*. Both processes involve energy transfer between the photon and phonons and result in a frequency shift of the scattered light relative to the incident light. Raman scattering involves interaction of the light with vibrational properties of the medium. Its power (the anti-Stokes component) has a very strong temperature dependency and is therefore used for distributed temperature measurement. In case of Brillouin scattering, the interaction is between the photons and acoustical phonons, an effect that is linearly dependent on temperature and strain of the fibre. Stimulated Brillouin scattering occurs at higher optical power and narrow linewidth laser beams and produces an acoustic grating in the fibre via electrostriction. This effect is commonly used for distributed strain and temperature measurement. Both effects, Raman and Brillouin scattering, can be used for distributed sensing but are of negligible power under the conditions at which the I-OFDR setup is operated (relatively broad linewidth and medium power). It can be assumed that nonlinear scattering effects are negligible and predominantly linear scattering is detected.

Rayleigh scattering

Rayleigh scattering is under the operation conditions of the here proposed I-OFDR technique the predominant scattering process. It is a linear process. There is no frequency shift of the scattered light relative to the incident spectrum. The photon energy is conserved, only its direction is changed. The Rayleigh scattering power is an important measurement parameter in this thesis and is therefore introduced in more detail. Rayleigh scattering is scattering of electromagnetic radiation on particles much smaller than the wavelength λ (< λ /10 [17]) and appears in solids, liquids and gases. Scattering on particles of the size of the wavelength or larger can be described by the Mie scattering theory [18]. The Rayleigh scattering theory is based on the electric bipolar radiation model. Rayleigh-scattered light propagates in forward and backward direction of the fibre with the same optical powers. The sources of Rayleigh scattering in optical fibres are random density fluctuations, inhomogeneities, compositional and refractive index fluctuations that become frozen into the fibre during the manufacturing process. Rayleigh scattering has a strong dependence on the incident wavelength proportional to $1/\lambda^4$ and is therefore much higher at shorter wavelengths. Rayleigh scattering loss α_s in silica fibres is the main contributor to the total optical loss in the most common telecommunication transmission windows. Mie scattering has generally a negligible contribution to the scattering loss. The total attenuation coefficient α is commonly expressed in dB/km and comprises the Rayleigh scattering loss α_s and absorption loss α_a [17]:

$$\alpha = \alpha_s + \alpha_a \tag{1.1}$$

Optical loss due to absorption loss may have a significant impact in POF. Its dependency on humidity and temperature is investigated for the PF POF sensor fibre in section 4.3.1. The transmitted optical power I_t along an optical fibre axis with increasing distance z can be described as a function of incident optical power I_0

$$I_t(z) = I_0 \cdot e^{-\alpha z} \tag{1.2}$$

The backscattered Rayleigh power, caused by the forward-propagating optical pulse, is a function of distance and depends on various fibre properties. The length of the fibre section that gives rise to the Rayleigh scattering corresponds to the pulse length Δp in the fibre and is derived from the optical pulse duration τ_p

$$\Delta p = \frac{c_0}{n_{gr}} \cdot \tau_p \tag{1.3}$$

with c_0 being the vacuum speed of light and n_{gr} the effective group refractive index of the fibre. The effective group refractive index (also referred to as 'group index' or 'group velocity refractive index') is

used here since precise signal propagation delay measurement is intended in this thesis and n_{gr} is commonly the only parameter specified by the fibre manufacturers. Assuming a narrow linewidth optical source [19], the signal propagates with a constant group velocity $v_{gr} = c_0/n_{gr}$ and the effective group refractive index can be described with

$$n_{gr} = n_e - \lambda \cdot \frac{dn_e}{d\lambda} \tag{1.4}$$

with n_e being the effective index of the fibre and λ the vacuum wavelength.

The distance z of an event in the fibre that gives rise to backscattered power can be calculated as the temporal delay that the pulse experiences when propagating in forward and backward direction:

$$z = \frac{1}{2} \cdot \frac{c_0}{n_{ar}} \cdot t \tag{1.5}$$

Since the common visualisation of backscatter signals in optical fibres is in distance z from the fibre start (z = 0), the expression requires multiplication by the factor 1/2.

For a rectangular optical pulse of the length Δp , the backscattered power I(z) from a fibre section of the length Δp at the distance z can be described by the following expression [17]:

$$I(z) = S \cdot \alpha_s \cdot \Delta p \cdot I_0 \cdot e^{-2\alpha z}$$
(1.6)

 I_0 is the instantaneous optical power that is maintained during the pulse duration τ_p . *S* is the backscatter capture coefficient of the fibre and determines how much of the scattered power is captured by the fibre in backward direction. This value depends on the fibre type and a number of other parameters such as the numerical aperture (NA), the core refractive index of the fibre and the wavelength [19]. The attenuation coefficient α is multiplied by two since the optical signal experiences the same attenuation travelling in both directions of the fibre. The amount of backscattered power is proportional to the pulse length Δp or the pulse duration τ_p respectively. The total backscattered Rayleigh power I_{RB} , as it would be received when the fibre is filled with a continuous wave (CW) signal, can be calculated from equation (1.6) and is a function of the fibre length *L* and the fibre parameters:

$$I_{RB}(L) = \int_{0}^{L} I(z) \cdot \frac{1}{\Delta p} dz = \frac{1}{2 \cdot \alpha} \cdot S \cdot \alpha_s \cdot I_0 \cdot (1 - e^{-2\alpha L})$$
(1.7)

The total Rayleigh backscattered power from long fibres is mainly determined by the capture coefficient S.

Optical fibres are commonly characterized by the backscatter factor σ for a given pulse duration τ_p or pulse length Δp in the fibre. The backscatter factor specifies the backscattered power that is detected by the receiver without accounting for optical loss in the fibre. For rectangular pulses with a peak power of I_0 , the backscatter level is defined to be σ dB 'below' the peak power of a pulse of the given duration τ_p as

$$\sigma = 10 \cdot \log_{10} \left(\frac{I(z=0)}{I_0} \right) = 10 \cdot \log_{10} \left(S \cdot \alpha_s \cdot \frac{c_0}{n_{gr}} \cdot \tau_p \right) \quad [dB]$$
(1.8)

This approximation is valid as long as the attenuation of the fibre is negligible over the length of the optical pulse in the fibre [17]. Different fibre types exhibit different backscatter coefficients. Typical values for relevant singlemode fibre (SMF) types and multimode (MM) gradient-index (GI) fibres are given in Table 1.1. The backscatter coefficient σ is commonly specified in dB/µs.

λ [nm]	Fibre type	α _s [km ⁻¹]	S	σ [dB] ($ au_p=$ 1 μ s)	NA
1300	MM GI 62.5 μm core diameter	6.5·10 ⁻²	1.0·10 ⁻²	-38	0.275
1300	MM GI 50 μm core diameter	6.5·10 ⁻²	5.0·10 ⁻³	-41	0.2±0.015
1310	SMF 9 µm core diameter	6.3·10 ⁻²	1.0·10 ⁻³	-49 (-47 ¹)	0.14

Table 1.1: Backscatter parameters for different types of optical fibres, data from [17].

Corning specifies its standard SMF-28e+ fibre, which is also used in this thesis, with a Rayleigh backscatter coefficient of $\sigma = -47$ dB for $\tau_p = 1$ µs. The fibre-specific Rayleigh backscatter level σ is also used as an absolute reference in the following chapters.

1.2.3 Reflectometer characteristics

Various techniques have been proposed to retrieve the backscatter powers as a function of fibre length with the purpose of measuring fibre attenuation, backscatter levels or detecting and locating reflections, optical loss or fibre breaks. The probe signal may be pulsed, chirped, sinusoidal modulated or continuous wave. The most important backscatter measurement techniques are briefly introduced in section 1.3. The most widely used approach is the optical time domain reflectometry (OTDR). Most OTDR employ a similar basic principle: a short optical pulse is generated and sent down the fibre under test (FUT) via a fibre coupler or optical circulator. The backscattered power is recorded as a function of time by a photo detector. The general principle of an OTDR is depicted in Figure 1.1.



Figure 1.1: General OTDR principle.

OTDRs have been the standard tool for fibre characterization from the beginning of fibre optic technologies. Commonly used measurement parameters and performance characterization of backscatter measurement devices have therefore been derived from the OTDR technique. These general reflectometer characteristics are not always consistent for different OTDR manufacturers but are summarized in the following.

The I-OFDR, however, exhibits systematic and technological differences compared to OTDR. The OTDR characteristics are therefore not always appropriate to describe the performance of an I-OFDR system. Appropriate I-OFDR characteristics and performance parameters are therefore discussed and defined in section 2.2.2 and section 2.4.

• Spatial resolution

The spatial resolution of an OTDR, sometimes referred to as two-point resolution, defines the minimum distance at which two reflective events of equal power in a fibre can be separated from another. This value is equal to the full-width half-maximum (FWHM) of a single reflection on a reflectometry trace [17],[20] and corresponds to the FWHM of a pulse in standard pulsed-probe reflectometry (OTDR). This definition is also used to define the spatial resolution of an I-OFDR system in section 2.2.2.

¹ From data sheet: Corning[®] SMF-28e+ (http://www.corning.com/WorkArea/showcontent.aspx?id=41261)

• Distance resolution

The distance resolution describes how precisely the absolute distance of a single event can be resolved. The sampling resolution (distance between two consecutive sampling points) of an OTDR is generally better than the length of the optical pulse. The position of an event in the fibre can therefore be obtained with a resolution exceeding the definition of the spatial resolution by using the characteristics of the detected pulse shape (e.g. rising or falling edge, peak maximum or pulse fitting) for the distance evaluation. This distance resolution or 'single point resolution' is therefore more closely linked to the sampling resolution of the device. Its precision in pulse reflectometry is often degraded by pulse shape instability, temporal and thermal variations of the detector electronics or saturation of the detector. Distance resolution is not necessarily important for telecom fibre characterization but crucial for sensing applications targeting precise distance measurement and relative distance measurement as it is intended in this thesis.

• Dynamic range

For telecommunication applications, the most interesting instrument specification is the total fibre length that can be analyzed with an OTDR. For practical applications, this dynamic range value *D* (for one-way optical loss) corresponds to one half of the spacing between the initial backscatter signal and the noise level of the detected backscatter trace of a reflectometer (system dynamic range 2*D*) [19], Figure 1.2. Backscatter traces are commonly displayed as a function of distance in the fibre using equation (1.5). The definition rms (root mean square) dynamic range is the distance between the initial backscatter level and the noise signal at which the signal-to-noise ratio (SNR) equals 1. This definition is related to the detection principle of OTDRs and is nowadays not used very often [20]. An alternative definition, established by the International Electrotechnical Commission (IEC), is that 98 % of the noise is below the IEC noise limit. The IEC dynamic range is therefore about 1.8 dB smaller [20] than the rms dynamic range [17]. The manufacturers generally specify their dynamic range after 3 minutes of averaging and for the longest pulse length of the device (highest Rayleigh level). The length of the FUT and number of averaged pulse responses) is usually not given.



Figure 1.2: Common definition for backscattered power trace: IEC dynamic range and rms dynamic range (2D).

The dynamic range and spatial resolution are two mutually conflicting characteristics in optical time domain reflectometry. Sending short pulses into the fibre for high spatial resolution measurement reduces the available backscattered optical power for detection and also requires wide receiver bandwidth which further decreases the SNR and therefore the dynamic range. Longer pulses result in increased backscatter power and low noise (low bandwidth) receivers can be used. This way, improved sensitivity and dynamic range can be obtained at correspondingly reduced spatial resolution. The dynamic range values given by the manufacturers are not always comparable and should be carefully considered with respect to the measurement constraints (pulse width, measurement time, fibre type and measurement distance). In the case of I-OFDR, the dynamic range is more appropriately described using a modified definition proposed in section 2.4.2.

Fibre attenuation is generally given in dB/km and is stated in transmission (one-way propagation). Equivalently, the attenuation of an optical fibre can be directly obtained from the optical loss (one-way) depiction of the backscatter trace in km by scaling the backscattered power from equation (1.6) by 1/2.

$$I_{loss}(z) = 5 \cdot \log_{10}(I(z)) \quad [dB/km] \tag{1.9}$$

• Sensitivity

For most OTDRs used in the telecommunication industry, absolute sensitivity specifications cannot be found in the performance sheets. A general definition for the sensitivity of a backscatter reflectometer is not explicitly defined in the literature and is not always useful for pulse OTDRs. The system backscatter sensitivity is here defined as the lowest backscatter power that can still be detected (noise level) after a certain measurement time t_{meas} (commonly stated by the manufacturer for $t_{meas} = 3 \text{ min}$) and for a certain pulse duration. For some frequency domain approaches and very high spatial resolution instruments, the absolute sensitivity is an important performance parameter. The sensitivity may be a more informative parameter for customers and could be stated in addition to the system dynamic range. The system sensitivity is closely related to the signal-to-noise ratio (SNR) of the measurement system. Especially for the I-OFDR approach, the parameters dynamic range and sensitivity are important system performance parameters and are thoroughly discussed and defined in section 2.4.

1.3 Optical backscatter measurement techniques

One aim of this work is to analyze and optimize the I-OFDR principle in order to reach the highest possible precision, dynamic range and optimum sensitivity to be used as a general backscatter measurement system with the requirement to measure SMF as well as MM fibre networks. In order to discuss its advantages and limitations with respect to the state of the art, the most relevant and established techniques are briefly introduced in this section and considered for the general use of backscatter measurement. The different methods feature differing characteristics, measurement parameters and tradeoffs regarding spatial resolution, dynamic range, measurement range, measurement time, sensitivity, accuracy and applicability for example to measure MM fibres.

The I-OFDR technique itself, its historical development and state of the art is thoroughly introduced in section 2.1. Differences, advantages and limitations in comparison with the most relevant alternative techniques that are introduced in this section are discussed in section 2.6.

Optical time domain reflectometry (OTDR)

The most versatile and most widely used technique for fibre characterization and fault detection in telecommunication networks is the *optical time domain reflectometry (OTDR)*. This technique has already been introduced in 1976 by Barnoski et al. [21] and has since evolved to become the standard tool for distributed backscatter measurement and fibre testing. All OTDRs basically use the same measurement principle. A short optical pulse is sent into one end of the optical fibre. All backscattered and reflected light of the forward propagating light pulse is detected by the OTDR as a function of the light's delay in the fibre. Since the group refractive index of the fibre is known, a spatially resolved backscatter signature of the fibre can be retrieved. The duration of the optical pulse determines the spatial resolution of the OTDR. Although the signal generation techniques are basically the same for all OTDRs, several detection mechanisms have been developed.

Simple time-resolved sampling of the backscattered power is the most widely used technique. The spatial resolution of such *direct-detection OTDRs* is determined by the length of the optical pulse sent into the fibre and the response time of the receiver. Because of the single pulse measurement, the mean optical power in the fibre is very small which requires low-noise detectors and high amplification. For high spatial resolution measurements, high bandwidth detectors have to be used which further limits the receiver sensitivity and therefore the overall sensitivity of the OTDR. Also, there is a trade-off

between receiver sensitivity and the overload recovery of the receiver [22]. One way to improve the sensitivity is to increase the optical pulse power which is again limited by nonlinear scatter phenomena in the fibre. The spatial resolution and dynamic range are therefore mutually conflicting requirements for conventional OTDR measurements. Another limitation of direct-detection OTDRs is the saturation of the receiver when detecting strong signals originating for instance from Fresnel reflections or fibre connectors. The receiver and amplifier slowly recover sensitivity in an exponential manner after saturation. Therefore the fibre trace is superimposed by the receiver's overload behaviour leading to a loss of information. This time-equivalent distance of the receiver recovery is known as "dead zone" and is an important quality parameter in OTDR. 'Optical masking' is often used to reduce the negative effects of the dead zones. Direct-detection OTDRs are a commercial success and are widely used for general characterization of long fibres with low to medium spatial resolution.

One possibility to increase the dynamic range or sensitivity of an optical reflectometer is to use pulse sequences instead of single pulses. This technique is generally referred to as correlation OTDR (C-OTDR). Various types using different sequences and coding techniques have been proposed. All approaches are based on the idea to increase the energy launched into the fibre compared to single pulse OTDR. The simplest version launches a periodical pseudorandom signal (PRS) into the fibre [23], [24]. Using an internal synchronized variable delay, autocorrelation is conducted for each period of the PRS along the whole "length of the fibre". The correlation signal represents the backscattered power for each period or fibre section. Recent efforts using pseudo-random codes such as the maximumlength sequence superimposed on the downstream data of a time-division-multiplexed passive optical network showed that backscatter traces can be obtained without interrupting the network service. Due to limitations owing from the periodicity of the sequence this approach has not found practical applications. An improvement to PRS C-OTDR has been complementary correlated OTDR (cc-OTDR) using for example Golay code [22]. Aperiodic pairs of codes with complementary autocorrelation functions led to an increased dynamic range and reduced measurement times. This approach resulted in the only correlation OTDR that has been commercialized¹ with better performance than standard OTDR at the time of realization [25]. Later, a simplex code OTDR (sc-OTDR) using a more complex mathematical approach has been introduced [26] and a 9.2 dB SNR increase compared to the single pulse OTDR has been shown [27]. Code gain is the increase of SNR relative to single pulse technique and depends on the code used and the length of the code [27]. Research on optimization of coding schemes is still ongoing. Although correlation-OTDRs have been commercialized, they have not been a major success. The main reason is that they improve dynamic range on long fibres but are inferior to standard OTDR on short fibres [20]. The coding gain is a function of code length and is therefore also limited by the fibre length. The performance of the state of the art seems to lack behind what is possible with other OTDR techniques. Current commercial availability of a high-end correlation OTDR is not known but research in this field is ongoing and further performance improvement can be expected.

One of the most precise OTDRs for the measurement of relatively short fibre lengths is the *photon counting OTDR*, also called v-OTDR. Whereas most standard OTDRs use avalanche photo diodes (APDs) in the linear regime, APDs are used at an increased bias voltage, in the so-called Geiger mode, where even a single photon can trigger a strong signal with a very high gain [20]. In this regime, the backscattered light is attenuated so that the probability of detecting a single photon from each pulse that is sent into the fibre is below 1. A delay timer is triggered each time an avalanche signal is detected. The single detected photons represent a statistical spatial distribution of backscattered optical power and the averaged trace becomes a time-correlated histogram. The high sensitivity of this approach allows for using much shorter pulse widths than required for standard OTDRs, effectively increasing the spatial resolution. Also, the attenuation dead zones after strong reflections are less of a problem compared to direct detection OTDRs when certain measures are taken such as using an optical

¹ Hewlett Packard 8145A OTDR

shutter to prevent afterpulsing and charge-trapping [28], [29]. On the downside, it takes much more time to average a v-OTDR trace compared to direct detection OTDRs to achieve comparable results since less than one photon is detected after each pulse. v-OTDRs provide a high resolution measurement but typically short distances of several hundreds of meters. The absolute measurement range can be extended by combining numerous single traces of time-shifted detection windows. Long-distance measurement for telecom applications is therefore impractical. So far, commercial devices only penetrated niches of the OTDR market [29] but provide excellent results. Such high-end v-OTDR devices¹ have therefore been chosen as the reference technique for direct comparison with the developed I-OFDR approach in this thesis [30].

The coherent detection in *coherent OTDRs* has the advantage of increased dynamic range. That is achieved by heterodyne detection of the optical source signal with the backscatter signal from the FUT. Commonly, an acousto-optic modulator (AOM) is used to form the pulse as well as to modulate an frequency offset onto the narrow linewidth CW optical source before entering into the FUT. The backscattered light is then mixed with a portion of the CW source which acts as the local oscillator. The mixing product with the frequency offset is then detected and filtered for data processing. The advantage is that the signal amplitude can be increased by increasing the power of the local oscillator component and that the dynamic range is increased since the output current is proportional to the square root of the output detected power and not a linear function thereof. Disadvantages of this technique are coherent fading and related signal fluctuations of the backscattered trace as well as signal fading due to polarization changes along the fibre that have to be accounted for. The hardware requirements (narrow linewidth laser source, balanced detection, polarization fading reduction,...) increase the complexity and therefore the costs of a coherent OTDR device. Coherent OTDRs have therefore only found applications in niches of the OTDR market.

The optical low coherence reflectometry (OLCR), sometimes referred to as white light reflectometry, is a coherent detection technique for high-resolution backscatter measurement but very short measurement lengths. A broadband light source with a very short coherence length in the µm-range is coupled into a directional coupler. The light passes into the fibre under test and a reference arm with a movable optical mirror providing an optical delay. The backreflected and backscattered light from both paths interferes at a photo detector and results in interference signals as a function of reflectivity of the FUT at the corresponding optical delay. Only the FUT section matching the delay with the reference arm within the coherence length of the source results in a measurable interference signal. By recording the magnitude of interference as a function of delay (distance along the FUT) while moving the reference mirror, very high spatial resolution measurement (below 2 µm [31]) and high sensitivities up to -161 dB [32] have been achieved in the laboratory. The absolute measurement range is limited by the maximum delay that can be achieved by a mechanical translation stage and is limited to about 1 m or less [17]. The OLCR approach is an excellent method for high-resolution measurement and characterization of optical components but is not suitable for distributed fibre sensing applications due to the length limitation.

Another technique which gained increased attention during the last decade is the *swept wavelength interferometry (SWI)*. This technique was first proposed by Eickhoff et al. [33] and is often called frequency-modulated continuous wave (FMCW) technique, coherent optical frequency domain reflectometry (C-OFDR) or simply OFDR and is not to be confused with the here investigated I-OFDR approach. SWI is based on homodyne interferometry [34]. Generally, the light of a narrow-linewidth single-frequency tuneable laser source is split into a reference arm and the FUT. The signal of the reference arm acts as a local oscillator and is coherently combined with the backscattered signal from the FUT at a photo detector. The detected interference fringes when the laser is tuned are a function of distance and amplitude and are recorded in the spectral domain. A Fourier transform translates the

¹ High-end photon counting OTDRs by Sunrise Luciol are used for comparison measurements in SMF and MM fibres.

measurement result into a time domain signal, the equivalent of an OTDR trace. The coherent detection allows for high dynamic range measurement and high sensitivity so that the Rayleigh backscatter level can also be resolved at very high spatial resolution.

SWI has been used for high-resolution backscatter measurement and component characterization [34]. The emergence of appropriate lasers that can be linearly tuned over a wide wavelength range triggered intense research in this field. Such a system is now commercially available and is unrivalled in terms of spatial resolution for short and medium fibre lengths (10 μ m over 30 m distance) [35]. The high precision and resolution of this approach also allows for distributed measurement of strain and temperature in standard SMF [36]. The spectral shift of the Rayleigh backscattering along an optical fibre can be evaluated as length or temperature changes [37] with cm-spatial resolution up to 70 m fibre length [35]. The spatial resolution of this approach is only matched by OLCR but some restrictions limit the use of this technique for general backscatter detection application. The backscatter spatial resolution is reduces to 1 mm for the maximum possible measurement length of 2 km of the commercial device [35]. Another limitation is that this coherent detection mechanism is only fully applicable if singlemode propagation is ensured. Precise backscatter measurement in MM POF is not feasible.

1.4 Organization of the thesis

This thesis deals with the advancement of the incoherent OFDR approach and its application for optical fibre sensing. Although the proposed sensing techniques and approaches seem to be independent topics, they all rely on the high precision and unique features of the measurement principle, the I-OFDR technique. Sensing approaches and detection mechanism are developed and optimized in mutual consideration of possible interference and limitations throughout this thesis. The structuring of the single sections is therefore not always straightforward and relies on referencing between the relevant chapters. The author hopes that this thesis is understandable in the chosen topical structure.

Chapter 2 summarizes all relevant considerations on the I-OFDR technique and starts with a summary of the state of the art and relevant works on I-OFDR techniques. After a brief theoretical discussion on the analogy of the frequency domain approach to time domain measurements, the laboratory measurement setup is introduced. Systematic characteristics and parameters of the I-OFDR approach are discussed and defined. The importance of the choice of the light source in terms of coherence/interference and limitations on the signal-to-noise ratio of the measurement system is theoretically considered and experimentally confirmed. An active reflection suppression technique as well as an interference compensation approach is proposed. Chapter 2 is concluded with a critical discussion and a comparison to conventional backscatter measurement techniques. Chapter 3 introduces the low-loss perfluorinated (PF) POF and its properties. Dispersion and mode propagation issues in multimode fibres in general and the POF in particular are considered and investigated. The application of distributed strain measurement in PF POF is presented in chapter 4: The effect of backscatter power change with strain is investigated for distributed strain sensing application and the spatial shift of random scattering centres in the POF is proposed for distributed length change measurement by means of backscatter correlation analysis. Cross sensitivities and limitations of this POF type are investigated and discussed. Chapter 5 introduces a sensing technique based on I-OFDR for dynamic length change and optical power change measurement at reflection points in optical fibres. Systematic sources of error are discussed and compensation and fault detection techniques are presented. Laboratory and field test results demonstrate the practical applicability of this approach. Chapter 6 concludes the technological advancements of the I-OFDR technique as well as the proposed sensing principles presented in this thesis.

2 Incoherent optical frequency domain reflectometry (I-OFDR)

The optical time domain reflectometry, or pulse reflectometry, is the most common technique to detect spatially resolved backscattering in optical fibres. Measuring the impulse response of a fibre is the mathematical equivalent of a measurement in the frequency domain and calculating the time domain response by conducting an inverse Fourier transform. The practical implementation of an optical frequency domain reflectometer however, is essentially different. Signal generation, signal detection as well as signal propagation and interaction in the fibre are fundamentally different from pulse domain principles. This chapter analyzes the advantages and limitations of the frequency domain approach. After summarizing the historical development and state of the art of this technique, the I-OFDR laboratory setup is introduced and analyzed from the system point of view. Appropriate performance parameters are defined and determined and an active reflection suppression technique is proposed. The crucial influence of the light source and its spectrum is thoroughly analyzed in terms of interference and noise before comparing the time and frequency domain approaches regarding practical implementation and systematic advantages and disadvantages for backscatter measurement and fibre optic sensing.

2.1 I-OFDR approaches and development

Several measurement principles based on incoherent optical frequency domain reflectometry have been proposed over the last 30 years. All these principles are based on optical power modulation of a continuous wave light source and incoherent detection in order to obtain backscattered power information for each modulation frequency (frequency response measurement) that has to be Fouriertransformed to be analyzed as a function of distance. The terminology in literature is unfortunately not consistent. The swept wavelength interferometry (SWI) is often simply called OFDR without emphasizing the coherent detection mechanism. Since the majority of recent publications describe the SWI approach, the technique investigated in this work is referred to as incoherent OFDR (I-OFDR).

Classification of I-OFDR

Various principles of the incoherent detection approach have been proposed differing in signal generation, detection mechanism, measurement resolution and quality of the time domain result. The proposed principles can be grouped into two techniques. In both cases, the frequency of the optical carrier is maintained whereas the amplitude of the optical source is modulated over a wide frequency range. This is either done using a linear modulation frequency sweep (swept frequency I-OFDR) or by measuring the frequency response for discrete frequencies (step frequency method I-OFDR). The detected frequency response in both cases is transferred into the time domain by Fourier transformation in order to retrieve some spatial information from the fibre under test.

Swept frequency I-OFDR

The swept frequency I-OFDR is based on linearly chirping the modulation frequency of a continuously amplitude-modulated source and either electrical or optical mixing of the delayed return signal from the fibre with the non-delayed probe signal. The resulting mixing products of the probe signal and the reflection signals from an optical fibre are analyzed by means of a spectrum analyzer or by time sampling and Fourier transforming the output. The mixing is either conducted electrically (detected probe signal mixed with the source modulation signal) or by optical mixing of the probe and source signal at a photo diode. The frequencies of the detected low-frequency beat signals are a function of propagation delay or distance in the fibre. This technique is in literature also referred to as 'incoherent FMCW' (frequency-modulated continuous wave) reflectometer, 'beat frequency method' or 'sweep frequency method'. Several laboratory setups using this approach have been demonstrated. MacDonald et al. first showed the detection of weak discrete reflections in an optical fibre using this approach [38]. The mixing in the electrical domain requires high-bandwidth detectors for high resolution measurement and limits therefore the sensitivity or resolution.

Venkatesh et al. [39] utilized a broadband electro-optic modulator to optically down-convert the signal enabling the use of a low frequency optical receiver and demonstrated 6.8 cm two-point resolution measurement of discrete reflections in an optical fibre. MacDonald et al. 1990 used a mixing photodetector to reduce the post-detection bandwidth of the system and achieved 10 m distance resolution [40]. Pierce et al. showed that the location of optical loss in an optical fibre can be derived from changes of the beat frequency of a simple swept frequency setup [41]. Ryu et al. [42] demonstrated a system using electrical mixing that is capable of measuring fault location with accuracy better than 2 mm.

The swept frequency method has the disadvantage that it cannot be easily calibrated. The frequency roll-offs of the single components of the setup cannot be neglected and contribute to the entire swept frequency spectrum leading to nonlinearities [43]. This might be the reason that only the detection of discrete reflections and no distributed backscatter measurement has been demonstrated using the swept frequency technique.

Step frequency I-OFDR

A step-wise measurement of phase and amplitude of each discrete modulation frequency yields the complex transfer function, or frequency response, of the measurement system and the fibre under test. The linearity of this approach is discussed in section 2.2.3 and section 2.5. This is the prerequisite for accurate calibration and precise general purpose backscatter measurement. Bandpass filtering of each modulation frequency reduces the noise and enables high sensitivity. The measurement time for a single sweep using the step-frequency I-OFDR is generally longer than that of the sweep-frequency method but discrete reflections as well as Rayleigh backscattering and optical loss can be detected. This technique has been named step frequency method (SFM) or network analysis (NA) OFDR technique since a vector network analyzer (VNA) is commonly used to measure the complex frequency response of the FUT over a wide frequency range. This approach is the subject of research of this thesis and is therefore discussed in great detail. This technique is in the following simply referred to as I-OFDR.

The first works related to step frequency I-OFDR have been conducted in the 1980s and remained at a stage of simulation results and laboratory tests [44], [45], [46]. The intended use and practical capabilities of the published results were limited to fault localization or for backscatter loss measurement at low spatial resolution. The spatial resolution is defined in section 2.2 and is inversely proportional to the maximum modulation frequency. Further theoretical considerations for the use of the I-OFDR have been conducted by Kapron et al. [44]. Shadaram et al. later theoretically discussed the frequency domain response of an optical fibre for the analysis of discrete and distributed reflections in optical fibres [45], [46]. Based on theoretical investigations, they concluded that this technique is an efficient way to detect discrete reflections in the fibre but is not suitable to measure distributed reflections such as Rayleigh scattering and loss due to the small amplitude of distributed reflections for higher modulation frequencies [45]. These conclusions have later been proven to be wrong. Ghafoori-Shiraz et al. were the first to successfully conduct an I-OFDR backscatter measurement [47]. They detected reflections in silica fibres as well as fibre attenuation by measuring the Rayleigh backscattering change along the fibre with a maximum modulation frequency of 2 MHz (corresponding to 50 m spatial resolution) [47], [1], [2]. Nakayama et al. [48] conducted incoherent OFDR calling the technique step frequency method (SFM) and demonstrated an optical fibre fault locator with a maximum modulation frequency of 4.096 MHz (corresponding a spatial resolution of 25 m). The measurement of Rayleigh levels and optical loss however, has not been shown. Schlemmer realized a heterodyne and homodyne network analyzer and used it for distributed backscatter measurement with modulation frequencies up to 10 MHz (corresponding to 10 m spatial resolution) [49].

Dolfi et al. [50] demonstrated a measurement with a high modulation frequency envelope of 20 GHz allowing for the detection of reflections in an optical fibre with a spatial resolution of 5 mm. This is the highest resolution for full bandwidth modulation and detection reported so far. The same group later

used an electro-optic modulator as an electrical-optical mixer to down-convert the return signal to a lower intermediate frequency and achieved a resolution of 4 mm [51]. Distributed Rayleigh backscattering could not be detected using these high modulation frequencies.

The I-OFDR approach has also been used for distributed measurement of nonlinear scattering effects in optical fibres. Distributed temperature sensing has been realized by analyzing the relation between Stokes and Anti-Stokes of the Raman components of the backscattered light using the I-OFDR approach [52], [53]. A Raman device with a spatial resolution in the order of 1 m has been realized. Also the measurement of the Brillouin frequency shift as a function of strain and temperature has been demonstrated using the I-OFDR technique [54], [55], [56]. This technique has further been advanced using digital signal generation and signal processing [57] and also became commercially available with a spatial resolution of about 1 m.

Compared to the detection of Rayleigh backscattering and discrete reflections, the detection of Raman powers and the measurement of Brillouin spectra present different challenges in terms of source spectrum, dynamic range and detection mechanisms. The detection of Stokes and Anti-Stokes of the Raman spectra represents a simple power comparison between these components after carefully filtering the Rayleigh and Brillouin backscattering components. The measurement of Brillouin spectra on the other hand is basically a frequency measurement. Although the Rayleigh backscattering signal is 15–20 dB stronger than that of Brillouin scattering [58], Brillouin I-OFDR has advantages regarding the signal to noise ratio due to fitting of the detected Brillouin spectrum.

A general optical reflectometer, as targeted in this thesis, has to be able to detect distributed backscattering as well as reflective events in an optical fibre. In the frequency domain, this requires a highly linear measurement system over the whole frequency range. The linearity of the system is discussed in more detail in section 2.2.3 and section 2.5. Very weak signals originating from the Rayleigh scattering of the fibre have to be detected at the presence of strong signals arising for example from reflections in the fibre under test. Considering the promising first results for distributed backscattering measurement [2] and the extended approach by Dolfi et al. [50], it is somewhat surprising that this technique has not thoroughly been considered for general backscatter measurement as an alternative to OTDR. It is the scope of chapter 2 to analyze the I-OFDR technique in depth and discuss its limitations, advantages and disadvantages with respect to established optical reflectometers like OTDR.

2.2 Theoretical background

The general concept of the I-OFDR has briefly been introduced. In this section, the I-OFDR approach is explained from the system point of view and in terms of the analogy to time domain measurement. Signal processing techniques and their influence on important system parameters are simulated and the impact of interference influences is derived.

2.2.1 Analogy time domain / frequency domain measurement

Measurement in the time domain

Measurement applications in the time domain using pulses have been used in various fields including Radar, Lidar, Sonar as well as for the measurement of the characteristics of electrical lines. The time domain reflectometry approach in optical fibres is called OTDR, section 1.3. The general principle has been introduced in section 1.2.3 and is depicted in Figure 1.1. A short optical pulse of the duration τ_p is generated by either directly pulsing an optical source or using an external power modulator. The pulse is coupled into the FUT via an optical coupler or circulator and the backscattered signal h(t) is detected by a photo detector. The delay of the optical pulse in the fibre is measured by some timer electronics and is translated into spatial dependency of the OTDR using equation (1.5). The spatial resolution of an OTDR is defined by the full width half maximum (FWHM) of the system response time Δt_s , which is

approximately the pulse duration τ_p . Analogous to the expression in equation (1.5), the spatial resolution δz can therefore be calculated using

$$\delta z = \frac{1}{2} \cdot \frac{c_0}{n_{gr}} \cdot \Delta t_s \tag{2.1}$$

An ideal system is assumed here with no broadening of the pulse when propagating along the fibre. If the response time of the receiver τ_r is slower than the optical pulse duration τ_p , the effective optical pulse duration, or system response time, Δt_s increases [17] according to

$$\Delta t_s \cong \sqrt{\tau_p^2 + \tau_r^2} \tag{2.2}$$

Mathematically, any linear and time-invariant system is completely characterized by its impulse response h(t). That means that for any input signal, the output can be calculated from the input and the impulse response. The impulse can be modelled as a Dirac delta function (δ function) with an infinitely short impulse ($\tau_p = 0$):

$$\delta(t) = \begin{cases} +\infty & , t = 0\\ 0 & , t \neq 0 \end{cases}$$
(2.3)

satisfying

$$\int_{-\infty}^{+\infty} \delta(t)dt = 1$$
(2.4)

The Dirac delta function contains all frequencies corresponding to an infinitely broad spectrum in the frequency domain. This assumption is only made here to derive the analogy of the time domain and the frequency domain. In reality, neither a Dirac impulse can be generated or propagate along an optical fibre nor can an infinite frequency response be measured. Since the I-OFDR measurement is defined and conducted for a finite frequency range, theoretical implications involving the Dirac impulse are neglected. Actual pulses generated by an OTDR have a finite width and result in a measured signal representing a convolution of the impulse response h(t) with the generated optical pulse (pulse broadening neglected). The issue of system linearity of OTDR and I-OFDR is further discussed in this chapter. It is usually easier to determine the transfer function from measurements in the frequency domain and conduct a Fourier transform to analyze the impulse response of a system. This frequency domain approach is described and investigated in the following.

Measurement in the frequency domain

If the system is linear and time-invariant, the impulse response h(t) can be transferred into the system's frequency response $H(j\omega)$ by Fourier transform:

$$H(j\omega) = \int_{-\infty}^{+\infty} h(t) \cdot e^{-j\omega t} dt$$
(2.5)

The inverse operation is described as

$$h(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} H(j\omega) \cdot e^{j\omega t} d\omega$$
(2.6)

This ideal expression implies a continuous frequency response over an infinite frequency range. In practical application, the frequency response is often determined by a Vector Network Analyzer (VNA). The actual frequency response is therefore only known for a finite number of modulation frequencies f_m (with $f_m = \omega/2\pi$) within a limited frequency band between $-f_{m,max} \leq f_m \leq +f_{m,max}$ with a fixed frequency step $\Delta f = \Delta \omega/2\pi$. The resulting discretized transfer function $H_d(j\omega)$ for an infinite spectrum (assumed $H(j\omega) = 0$) for frequencies exceeding $|f_{m,max}|$ can be described with the help of the sifting property of the δ function [59]:

$$H_d(j\omega) = \sum_{k=-\infty}^{+\infty} H(j \cdot k \cdot \Delta\omega) \cdot \delta(j(\omega - k \cdot \Delta\omega))$$
(2.7)

The Fourier transform of the discrete frequency domain function (discrete Fourier transform (DFT)) results in the periodic function $h_p(t)$ with the periodicity $T_P = 1/\Delta f$

$$h_p(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} H_d(j\omega) \cdot e^{j\omega t} d\omega = T_P \cdot \sum_{d=-\infty}^{+\infty} h(t - d \cdot T_P)$$
(2.8)

h(t) is the inverse Fourier transform of the continuous transfer function $H(j\omega)$. If the signal of h(t) is shorter than the period T_P , the signal $h_p(t)$ has no periodic overlap and the time domain result h(t) can be correctly obtained. The maximum length z_{max} of a fibre which can be uniquely obtained without overlap depends on T_P and thus the discrete frequency step size Δf that is used for the measurement:

$$z_{max} = \frac{1}{2} \cdot \frac{c_0}{n_{gr}} \cdot \frac{1}{\Delta f}$$
(2.9)

Considering a singular reflection in the fibre at the distance z_1 with an amplitude attenuation described by A_1 , the resulting transfer function can be described as

$$H_1(j\omega) = A_1 \cdot e^{-j\omega\tau_1} \tag{2.10}$$

where $\tau_1 = 2 \cdot z_1 \cdot n_{gr}/c_0$ is the time delay of the signal propagating to and from z_1 .

For an infinite spectrum, the impulse response with equation (2.10) is

$$h(t) = \frac{A_1}{2\pi} \int_{-\infty}^{+\infty} e^{-j\omega\tau_1} \cdot e^{j\omega t} d\omega = A_1 \delta(t - \tau_1)$$
(2.11)

A practical implementation of frequency domain measurement is generally low pass frequencylimited to a maximum modulation frequency $f_{m.max}$. The resulting impulse response is described as

$$h(t) = \frac{A_1}{2\pi} \int_{-2\pi f_{m,max}}^{+2\pi f_{m,max}} e^{-j\omega\tau_1} \cdot e^{j\omega t} d\omega = 2A_1 \cdot f_{m,max} \cdot \operatorname{sinc}(2\pi f_{m,max} \cdot (t - \tau_1))$$
(2.12)

The fast Fourier transform (FFT) is an efficient implementation of the discrete Fourier transform and uses the symmetry properties of the complex exponential function. The negative frequency samples are conjugate symmetric values of the measured frequency response:

$$H(j\omega) = H^*(-j\omega) \tag{2.13}$$

and the IFFT of the conjugate symmetric DFT results in a real-valued time domain response h(t). The IFFT of $H(j\omega)$ is described as

$$h(t) = \mathcal{F}^{-1}\{H(j\omega)\}$$
(2.14)

Since the transfer function $H(j\omega)$ is determined for discrete frequency points and a limited frequency range, the discrete Fourier transform results in a time response (or spatial response) with discrete values. These resulting 'FFT bins' are separated in the time domain by

$$\delta t_{bin} = \frac{1}{2} \cdot \frac{1}{f_{m,max}} \tag{2.15}$$

The time domain response h(t) can be transferred into the spatial backscatter response h(z) by applying equation (1.5). Most backscatter measurement results are in this thesis plotted in the spatial domain h(z) instead of the directly calculated time domain response since distance measurement and distance resolution results are more relevant for the application as a backscatter sensor.

Obtaining the DC value

An implementation problem that has not yet been addressed is the value $f_m = 0$. The 'DC value' of the transfer function cannot be measured with a practically implemented I-OFDR setup which is passband-limited to $f_{m,min} = 10$ kHz. Neglecting the DC value ($H(j\omega = 0) = 0$) results in a negative offset of the time domain response h(t) and negative values for very low signal powers (i.e. the noise level of the measurement system at distances after the fibre end). The DC value of the frequency response of a backscatter measurement is the equivalent of the sum of all backscatter components from the fibre in the time domain. This value can, however, not be directly retrieved from the frequency domain results $H(j\omega)$. An indirect calculation of $H(j\omega = 0)$ using the time domain result is necessary. It can be assumed that the system noise power is very small compared to the signal itself. The time domain trace h(t) is therefore levelled to zero power at the location of no backscatter signal (noise only after the end of the fibre), see Figure 2.1. The summation of each bin of the time domain result of the levelled time domain trace h(t) corresponds to the sum of all backscattering power from the fibre. This integrated backscatter power value

$$H(j\omega = 0) = \sum_{n=0}^{T_P/\delta t_{bin}} h(n \cdot \delta t_{bin})$$
(2.16)

is a good approximation of the DC value and can be used to conduct an IFFT using the result of equation (2.16) as the 'DC value'. The result is mathematically identical to the zero-levelled time domain result. Figure 2.1 shows the corresponding time domain result for $H(j\omega = 0) = 0$ and the DC-corrected result.



Figure 2.1: Backscatter traces h(t) from same measurement: zero DC value ($H(j\omega = 0) = 0$) and the zero-levelled trace.

Another option which would require additional hardware implementation would be to measure the DCcoupled backscattered optical power and calculate the equivalent DC value from the modulation depth (or modulation index) m used for frequency modulation. This approach is not necessarily more precise than the zero-levelling approach, for example due to possible bias point drift of the modulator. The zero-levelling of the noise of h(t) is therefore conducted in all following measurements. This step is necessary in order to correctly level the backscatter traces and be able to conduct correct reflectivity measurement as well as Rayleigh scattering measurement in the FUT.

2.2.2 Spatial resolution and windowing

The measurement system represents an ideal low-pass filter (rectangular function) which translates, after Fourier transformation, into a sinc function:

$$\operatorname{sinc}(x) = \frac{\sin(\pi x)}{\pi x}$$
(2.17)

Instead of the δ function, as it would be the case for an ideal infinite and continuous frequency spectrum, the resulting temporal or spatial resolution is not infinitely small but broadened by the band-limited sinc function.

The spatial separation between the 'FFT bins' δz_{bin} can be calculated from the temporal separation of the discrete 'FFT bins' (equation (2.15)) in reflection and equation (1.5):

$$\delta z_{bin} = \frac{1}{4} \cdot \frac{c_0}{n_{gr}} \cdot \frac{1}{f_{m,max}}$$
(2.18)

Two events in the fibre can therefore only be separated with twice the bin distance and the *spatial resolution of an IFFT result* is defined as

$$\delta z = 2 \cdot \delta z_{bin} = \frac{1}{2} \cdot \frac{c_0}{n_{gr}} \cdot \frac{1}{f_{m,max}}$$
(2.19)

The spatial resolution is therefore limited by the maximum modulation frequency. This value is generally considered to be the direct equivalent to the system response time of the time domain approach ($\sim \Delta t_s$), as in equation (2.2), and has in all previous publications been used to characterize the spatial resolution of an I-OFDR measurement result. The IFFT results in discrete time domain samples are equally spaced at distances of δz_{bin} . The absolute position of a reflection can therefore only be determined with a resolution of $\delta z/2$. Also, the magnitude (peak maximum) of a reflection directly obtained from the time domain plot depends on the location of the reflection relative to the IFFT bins. h(t) and h(z) basically contain discrete values of a sinc function (as described in equation (2.12)). Figure 2.2 shows simulated IFFT results of single reflections at the distances $z = 10 \cdot \delta z_{bin} \approx 0.25$ m and $z = 12 \cdot \delta z_{bin} \approx 0.3$ m coincide exactly with an IFFT bin. All other bins coincide exactly with the zero-crossing of the sinc function. Reflections at $z = 18.5 \cdot \delta z_{bin} \approx 0.47$ m and $z = 20.5 \cdot \delta z_{bin} \approx 0.52$ m correspond to a location exactly between two bins.



Figure 2.2: Simulation results for equally strong reflections at different positions at exact multiples of δz_{bin} ($z \approx 0.25$ m and $z \approx 0.3$ m) and reflections exactly between two bins of δz_{bin} ($z \approx 0.47$ m and $z \approx 0.52$ m); $\Delta f = 1$ MHz, $f_{m,max} = 2$ GHz, $n_{gr} = 1.4677$.

These two results are the extremes that can occur after conducting the IFFT. Reflections at multiples of δz_{bin} coincide with a single FFT bin and give correct indication of the reflection power. At all other locations, the power is partitioned to neighbouring bins and reduced reflection peak power is measured. This effect of reduced peak power is known as *scalloping loss* and prevents correct determination of reflection magnitudes from IFFT results.

Another perturbing effect that is visible in Figure 2.2 is in signal processing often called *spectral leakage*: the band limited detection of the system response results in spreading of the result (sinc function) into other output bins of the IFFT result. In the case of reflections at distances at multiples of δz_{bin} , all other bins are exactly at the zero crossings and give the impression of no spectral leakage. Signal contributions from intermediate distances cause significant side lobes that can deteriorate the backscatter measurement performance. This issue and possibilities to reduce side lobes are further addressed in the following section.

Zero padding

An efficient method to reveal additional information from a FFT result and prevent scalloping loss is known as *zero padding*. This process increases the number of input data samples by adding zero-valued data samples to the original measured input sequence, virtually extending the measurement bandwidth. This way the output resolution of the time domain is improved [60] by 'interpolating' additional bins between the original IFFT results. However, no new information is added. Zero padding does mathematically not increase the resolution but 'reveals' useful information of the signal between the bins of the original measured input sequence. The zero padding factor f_{zp} describes the number of additional zeros n_{zero} added to the IFFT input:

$$f_{zp} = n_{zero} \cdot \frac{f_{m,min}}{f_{m,max}}$$
(2.20)

Figure 2.3 shows the same simulated measurement results as in Figure 2.2 but with zero padding applied.



Figure 2.3: Simulation results for single reflections at the same positions as in Figure 2.2 but with zero padding applied $(f_{zp} = 50)$; $\Delta f = 1$ MHz, $f_{m,max} = 2$ GHz, $n_{gr} = 1.4677$.

The reflection magnitude and reflection position can be precisely obtained from the zero-padded results. As the output magnitude of the time domain response is decreased by the factor of added zeros f_{zp} , it has therefore to be multiplied with f_{zp} to obtain correct magnitude results. Zero padding is an efficient method to correctly interpolate intermediate bins and therefore improve the data available for precise position and power evaluation of reflective events. The spatial separation between the single FFT bins δz_{res} is calculated as

$$\delta z_{res} = \frac{1}{4} \cdot \frac{c_0}{n_{gr}} \cdot \frac{1}{f_{m,max}} \cdot \frac{1}{f_{zp}}$$
(2.21)

The spatial resolution or 'two-point' resolution of an OTDR is defined by the FWHM of the pulse (equation (2.1)). Whereas Δt_s determines the spatial resolution of the time domain approach, the mathematically limiting value of the discrete frequency domain approach is proportional to δz . Zero padded discrete IFFT results however, allow for practically increasing the spatial resolution based on the FWHM definition in optical reflectometry measurement by interpolating intermediate values as shown in Figure 2.3. The FWHM (or 3 dB value of the logarithmic backscatter plot) of a zero padded sinc function is smaller than the definition for δz in equation (2.19). The actual FWHM is obtained by simulating a zero padded reflection response corresponding to the sinc function. It is useful to define the FWHM of this reflection response in multiples of FFT output bins *b*. The 3 dB bandwidth (FWHM) or spatial resolution, of a zero padded I-OFDR result is therefore given in bins and is simulated to be b = 1.21 for the calibrated bandlimited frequency response (the sinc function). According to the FWHM definition, two reflective events can be separated with an improved effective two point resolution

$$\delta z_{eff} = b \cdot \frac{\delta z}{2} \tag{2.22}$$

This corresponds to a spatial resolution improvement by the factor of 1.653 compared to δz from equation (2.19): $\delta z_{eff} = \delta z/1.653$. The actual spatial resolution of an I-OFDR measurement is therefore higher than stated in all previous publications [56],[57]. This value is only valid for a not windowed IFFT result (sinc function). The necessity and advantages of windowing the frequency domain response before conducting the IFFT as well as its impact on the spatial resolution are quantified and discussed in the following section.

Windowing

The calibrated transfer function of the FUT is an ideal low-pass filtered result and corresponds to a rectangular-windowed result of an infinite frequency response. As it can be seen in Figure 2.3, IFFT results show symmetric side lobes, which may superimpose weak backscatter signals in the vicinity of a strong reflection. This effect is known as spectral leakage in signal processing. It is common practice to smoothen the edges of a time-sampled signal or a band-limited frequency response to reduce spectral leakage by applying a window function before conducting a Fourier transform. Various window functions with different characteristics, optimized for different purposes, have been proposed [61], [62]. The relevant characteristics are the main lobe width (FWHM of the main lobe in bins), the sidelobe suppression (highest sidelobe level relative to the main lobe) and the side lobe fall-off ratio (decay of sidelobe level with increasing sidelobe number given in dB/octave).

The most *important requirements* for this application are maintaining high spatial resolution (*main lobe width*) while minimizing the spectral leakage effects (*high sidelobe suppression*) in order to be able to resolve small backscatter events in the vicinity of reflective events in the fibre. Also, a window function with *sidelobe fall-off* is required in order to not superimpose distant low-power backscatter signals. This excludes the otherwise suitable Dolph-Chebyshev window. Three window functions qualify for all requirements and exhibit similar performance: the Barcilon-Temes window, the parameter-optimized Blackmann-Harris window and the Kaiser-Bessel window function [61]. The Kaiser-Bessel window function shows slightly better performance than the Barcilon-Temes window function. The Blackmann-Harris window exhibits slightly better sidelobe suppression but the Kaiser-Bessel window is chosen in this thesis because of its more flexible use and predictable sidelobe roll-off [61]. The Kaiser window function is parameterized with the value α_K : increasing α_K results in reduced side lobe levels but comes at the cost of a widened main lobe, which effectively decreases spatial resolution. The Kaiser window is defined as

$$W_{Kaiser}(n) = \frac{I_{\alpha} \left(\pi \alpha_K \sqrt{1 - \left(\frac{2n}{N}\right)^2} \right)}{I_{\alpha}(\pi \alpha_K)}, n = -\frac{N}{2}, \dots, \frac{N}{2} - 1$$
(2.23)

where I_{α} is the zero-order modified Bessel function of the first kind and N is the window length. For $\alpha_{K} = 0$ the window function corresponds to a rectangular window.

The Kaiser window function for frequency domain windowing $W_{Kaiser}(\omega)$ is defined as

$$W_{Kaiser}(\omega) = \frac{I_{\alpha} \left(\pi \alpha_{K} \sqrt{1 - \left(\frac{2\omega}{N \cdot \Delta \omega}\right)^{2}} \right)}{I_{\alpha}(\pi \alpha_{K})}$$
(2.24)
with $N = 2 \cdot \frac{f_{m,max}}{\Delta f}$ and $\omega = -\frac{N}{2} \cdot \Delta \omega, \dots, \frac{N}{2} \cdot \Delta \omega - 1$

Depending on the measurement task, a flexible use of the window (changing the parameter α_K) can be beneficial: resolving weakly scattering events in the vicinity of a strong reflection requires high side lobe suppression whereas resolving closely spaced scattering events requires high spatial resolution (narrow main lobe width). The importance of appropriate windowing will be evident in the following chapters. The side lobes appear in the time domain depiction at not equidistant distance from the main lobe and exhibit an asymptotic roll-off of 6 dB/octave. Window functions are commonly plotted and characterized in logarithmic magnitude. The normalization of the inverse Fourier transform of the Kaiser window function over $|w_{Kaiser}(t = 0)|$ is

$$w'_{Kaiser}(t) = 10 \cdot \log_{10} \left(\frac{|w_{Kaiser}(t)|}{|w_{Kaiser}(t=0)|} \right)$$
 [dB] (2.25)

Instead of analyzing spectra of Fourier-transformed time domain-sampled signals, the windowed IFFT result of the frequency response is analyzed in the time domain or spatial domain by applying equation (1.5):

$$h(z) \propto h(t) = \mathcal{F}^{-1}\{H(j\omega) \cdot W_{Kaiser}(\omega)\}$$
(2.26)

The window function is therefore calculated in the following and analyzed corresponding to the time domain backscatter result after conducting an IFFT of a Kaiser-windowed frequency response. The absolute and normalized backscatter description is

$$h'(z) = 10 \cdot \log_{10} \left(\frac{|h(z)|}{|h(z=0)|} \right)$$
 [dB] (2.27)

The following plots show simulation results of the time domain response with intermediate bins obtained by zero padding a rectangular windowed frequency response ($\alpha_K = 0$) up to $f_{m,max} = 2$ GHz. The 2 GHz maximum modulation frequency has been chosen for all simulations because the actual measurement setup, introduced in section 2.3, has a -3 dB bandwidth limit of about 2 GHz.



Figure 2.4: Rectangular window time domain results: linear magnitudes (left) and normalized logarithmic magnitude $10 \cdot log_{10}(|h(z)|/|h(z=0)|)$ (right); $\alpha_K = 0$, $f_{m,max} = 2$ GHz, $n_{gr} = 1.4677$.

It can be noticed that the first side lobe and from there every other side lobe of the sinc function has negative values. Negative values are just as valid and will be evident in the backscatter plot. For the analysis of the window parameters, absolute logarithmic backscatter values are evaluated as a function of distance according to equation (1.5). Figure 2.5 shows a simulation of the Kaiser window function for different α_K values and the corresponding time domain results as a function of distance corresponding to a measurement result with $f_{m,max} = 2$ GHz.



Figure 2.5: Kaiser Bessel window functions for different α_K (left) and the corresponding normalized time domain results $10 \cdot log_{10}(|h(z)|/|h(z=0)|)$ (right); $f_{m,max} = 2$ GHz, $n_{gr} = 1.4677$.

The two important window parameters, main lobe width and side lobe suppression, are calculated as a function of α_K . The main lobe width is the equivalent to the OTDR definition of the spatial resolution (FWHM of detected pulse). The 3 dB main lobe width obtained from simulations results of equation (2.27) is plotted in Figure 2.6 (left) as a function of α_K as the effective spatial resolution δz_{eff} and the equivalent resolution in bins (*b*) for $f_{m,max} = 2$ GHz. Figure 2.6 (right) shows the dependence of the side lobe suppression on α_K . Again, it has to be noted that all uneven side lobes have negative sign and are evident in the backscatter trace.



Figure 2.6: Simulation results: effective spatial resolution δz_{eff} and DFT bins b (left) and suppression of first side lobe peak magnitude $10 \cdot \log_{10}(|h(z)|)$ relative to main lobe peak magnitude (right) as a function of α_K ; $f_{m,max} = 2$ GHz, $n_{ar} = 1.4677$.

The spatial resolution according to equation (2.19) is about 5.1 cm for $f_{m,max} = 2$ GHz in SMF ($n_{gr} = 1.4677$). Using the FWHM definition for spatial resolution, events of equal power can be discriminated with better resolution than stated in equation (2.19) (not zero-padded DFT result) up to a Kaiser parameter of $\alpha_K \approx 2.008$ where b = 2. Using equation (2.22), the effective spatial resolution for $\alpha_K = 0$ is $\delta z_{eff} \approx 3.1$ cm.

As the main lobe broadens with increasing α_K , the main lobe maximum decreases with increasing α_K . Figure 2.7 shows the relative main lobe magnitude as a function of α_K compared to a rectangular window function ($\alpha_K = 0$). This leads to a decreased peak magnitude of the main lobe for singular reflections. The total energy ($\sum h(z)$) of the Kaiser-derived 'pulse' however, does not change with increasing α_K . Figure 2.7 (right) shows that the integrated magnitudes of h(z) (compare Figure 2.4 (left)) remains constant. Only the relation of positive values ($\sum [h(z) > 0]$) to negative values ($\sum [h(z) < 0]$) as well as the magnitude in the main lobe change with α_K , Figure 2.7 (right).



Figure 2.7: Simulation results: main lobe magnitude change relative to rectangular window result (sinc function for $\alpha_K = 0$) as a function of α_K (left) and magnitude changes of h(z) as a function of α_K for the sum of positive values, negative values, total values and main lobe only.

This independence of the 'pulse energy' on α_K means that the Rayleigh backscattering level is not affected by windowing of the frequency response and is constant for a given $f_{m,max}$. This is important since the backscatter level is used as a reference for obtaining absolute reflection magnitudes as well as for defining the sensitivity and dynamic range of I-OFDR in section 2.4.2. The independence on α_K holds

true for distributed scattering and under the assumption that the attenuation can be neglected within a distance equivalent to the first few side lobes around of the Kaiser-derived 'pulseform', which is generally the case for the fibre types used in this thesis. The peak magnitude difference from a discrete reflection only (Rayleigh backscattering power subtracted) relative to the peak magnitude of $\alpha_K = 0$ can be derived for different α_K from Figure 2.7 (left).

2.2.3 Linearity and time-invariance of the system

A linear and time-invariant system (LTI system) is a system that is characterized by its linear behaviour and its independence of the system response on the temporal delay of the input signal. These properties are a prerequisite for a correct I-OFDR measurement and its mathematical operations involved.

A system can be considered to be a **linear system** when the output signal is the linear superposition of individual outputs as they would have been obtained by applying the input signals separately. The general characterization in the time domain is as follows: If an input signal $x_1(t)$ produces a response $y_1(t)$ and a different input signal $x_2(t)$ produces a response $y_2(t)$, their scaled (by the factors c_1 and c_2) and summed combination results in a scaled and summed combination of the equivalent output signals:

$$c_1 \cdot x_1(t) + c_2 \cdot x_2(t) \Rightarrow c_1 \cdot y_1(t) + c_2 \cdot y_2(t)$$
 (2.28)

A system is **time-invariant** if a delay τ_0 of the input signal $x(t - \tau_0)$ results in a response delayed with the same time τ_0 as

$$f(x(t)) = y(t) \quad \Rightarrow \quad f(x(t-\tau_0)) = y(t-\tau_0) \tag{2.29}$$

The response of a time-invariant system is independent of the time at which the input signal is applied. A LTI system can therefore be entirely characterized by its impulse response h(t). The signal response y(t) of a LTI system is simply a convolution (denoted by *) of the input signal x(t) with the impulse response h(t).

$$y(t) = x(t) * h(t)$$
 (2.30)

Equivalently, in the frequency domain (Fourier domain), a LTI system is characterized by its transfer function $H(j\omega)$. The convolution theorem for Fourier transforms states that a convolution in the time domain is the equivalent of a multiplication in the frequency domain and vice versa:

$$Y(j\omega) = X(j\omega) \cdot H(j\omega)$$
(2.31)

with $Y(j\omega) = \mathcal{F}{y(t)}; X(j\omega) = \mathcal{F}{x(t)}; H(j\omega) = \mathcal{F}{h(t)}.$

For a sinusoidal frequency-modulated LTI system, as it is assumed for the I-OFDR, the response will also be a sinusoid with phase and amplitude depending on the transfer function of the system but the same frequency. A LTI system does not produce additional frequencies.

In reality, no system is strictly linear and time-invariant. Small deviations originate from the single system's components. Care has therefore to be taken to minimize the deviations from the LTI response when designing and operating the I-OFDR system. The I-OFDR measurement result itself, the Rayleigh backscatter, is a linear effect with respect to the optical field. A source of nonlinearity that is discussed in the following section and in section 2.5.1 is possible interferometric superposition of electrical fields. However, it is shown that this impact can be minimized or avoided by choosing a low-coherent light source. Nonlinear scattering effects such as Brillouin and Raman scattering can practically be ruled out to have an impact on the response due to the relatively broadband sources and moderate optical signal power. Due to the negligible deviations from the ideal response, the I-OFDR system is in the following considered to be a LTI system. System linearity is the prerequisite for accurate distance and power measurements. This is especially important for the assumptions made regarding the measurement technique introduced in chapter 5.
2.2.4 Nonlinearity due to interference

The interference of electrical fields is potentially the most important source of nonlinearity in I-OFDR. Optical interference occurs if the fields superpose under the assumption that they are correlated – or coherent – with another. The degree of coherence (respectively the emission spectrum or linewidth) of the optical source is therefore a crucial system parameter. Its impact is described by the following equations and is further discussed in section 2.5. The optical field of a source is commonly described as

$$E(t) = \hat{E}_0 \cdot e^{j(\omega_0 t + \phi(t))}$$
(2.32)

 \hat{E}_0 is the amplitude of the optical field, the centre angular frequency of the optical field is denoted ω_0 and the random phase noise of the laser source is described by $\phi(t)$. The field is scaled such that its square magnitude is the optical power $I_0(t)$:

$$I_0(t) = |E(t)|^2$$
(2.33)

If only this electrical field is directly detected on a photodetector, the induced photocurrent would only be a function of the input power variations $I_0(t)$ and the phase information $\phi(t)$ would be lost. However, backscatter measurement always involves the detection of optical power from different locations in the fibre. The reflected optical power I_r from a reflection of the reflectivity R_r with the index r ($r \in \mathbb{N}$) is

$$I_r = R_r \cdot I_0 \tag{2.34}$$

The mixing of the signal with a time-delayed version of itself results in a total complex field $E_T(t)$ at a photodetector. For the case of two reflections with the reflectivity R_1 and R_2 (the reflection coefficient for the field is \sqrt{R}) in the fibre (optical loss is neglected), the detected total field can be described with

$$E_T(t) = \sqrt{R_1} \cdot E(t - \tau_1) + \sqrt{R_2} \cdot E(t - \tau_2)$$
(2.35)

 τ_1 and τ_2 describe the delay of the reflected light components propagating in both directions of the fibre. Secondary reflection terms ($\propto \sqrt{R^3}$ for equal reflectivity, 'ghost reflections' see section 5.3.2) are neglected. The detected optical power at a photodetector $I_T(t) = |E_T(t)|^2$ is then

$$I_T(t) = R_1 |E(t - \tau_1)|^2 + R_2 |E(t - \tau_2)|^2 + 2\sqrt{R_1 R_2} \cdot \operatorname{Re}\{E(t - \tau_1) \cdot E^*(t - \tau_2)\}$$
(2.36)

The time-averaged power result $\langle I_T(t) \rangle$ is

$$\langle I_T(t) \rangle = (R_1 + R_2) \cdot I_0 + 2\sqrt{R_1 R_2} \cdot \text{Re}\{\langle E(t - \tau_1) \cdot E^*(t - \tau_2) \rangle\}$$
(2.37)

where $\langle \rangle$ denotes the average over t and Re{ } denotes the real value. Fully polarized light with parallel states of polarization (SOP) is assumed. The second term is the interference term which may be the cause of nonlinearity. For the general case of n reflections with the index r, the total detected power can be described by the summation of the single reflection components. The interference term is presented by a double summation since all reflection components interfere with another. The indices i and e ($i, e \subseteq r$) denote the ith and eth reflection in the fibre and τ_i and τ_e describe their corresponding delays.

$$\langle I_T(t) \rangle = \sum_{r}^{n} R_r \cdot I_0 + \sum_{i=2}^{n} \sum_{e=1}^{i-1} 2\sqrt{R_i \cdot R_e} \cdot \operatorname{Re}\{\langle E(t-\tau_i) \cdot E^*(t-\tau_e) \rangle\}$$
(2.38)

At this point, the complex coherence function $g(\tau_0)$ has to be introduced ($\tau_0 = \tau_e - \tau_i$ denotes the temporal delay). The coherence function is defined as the normalized autocorrelation of the optical field

$$g(\tau_0) = \frac{\langle E(t) \cdot E^*(t - \tau_0) \rangle}{\langle |E(t)|^2 \rangle}$$
(2.39)

resulting in

$$I_0(\mathbf{t}) \cdot g(\tau_0) = \langle E(t) \cdot E^*(t - \tau_0) \rangle \tag{2.40}$$

It is reasonable for semiconductor laser sources to describe the phase noise $\phi(t)$ by means of a Gaussian probability distribution function [63],[64] (Lorentzian lineshape of the source) and correlate the phase noise $\phi(t) - \phi(t - \tau_0)$ to the laser coherence time τ_{coh} as

$$\langle [\phi(t) - \phi(t - \tau_0)]^2 \rangle = 2 \cdot \frac{|\tau_0|}{\tau_{coh}}$$
(2.41)

and thus

$$\langle e^{j(\phi(t)-\phi(t-\tau_0))} \rangle = e^{-|\tau_0|/\tau_{coh}}$$
 (2.42)

The coherence function of a Lorentzian-shaped source is then

$$q(\tau_0) = e^{j\omega_0\tau_0 - |\tau_0|/\tau_{coh}}$$
(2.43)

and, after inserting (2.43) into (2.40) and (2.38), the detected optical power can be calculated as

$$\langle I_T(t) \rangle = \sum_{r}^{n} R_r \cdot I_0 + \sum_{i=2}^{n} \sum_{e=1}^{i-1} 2\sqrt{R_i R_e} \cdot I_0 \cdot \cos(\omega_0 \tau_0) \cdot e^{-|\tau_0|/\tau_{coh}}$$
(2.44)

The interference term vanishes if $\tau_0 \gg \tau_{coh}$ and the incoherent (linear) detection of the reflected light can be assumed. The spectral width $\Delta \nu$ (ν is the frequency of the optical field) of a Lorentzian-shaped laser source is commonly expressed in frequency [Hz] and is measured at 3 dB below its peak power. It is approximately related to the coherence time as [19]

$$\tau_{coh} = \frac{1}{\pi \cdot \Delta \nu} \tag{2.45}$$

which corresponds to the time τ_0 at which the coherence function $g(\tau_0)$ drops to 1/e of its maximum value. The coherence length L_{coh} is therefore defined as

$$L_{coh} = \tau_{coh} \cdot c_0 = \frac{c_0}{\pi \cdot \Delta \nu}$$
(2.46)

Spectral width, coherence time and coherence length described in the equations above, all refer to the same signal property and determine the degree of coherence or impact of interference on the sensor signal. As distributed sensing in an optical fibre is intended, the coherence length in the fibre $L_{coh,f}$ is determining:

$$L_{coh,f} = \frac{\tau_{coh} \cdot c_0}{n_{ar}} = \frac{c_0}{\pi \cdot \Delta \nu \cdot n_{ar}}$$
(2.47)

In case of I-OFDR, it is important to minimize interference between backscattered power portions from the fibre. The choice of the optical source with a reasonable broad linewidth is therefore essential to maintain system linearity and prevent interferometric power fluctuations originating from reflections or scattering centres in the fibre. It is later shown in section 2.5.2 that also 'incoherent interference' between reflections in the fibre has an influence on the detected power: the laser phase noise is transferred into intensity noise and is detected as a spectral noise source. Its impact on the system signal-to-noise ratio is analysed in section 2.5.2.

2.2.5 Amplitude modulation

The amplitude modulation technique is used to vary the incident optical power of the source $I_0 = \langle I_0(t) \rangle$. A harmonic modulation signal $u_m(t)$ with the amplitude *m* is generated:

$$u_m(t) = m \cdot \cos\left(2\pi \cdot f_m \cdot t\right) \tag{2.48}$$

The resulting amplitude modulated optical power signal $I_{am}(t)$ is described as the sum of the CW optical carrier I_0 and the product of the optical carrier and the modulation signal as

$$I_{am}(t) = I_0 \cdot [1 + u_m(t)] \tag{2.49}$$

with the optical carrier component and the modulation optical power signal $I_m(t)$ that is used for the measurment

$$I_{am}(t) = I_0 \cdot [1 + m \cdot \cos(2\pi \cdot f_m \cdot t)] = I_0 + I_m(t)$$
(2.50)

where m is the modulation index, or modulation depth, and $I_m(t)$ is described as

$$I_m(t) = m \cdot I_0 \cdot \cos\left(2\pi \cdot f_m \cdot t\right) \tag{2.51}$$

Amplitude modulation can be achieved by direct modulation of the laser current or, as conducted in this thesis, by external optical power modulation using an electro-optical modulator (EOM) with a Mach-Zehnder structure. The bias voltage of the EOM is set in the quadrature point (linear region of the cosine-shaped characteristic) and the modulation signal $u_m(t)$ is a voltage signal. On the assumption that $m \ll 1$, $I_m(t)$ can be considered to be proportional to the modulation signal voltage signal $u_m(t)$. As opposed to direct modulation of the laser source, external amplitude modulation using an EOM does not introduce significant chirp (instantaneous laser frequency change). Chirp is therefore not further considered.

2.3 I-OFDR measurement setup

There are basically three important requirements on the I-OFDR measurement setup that lead to the choice of the components and instruments used in the final setup:

- The first requirement is to ensure a linearity as high as possible from signal generation, transmission to the detection of the backscattered signal.
- The second important issue is the spectral property of the optical source. A wide spectral width source is favourable. Coherence and interference are especially crucial for I-OFDR measurement. Interference is a source of nonlinearity, as discussed in section 2.2.4. Also the noise spectrum depends on the emission spectrum of the optical source and is studied in section 2.5.2.
- The third requirement is the requested versatility for different measurement applications and the required high spatial resolution measurement in the cm-range. The targeted applications involve the measurement of standard SMF as well as MM fibres and MM PF POF of a core diameter of 50 µm. Due to a minimum of the PF POF transmission loss around 1300 nm wavelength, standard components operating in this wavelength region are used.

Figure 2.8 shows a schematic of the measurement setup. The measurement of the frequency response $H(j\omega)$ is conducted by an analogue vector network analyzer¹ (VNA). This important system component generates a sinusoidal voltage signal for discrete measurement frequencies f_m and enables sweeping over a frequency range from $f_{m,min} = 9$ kHz to $f_{m,max} = 3$ GHz. The RF signal is used to amplitude-modulate the optical power of a 1310 nm continuous wave (CW) laser source using a Mach-Zehnder type electro-optic power modulator² (EOM). The harmonic modulation signal at the output of the VNA is set to a value corresponding to a modulation depth of m = 0.5. Low modulation depth settings minimize transfer function distortions due to possible drift of the bias point away from the

¹ Rohde & Schwarz ZVL3, frequency range from 9 kHz to 3 GHz.

² Avanex PowerBit SD10 LiNbO₃ (lithium niobate) modulator with 12.5 GHz bandwidth.

quadrature point. The long term bias point drift of the EOM is only a few angular degrees. Distortion of the transfer function over time can therefore be neglected at the relatively low modulation depths. All backscatter measurements in this work are conducted with a modulation depth setting of m = 0.5. The amplitude-modulated optical signal passes a fibre optic circulator and is coupled into the FUT. All backscattered and back-reflected light from this fibre is then directed to and detected by a photodetector¹ (PD) with an integrated amplifier. The resulting electrical signal is fed to the VNA to measure the complex transfer function of the setup. Narrow bandwidth filtering of the received signal at the measurement frequency f_m ensures a high SNR.



Figure 2.8: Schematic of the I-OFDR setup.

Frequency sweeping, data transfer from the VNA, calculation of the calibrated signal, signal processing, IFFT and display of the backscatter signal in the time domain is fully controlled and obtained by an external PC over GPIB using a Matlab® script. The setup can easily be adapted for measurement of SMF or MM fibres by exchanging the circulator (using a SM circulator² or a MM circulator³). Although the system is theoretically capable of measuring the frequency response up to $f_{m,max} \approx 3$ GHz, most measurements have been conducted within the -3 dB bandwidth of the system which is mainly limited by the photodetector to a reduced frequency range up $f_{m,max} \approx 2$ GHz. Measurement results exceeding 2 GHz are impacted by increased noise due to the lower receiver signal which limits the sensitivity of the measurement system. The transfer function of the I-OFDR setup (measured by replacing the FUT with the PD) drops down to -14 dB at $f_{m,max} \approx$ 3 GHz. Practically, the measurement system can be operated up to $f_{m,max} \approx 3$ GHz with a slightly reduced sensitivity. The effective spatial resolution of this setup is depending on α_K and up to $\delta z_{eff} \approx 2.06$ cm for $f_{m,max} \approx 3$ GHz and up to $\delta z_{eff} \approx 3.1$ cm for $f_{m,max} \approx 2$ GHz in SMF, compare Figure 2.6 (left). This corresponds to equivalent pulse duration of $\tau_p \approx 0.2$ ns and $\tau_p \approx 0.3$ ns respectively. Using equation (2.9) the maximum distance range of this setup is limited to $z_{max} \approx 10.2$ km in SMF. This value is determined by the lowest modulation frequency step size $\Delta f = 10$ kHz, which is limited by the minimum modulation frequency $f_{m,min}$ (strictly considering the 3 dB bandwidth of the PD of 10 kHz: $\Delta f = f_{m,min} = 10$ kHz).

A crucial decision regarding the performance of the system is the choice of the optical source. The source spectrum determines various characteristics and is discussed in detail in section 2.5. A Fabry-Pérot (FP) laser diode⁴ has been chosen as the most suitable source and is used for all measurements presented in this work. The FP is operated at an output power of $I_{out} \approx 98$ mW at 1310 nm which corresponds to an input power into the FUT of $I_0 \approx 22$ mW.

Measurement time

The time to conduct a full frequency sweep (measuring the frequency response) in order to calculate a backscatter trace depends on various factors. The number of measured frequency points and the filter

¹ HAS-X-S InGaAs Photodiode by FEMTO with a -3dB bandwidth between 10 kHz and 2 GHz and a conversion gain of about about 2.55·103 V/W (http://www.femto.de/datasheet/DE-HSA-X-S-2G-IN_R8.pdf)

² SMF circulator CIR-1310-50-APC, datasheet available at: http://www.thorlabs.us/thorcat/15600/CIR-1310-50-APC-SpecSheet.pdf.

 $^{^3}$ MM fibre optical circulator MMCIR-3-1-M5-H-10-FA for 1310 nm wavelength range and 50 μ m core diameter, datasheet available at: http://www.sun-ins.com/lineup2/opneti/pdf-nonpm/circulators/3-port%20multimode%20optical%20circulator.pdf.

⁴ Anritsu AF3B310DM10L 14-pin Butterfly module with a centre wavelength of 1310 nm and a spectral width of about 5 nm. The laser module is controlled by Thorlabs Inc. TED200C temperature controller and LDC205C current controller and fixed in Thorlabs LM14S2 Butterfly Laser Diode Mount.

bandwidth *BW* settings of the VNA are the determining parameters. Table 2.1 summarizes the sweep times for a typical sweep measurement from $f_{m,min} = \Delta f = 500$ kHz to $f_{m,max} = 2$ GHz corresponding to 4000 frequency points (maximum number for a single sweep determined by the VNA) and $z_{max} \approx 204$ m using equation (2.9). Measuring longer fibres requires measuring more frequency points (smaller Δf) and conducting multiple sweeps of the VNA. The measurement time can be estimated from the measurement time given for a single frequency point. The values given below include a measurement delay of 100 µs for each frequency point (in order to account for the settling time of the I-OFDR system and the signal delay in the fibre up to the maximum measurement distance of 10.2 km) as well as communication times and data transfer times between the VNA and the external computer.

VNA filter bandwidth BW	Sweep time for 4000 frequency points ($\Delta f =$ 500 kHz, $f_{m,max} =$ 2 GHz)	Sweep time for single point	
100 Hz	40.03 s	10.01 ms	
1 kHz	5.17 s	1.29 ms	
10 kHz	1.62 s	0.40 ms	
100 kHz	1.32 s	0.33 ms	

Table 2.1: Measured sweep times for different VNA filter bandwidths with 100 μ s measurement delay.

2.3.1 Calibration

A frequency response measurement by the VNA $H'(j\omega)$ not only comprises the desired transfer function $H(j\omega)$ of the FUT only but is a product of the frequency responses of each electrical and optical component in the signal path:

$$H'(j\omega) = H(j\omega) \cdot H_{VNA}(j\omega) \cdot H_{EOM}(j\omega) \cdot H_{PD}(j\omega) \cdot \dots$$
(2.52)

The highest deviation from the ideal transfer function are expected to be caused by the electrical components (VNA, EOM, photodetector and amplifier, RF cables,...). In order to compensate for these transfer function distortions, a calibration measurement $H_{cal}(j\omega)$ is conducted with the same setup but replacing the FUT with the photodetector:

$$H_{cal}(j\omega) = H_{VNA}(j\omega) \cdot H_{EOM}(j\omega) \cdot H_{PD}(j\omega) \cdot \dots$$
(2.53)

In order to maintain the linearity of the system during the calibration measurement, the optical signal is attenuated to a reasonable power (high SNR but within the linear power range of the PD (< 240 μ W)), typically 20 μ W, using a variable optical attenuator (VOA) between the EOM and the circulator. The calibrated transfer function of the FUT only can then be calculated by dividing the measured frequency response by the calibration transfer function of the I-OFDR setup.

$$H(j\omega) = \frac{H'(j\omega)}{H_{cal}(j\omega)}$$
(2.54)

The time domain response h(t) is obtained by calculating the IFFT of the zero-padded and windowed transfer function

$$h(t) = \mathcal{F}^{-1}\{H(j\omega) \cdot W_{Kaiser}(\omega)\}$$
(2.55)

using Matlab's symmetric 'ifft' function.

Deviation of the I-OFDR transfer function

Virtually no measurement system can be considered to be strictly linear. This is also the case for the I-OFDR system. An important source of nonlinearity may be coherent mixing of the optical fields at the PD, as described in section 2.2.4. Another source of nonlinearity is the change of the transfer function of the I-OFDR system with changes of the detected signal power. Deviations of the magnitude and the phase of the calibration transfer function $H_{cal}(j\omega)$ are quantified in the following for different signal

powers I_{cal} , as detected by the PD. The deviations of the magnitude $\Delta |H(j\omega)|$ of the transfer function measured at different optical power values I_{cal} , that are incident at the PD, are calculated relative to the transfer function measured at $I_{cal} = 20 \ \mu$ W. The magnitude deviation $\Delta |H(j\omega)|$ is described by

$$\Delta |H(j\omega)| = 10 \cdot \log_{10} \left(\frac{\left| H_{cal(I_{cal}=20\mu W)}(j\omega) \right|}{\left| H_{cal(I_{cal})}(j\omega) \right|} \right) \quad [dB]$$
(2.56)

Measured $\Delta |H(j\omega)|$ results are plotted for various I_{cal} in Figure 2.9 (left). Equivalently, the phase differences $\Delta \varphi_{cal}$ for different I_{cal} relative to $I_{cal} = 20 \ \mu\text{W}$ are calculated as

$$\Delta \varphi_{cal} = \text{angle} \left(H_{cal(I_{cal}=20\mu W)}(j\omega) \right) - \text{angle} \left(H_{cal(I_{cal})}(j\omega) \right)$$
(2.57)

in degree angle and are plotted in Figure 2.9 (right).



Figure 2.9: Transfer function deviation for different optical powers I_{cal} : magnitude deviation $\Delta |H(j\omega)|$ (left) and phase deviation $\Delta \varphi_{cal}$ (right) relative to $H_{cal}(j\omega)$ at $I_{cal} = 20 \ \mu$ W; $t_{meas} = 150 \ s$, $\Delta f_m = 500 \ kHz$, $f_{m,max} = 2 \ GHz$, m = 0.5.

The magnitude and phase deviations for different signal powers are assumed to originate mainly from the electrical components of the setup (photodetector and amplifier as well as the VNA). The absolute deviations of magnitude and phase for strongly varying I_{cal} are relatively small. They result in a maximum position deviation of the zero-padded time domain response $h_{cal}(t) = \mathcal{F}^{-1}\{H_{cal}(j\omega)\}$ equivalent to a reflection position change of $\Delta z \approx 70 \,\mu\text{m}$ in SMF (between the incident powers $I_{cal} = 20 \,\mu\text{W}$ and $I_{cal} = 612.5 \,\text{nW}$). This value is negligible for most general backscatter measurement applications. Its impact should, however, be considered if precise position change evaluation is intended, as shown in section 2.4.1 and chapter 5. Significant changes of reflected powers lead to measurement deviations. In that case, adaptive calibration with $H_{cal}(j\omega)$ adjusted according to the detected backscatter measurement signal $H'(j\omega)$ with $(|H'(j\omega)| \approx |(H_{cal}(j\omega)|)$ should be conducted.

2.3.2 Determination of reflection properties

The properties of reflective events in the FUT are an important aspect throughout this thesis and are therefore introduced and described in more detail in this section. A reflective event may either be a disturbance in the backscatter trace or represent a measurement parameter. In the case of a disturbance, it may be removed from the measurement result as proposed in section 2.6 and section 4.2. For the sensing applications presented in section 2.4.1, section 4.2 and chapter 5, the properties of a reflection (i.e. position and magnitude) are very important measurement parameters in this work and are used for sensing.

The reflection signal properties, as measured by the I-OFDR, are the relevant information necessary for the signal processing and sensing techniques proposed in this thesis. Changes of reflection power and reflection position can be directly evaluated. The reflection properties in the time domain and frequency domain are therefore directly obtained from the measurement instead of calculating with

I-OFDR system parameters, specific reflectivity and reflected power or considering optical propagation loss along the fibre.

The first step to obtain the reflection properties is to measure the full calibrated complex frequency domain response $H(f_m)$ of the FUT. The equivalent time domain response h(z) is obtained using equation (1.5) and conducting an IFFT of the calibrated measurement result: $h(t) = \mathcal{F}^{-1}{H(f_m)}$. The time domain plot h(z) of an I-OFDR measurement of a FUT with two strong reflections at the positions z_1 and z_2 is exemplarily shown in Figure 2.10.



Figure 2.10: Time domain response h(z) of a FUT from I-OFDR measurement with two reflections at z_1 and z_2 with respective peak magnitudes P_1 and P_2 ; $t_{meas} = 10 \text{ s}$, $\Delta f_m = 2 \text{ MHz}$, $f_{m,max} = 2 \text{ GHz}$, $f_{zp} = 50$, $\alpha_K = 0$.

The peak magnitude P_r of each reflection in the backscatter plot is directly proportional to the reflected optical power I_r , as it is detected by the PD (equation (2.34)). All reflected optical powers $I_r \propto P_r$ and the reflection positions z_r can be obtained with high resolution from a zero-padded result h(z). Changes of P_r and z_r can be evaluated as reflection power changes and position (or length) changes in the FUT. For the calculations conducted in section 4.2 and section 5.2, the frequency response $H_r(f_m)$ of the individual reflections is required. Since a linear and time-invariant system is assumed, the ideal frequency domain responses $H_r(f_m)$ of the single reflections can be calculated from the position information z_r and the respective detected reflection peak values P_r using

$$H_r(f_m) = P_r \cdot e^{-j \cdot 2\pi \cdot f_m \cdot 2 \cdot z_r \cdot n_{gr}/c_0}$$
(2.58)

 P_r is directly proportional to the detected optical power. The frequency domain response $H_r(f_m)$ is related to the time domain response $h_r(t)$ of the reflection by inverse Fourier transform $h_r(t) = \mathcal{F}^{-1}{H_r(f_m)}$, whereas $h_r(t)$ is a sinc function with its maximum at z_r . The magnitude of any value of the calibrated reflection frequency domain response $|H_r(f_m)|$ is identical with the detected reflection peak magnitude P_r . The phase φ_r for each modulation frequency f_m is a function of the distance of the reflection ($\varphi_r(f_m) = -j \cdot 2\pi \cdot f_m \cdot 2 \cdot z_r \cdot n_{gr}/c_0$). These dependencies are described by equation (2.58) and will be used throughout this thesis to relate time domain and frequency domain responses of reflective events in the FUT.

2.4 Performance characterization

The most important general backscatter reflectometer characteristics have been introduced in chapter 1. The **spatial resolution**, or two-point resolution, of an I-OFDR has been analyzed in section 2.2.2 as a function of the modulation frequency range and the Kaiser window parameter α_K . In this section, the parameters distance resolution, power resolution, dynamic range and sensitivity are defined and determined for the previously introduced laboratory setup. Precise backscatter sensing is intended. The I-OFDR performance and technological differences are discussed in comparison to the OTDR technique.

2.4.1 Distance resolution and power resolution

General distance resolution and power resolution for backscatter measurement techniques cannot be easily defined since they depend on various conditions such as the magnitude of a scattering event, measurement time and degree of interpolation. These parameters are in the following explained in comparison to OTDR and are measured for a certain FUT.

The distance resolution is often defined as the resolution of the absolute distance of an event or the relative distance between two well-defined events in the fibre. Sometimes the term spatial accuracy is used to describe absolute or relative position values of characteristic events in the fibre. It is not always clear how these specifications are defined by the OTDR manufacturers and there might be a great discrepancy between different definitions for absolute accuracy of a single event or relative accuracy between two single events. Especially for distributed sensing applications, the distance resolution as well as distance accuracy are very important parameters. In the case of OTDR technology, the sampling resolution is generally better than the spatial resolution (proportional to the pulse length Δp). The distance resolution can therefore be better than the spatial resolution if the sampling points are used to evaluate the reflected or scattered pulse shape. The distance resolution can be further increased by interpolation but the distance accuracy is often limited in OTDR by other influences such as changes of the shape of the optical pulse, drift of electrical components or nonlinearities due to detector saturation or dead zones.

The I-OFDR is especially advantageous for sensing applications where high spatial resolution, *linearity and signal stability* are required. Due to the precise generation of 'pulses' in the frequency domain and the bandpass-filtered detection of its spectral components this technique is more stable than pulse reflectometry. All OTDR techniques suffer to some extend event or attenuation dead zones after events of increased backscattering or reflections due to detector overload and recovery. Less significant scattering events or optical loss after, for example, a reflection in the fibre is superimposed by the detector recovery signal and cannot be correctly detected. Also the photon counting technique is affected by this effect [29]. The I-OFDR result is not affected by saturation (as long as the PD is operated in the linear regime) since the variable attenuation of the signal detected by the VNA further reduces deviation from ideal system linearity.

Another parameter that is generally not defined for OTDRs but is of interest in backscatter sensing applications is the *power resolution* of reflective events in the fibre. Due to the overload at strong reflections, the reflection power cannot be correctly measured with most direct detection OTDRs. Changes of the generated pulse form or drift of the timer or detection electronics are a serious limitation also for precise position measurement of reflective events. The following measurements determine the spatial accuracy and the power resolution of reflections in the fibre and demonstrate the high stability and linearity of the I-OFDR technique compared to OTDR. As a suitable measurement object, a fibre with multiple moderately scattering points has been measured. Focused femtosecond laser pulses at pulse energies exceeding the material damage threshold have been used to inscribe scattering 'micro voids' into SMF cores [8], [65]. This technique is later described in more detail in section 5.1.1. The intention was to create reference points in optical fibres for relative length change or strain measurement using I-OFDR. Such a processed SMF with 12 scattering centres separated by about 1 m each has been measured by a high-resolution photon counting OTDR¹ and I-OFDR². Although the spatial resolution of both measurement techniques is in the cm-range, the actual position resolution of a scattering point can, after interpolation or zero-padding, be resolved with a far better resolution. Figure 2.11 shows an I-OFDR measurement of this sensor fibre [65].

¹ Photon counting OTDR by Luciol Instruments SA (FP source at 1313 nm) for singlemode fibres and a spatial resolution of about 12.6 cm.

² Effective spatial resolution of $\delta z_{eff} \approx 6$ cm after windowing ($\alpha_K = 3$) and $f_{m,max} = 2$ GHz.



Figure 2.11: I-OFDR measurement of a SMF with 12 laser-induced scattering centres; $t_{meas} = 15 \text{ min}$, $\Delta f = 2 \text{ MHz}$, $f_{m,max} = 2 \text{ GHz}$, $\alpha_K = 3$, $f_{zp} = 500$.

The position accuracy of each scattering event is determined from the single maxima of the interpolated I-OFDR traces. The backscattered power value P (proportional to the optical power I) from each reflection can be determined from the backscatter peak with a high power precision¹. The precision of the power P and the accuracy of the position z of an individual single reference point is dependent on the backscattered power of the corresponding scattering point. A great number of single measurements ($t_{meas} = 60$ s each) of this fibre have been conducted over a period of time with both techniques, OTDR and I-OFDR. Figure 2.12 shows the evaluated position changes from the single measurements of the 12 scattering centres for OTDR and I-OFDR over a time period of 150 minutes.



Figure 2.12: Position change results of all 12 scattering centres from OTDR and I-OFDR measurements (left) and from I-OFDR measurements only (right); $t_{meas} = 60$ s.

The standard deviation of power σ_P and position σ_Z for each point from multiple measurements of integration time $t_{meas} = 60$ s has been calculated for OTDR and I-OFDR respectively as a measure of stability and resolution of the two techniques. The I-OFDR approach delivers astonishing position accuracy and power precision results with standard deviations down to $\sigma_Z \approx 9.0 \,\mu\text{m}$ for the position evaluation and $\sigma_P \approx 0.0015$ dB for the power evaluation (at the scattering point at 16.6 m) after 60 seconds of measurement time. Although the backscattered power of the scattering points is only about 20 dB above the Rayleigh level and the effective spatial resolution is $\delta z_{eff} \approx 6$ cm, the averaged standard deviation for all 12 scattering points is $\sigma_Z \approx 15.9 \,\mu\text{m}$ and $\sigma_P \approx 0.0025$ dB. The OTDR results suffer similar delay drift for all scattering centres. Still, after removing this drift, the measurement resolution is far below that of the I-OFDR setup (OTDR standard deviation, averaged for all reference points, is $\sigma_Z \approx 750 \,\mu\text{m}$ and $\sigma_P \approx 0.057 \,d\text{B}$). Compared to the OTDR, the I-OFDR delivers an increased averaged resolution of the factor 47 for the position and 22.5 for the power evaluation at equal measurement times. Reasons are the precise generation and detection of the 'pulse components' and

¹ Power precision is used here rather than power accuracy since precise optical power measurement (*I*) depends on the precision of the levelling of the backscatter trace, see equation (2.60). Relative powers of single reflections (relative to another and from measurement to measurement), however, can be determined with high relative accuracy due to the linearity of the I-OFDR.

effective interpolation by zero padding. Using I-OFDR allows for even faster measurement repetition rates. This is achieved by increasing the filter bandwidth of the VNA and reducing averaging. The average standard deviations of position and power values of all reflections are $\sigma_P \approx 0.03$ dB and $\sigma_z \approx 200 \,\mu\text{m}$ for $t_{meas} = 1 \,\text{s}$ and $\sigma_P \approx 0.0094 \,\text{dB}$ and $\sigma_z \approx 60.7 \,\mu\text{m}$ for $t_{meas} = 5 \,\text{s}$ respectively. The standard deviation of power deviations σ_P is calculated from the measured logarithmic backscatter trace $(5 \cdot log_{10}(h(z)))$. Quasi-distributed low-dynamic measurement can therefore be conducted with the I-OFDR setup [65].

Application as length change sensor

Due to the high position accuracy of the I-OFDR technique, relative length change measurement between scattering points or reflective events in the fibre can be conducted. The length change Δl relative to the initial length of the fibre section L_0 is commonly expressed as strain ε

$$\varepsilon = \frac{\Delta l}{L_0} \tag{2.59}$$

A simple length change or strain measurement with the sensor fibre in Figure 2.11 is demonstrated by clamping the fibre at z = 3.7 m and z = 18 m and applying an increasing length change Δl in three steps along this whole fibre section before releasing the strain in the fibre. Figure 2.13 (left) shows the measured position change of each inscribed scattering point along the fibre using I-OFDR results after $t_{meas} = 5$ s. Scattering points towards longer distances experience increased position changes. From relative position results, strain values for each of the fibre sections between adjacent scattering points can be calculated. The resulting strain based on the gauge length of 1 m after $t_{meas} = 5$ s is shown in Figure 2.13 (right).



Figure 2.13: Measured position changes (left) at each scattering point from I-OFDR measurements and measured strain from the relative length changes of adjacent scattering points (right); single measurements conducted with following parameters: $t_{meas} = 5 \text{ s}$, $\Delta f = 2 \text{ MHz}$, $f_{m,max} = 2 \text{ GHz}$, $\alpha_K = 3$.

The position change resolution can be considerably increased by increasing the measurement time or inscribing scattering centres with higher reflectivity. These measurements demonstrate that high spatial accuracy as well as reflection power precision can be obtained using I-OFDR. These parameters are very important for precise and distributed backscatter sensing applications.

2.4.2 Dynamic range and sensitivity

The dynamic range of OTDRs has been specified as half the power between the initial backscatter level and the noise level after 3 minutes measurement time (compare Figure 1.2). This definition however, does not take the optical pulse length (the Rayleigh backscattering level is linearly scaled with the pulse length) and the fibre type (varying backscatter coefficients) into account and is rather a measure for backscatter sensitivity of the measurement device. Most manufacturers specify their dynamic range for the longest possible pulse duration which can be up to tens of μ s. Measurement with shorter pulse lengths reduces the effective dynamic range of the system and thus the backscatter measurement distance. For statistical techniques such as photon counting OTDR, this definition is also not entirely applicable since the measurement time needed to arrive at a given dynamic range strongly depends on the backscattered power of the FUT (presence of strong scattering events or reflections in the fibre).

A modified definition of dynamic range is also more appropriate for the I-OFDR technique. Due to the measurement using a continuous sinusoidal signal filling the whole length of the fibre, high reflection powers, for example from fibre connectors, as well as very weak backscatter events are superimposed on the same measurement signal. The separation capability between the strong and weak signals ultimately limits the dynamic range of the system. The *dynamic range of an I-OFDR* is therefore defined as the maximum power difference between the highest scattering event or reflection peak in the fibre and the noise level of the backscatter trace (Figure 2.14).



Figure 2.14: Schematic of I-OFDR definition of dynamic range.

This definition is more suitable for I-OFDR. Strong reflections in the fibre ultimately limit the smallest measurable backscatter level which can best be characterized using this peak-to-noise definition of the dynamic range. This limit cannot be increased by averaging and is determined by the VNA.

Another useful characteristic, not only for an I-OFDR system, is the minimum backscatter level that can be detected. This *sensitivity of an I-OFDR system* is closely related to the signal to noise ratio (SNR). The sensitivity is of an I-OFDR backscatter measurement is here defined as the peak noise intensity level as indicated in Figure 2.14 after 3 minutes of averaging. For a measurement of a weakly scattering FUT without strong reflections, the sensitivity is the limiting characteristic rather than the dynamic range and can be improved by averaging. In order to determine the sensitivity of the system, the measurement trace has to be related to a suitable and absolute reference. The definition of a reference is also a prerequisite to conduct absolute power measurements of distributed scattering as well as for the measurement of reflected powers.

The definition of backscatter levels σ relative to the peak power I_0 of an ideal rectangular optical pulse for a given pulse duration τ_p or equivalent pulse length Δp is a suitable reference. The backscatter power is therefore adapted to define an equivalent reference level for the sinc-function-derived pulse shape. The rectangular pulse peak power input I_0 defines the 0 dB value in the backscatter trace whereas the Rayleigh backscattering level of a fibre $\sigma = f(\tau_p)$ is given in dB below this pulse peak power, equation (1.8).

Due to the different 'pulse forms' (rectangular pulse versus Kaiser window-derived sinc function), the equivalent of pulse energies at a given pulse duration τ_p has to be calculated to arrive at the same backscatter levels. Assuming equal pulse energy of the rectangular pulse $E_{pulse} = I_0 \cdot \tau_p$ and the Kaiser-derived function, the virtual incident power I_0 is calculated for the effective spatial resolution $\delta z_{eff} = \Delta p$ for $\alpha_K = 0$. Figure 2.15 (left) shows the ideal rectangular pulse and the Kaiser-derived 'pulse' for different α_K . The peak power of the sinc-derived function of a reflective event in the fibre is a function of α_K and is simulated relative to the peak power of the equivalent rectangular pulse $(\alpha_K = 0)$ in Figure 2.15 (right). The relative peak power is independent of $f_{m,max}$ and Δf .



Figure 2.15: Simulation results: Rectangular pulse of the length equal to $\delta z_{eff}(\alpha_K = 0)$ with equal energy to Kaiser-derived pulses plotted for $\alpha_K = 0$;1;2 (left) and magnitude of Kaiser-derived peak relative to rectangular pulse peak magnitude for $\delta z_{eff}(\alpha_K = 0)$ (right); $\Delta f = 1$ MHz, $f_{m,max} = 2$ GHz, $n_{gr} = 1.4677$.

The values simulated in Figure 2.15 (right) are important for determining the absolute reflectivity of a reflective event in the fibre. It has been shown in Figure 2.7 (right) that the 'pulse energy' and therefore the detected Rayleigh level is independent of α_K and only a function of $f_{m,max}$. Whereas the effective spatial resolution δz_{eff} increases and the peak power decreases with increasing α_K (compare Figure 2.6), the 'pulse energy' and therefore the backscatter level remains unchanged. The backscatter level is here defined for the effective spatial resolution δz_{eff} and $\alpha_K = 0$. The correct peak power (i.e. the reflectivity of an event) for different α_K can then always be calculated by adding the simulation data depicted in Figure 2.15 (right). This pulse length definition for $\tau_p = \delta z_{eff}(\alpha_K = 0)$ is used throughout this thesis to define the measured Rayleigh backscatter level power for I-OFDR backscatter plot is fitted to the backscatter level of the standard input fibre according to the values α_S and S, which can be found in Table 1.1. The resulting backscatter level is then a function of the maximum measurement frequency $f_{m,max}$ (effective spatial resolution δz_{eff}) and can be derived from the equations (1.8), (2.19), (2.22) and the simulation results of b for different α_K from Figure 2.6 (left); $b(\alpha_K = 0) = 1.21$ using

$$\sigma = 10 \cdot \log_{10} \left(S \cdot \alpha_S \cdot \frac{c_0}{4 \cdot n_{gr}} \cdot \frac{b(\alpha_K = 0)}{f_{m,max}} \right) \quad [dB]$$
(2.60)

This way, measurement-to-measurement reproducibility is ensured and the sensitivity of the system can be characterized. This approximation of the backscatter level is valid as long as the attenuation of the fibre is negligible over the length of the symmetric 'Kaiser-windowed' sinc function. As simulated in Figure 2.7 (right) and Figure 2.6 (right), the side lobe impact rapidly decreases with increasing α_K and can be neglected in standard fibres with low attenuation.

Backscatter plots in this thesis therefore describe the detected backscattered optical power in dB relative to the incident power I_0 of a rectangular optical pulse of the duration $b(\alpha_K = 0)/f_{m,max}$ that is sent into the FUT. The peak magnitude of a Kaiser-derived I-OFDR 'pulse' deviates from the ideal rectangular pulse level by the values simulated in Figure 2.15 (right) as a function of α_K .

Measurement of the sensitivity and dynamic range

The above defined performance parameters, sensitivity and dynamic range, are obtained for the laboratory I-OFDR setup. Figure 2.16 shows two measurements that characterize these performance parameters for the I-OFDR setup. The left plot shows a sensitivity-limited measurement trace of a low-scattering SMF and the right plot shows a dynamic range-limited measurement of the same fibre but a single strong reflection at the fibre end.



Figure 2.16: I-OFDR backscatter measurements of the same 200 m long SMF limited by the sensitivity (left) and dynamic range (right); $t_{meas} = 3 \text{ min}$, BW = 1 kHz, $\Delta f = 400 \text{ kHz}$, $f_{m,max} = 2 \text{ GHz}$, $\alpha_K = 3$.

The sensitivity of the system is about -92 dB after 3 minutes measurement time. The peak-to-noise dynamic range of the laboratory I-OFDR system is measured to be $2D \approx 40$ dB. The quality of the frequency response result provided by the VNA seems to be the factor that limits the dynamic range. Reducing the noise by averaging or using a lower noise PD and amplifier does not extend the dynamic range limit. Neglecting spectral noise sources, the dynamic range and the sensitivity should be more or less independent of the maximum modulation frequency $f_{m,max}$, i.e. the spatial resolution. The sensitivity of a single sweep can to some degree be increased by narrowing the filter bandwidth of the VNA but that in return increases the measurement time (see Table 2.1). Comparison measurements for the same measurement time but different filter bandwidths (different number of averaged frequency sweeps) result in comparable sensitivities. The improvement of sensitivity or signal-to-noise ratio (SNR) is ideally a function of the square root of the number q of averaged measurements. The sensitivity improvement or SNR improvement with the number of measurements (or measurement time) can therefore be described in dB by $10 \cdot \log_{10}(\sqrt{q})$. Sensitivity measurement results for different numbers of averaging proved that this sensitivity or SNR improvement is also valid for the I-OFDR technique and higher sensitivity can be obtained after longer measurement times. The dynamic range of the measurement system is, however, the fundamental limit and cannot be increased by averaging. The noise level does not decrease with longer averaging once the dynamic range limit of $2D \approx 40$ dB is reached.

The exact reason for the dynamic range limit of the measurement system is not known. It is assumed that the determining parameter is related to the signal detection of the VNA: comparison measurements with the digital implementation of the VNA (developed within the cooperation project with the fibrisTerre GmbH) with the same I-OFDR setup¹ up to $f_{m,max} = 100$ MHz exhibits a considerably increased dynamic range of $2D \approx 52$ dB [66].

2.5 Spectral influences

The spectrum and linewidth of the optical source of an I-OFDR system may have a more crucial impact on the backscatter trace than it is the case in pulse domain reflectometry.

One reason for its impact is that interference from the FUT occurs from fibre sections within (and exceeding) the coherence length of the optical source. In pulse domain reflectometry, interference is generally limited to the length of the optical pulse in the fibre. In I-OFDR, the whole fibre is filled with the CW optical carrier and the power-modulated component. Significant interference in I-OFDR can therefore occur along the whole fibre within a distance exceeding the definition of the coherence length of the source (interference can only be ruled out for $\tau_0 \gg \tau_{coh}$). Power fluctuations between reflective events in the fibre as well as originating from Rayleigh scattering can therefore considerably

¹ The PD has been exchanged for both measurements (digital/analog VNA) to TIA-525 with a bandwidth up to 125 MHz (http://www.terahertztechnologies.com/pdfmanuals/TIA525-Manual.pdf).

disturb the backscatter signal when using coherent sources. The choice of the optical source and its emission spectrum are therefore important parameters when designing an I-OFDR system. Singlemode DFB lasers, multimode FP lasers and amplified spontaneous emission (ASE) sources are considered under these aspects in this section.

Another important issue, specific to the I-OFDR approach, concerns the optical source spectrum and its impact on the SNR of the system. Time-delayed mixing of the source spectrum with itself, as it is the case for an interferometer but also in general backscatter measurement, leads to coherent mixing of the source spectra. The resulting *phase-to-intensity noise* may in this case be the most significant noise source. The detected signal is a superposition of the optical carrier intensity and the intensity-modulated measurement signal originating from the whole FUT. The resulting noise power spectral densities (NPSD) due to phase-to-intensity noise may have significant impact on the SNR of the measurement system. This phase-to-intensity noise is not a 'white noise' source but has a frequency dependence of the noise power as a function of the source spectrum as well as the properties of the FUT itself and is investigated in section 2.5.2.

2.5.1 Source spectra and interference

As described in section 2.2.4, the linewidth and lineshape of the optical source determines the coherence function $g(\tau_0)$ The coherence function is an important system design parameter but cannot be easily described or calculated for multimode lasers [63]. In this case, direct measurement is the only way to approximately predict the source spectrum impact on the measurement.

Source type consideration and characterization

The most important requirement on the spectral properties of the source to be used for I-OFDR are minimal coherence length and therefore broad linewidth in order to reduce interference effects on the sensor signal. Different optical sources were considered and tested in the I-OFDR setup in this work:

- Singlemode distributed feedback (DFB) laser
- Multimode Fabry-Pérot (FP) laser
- Superluminescent diode (SLD)

Additional requirements on the source are sufficient optical power output, spectral stability and power stability. Very important is the ability to be directly or externally power-modulated over a wide frequency range from $f_{m,min}$ to $f_{m,max}$. It is later shown that phase-to-intensity noise may also be a relevant system parameter in I-OFDR in terms of SNR and that it has a strong dependence on the spectrum of the optical source. This noise source is analyzed and discussed in more detail in section 2.5.2.

A singlemode DFB laser has initially been considered as an option. This source type features high output powers and the possibility to be modulated directly or externally using an EOM. The disadvantage of using standard singlemode laser sources for this application is their relatively narrow linewidth of typically several MHz. In order to investigate the possible use of a singlemode laser, a standard DFB laser was exemplarily considered in terms of interference and noise for use in the I-OFDR system. Its spectral properties are determined, also for later systematic comparisons and for the analysis of the phase-to-intensity noise considerations presented in section 2.5.2. The linewidth of the DFB laser¹ that is used for these experiments has been determined using delayed self-homodyne detection in an unbalanced Mach-Zehnder setup and a time delay $\tau_0 \gg \tau_{coh}$. A polarization controller in one path has been set to ensure equal polarization states in both paths. The resulting noise power spectrum is measured after detection with the wideband PD and amplification using an electrical

¹ DFB laser AOI-DFB-1310-BF-31-A5-FC/APC with integrated bias T, typical parameters: $I_{out} = 31$ mW at $\lambda = 1310$ nm.

spectrum analyzer¹ (ESA). This setup is used to determine the source linewidth and a modified setup (Figure 2.24) is later employed in section 2.5.2 to analyze noise power spectral densities.

The spectral characteristic of the source optical field is commonly described as in equation (2.32) with the centre angular frequency ω_0 and the phase noise term $\phi(t)$. It is common to describe the frequency of an optical field with ν [Hz]. Recombination of the time-delayed electric fields on a photodetector results in a photocurrent proportional to equation (2.37). The ESA displays values proportional to the photocurrent power spectrum $S_i(f)$. The measured spectrum comprises the direct detection values $S_d(f)$ (as measured directly, not mixed signal) and the homodyne optical mixing product of the source signal spectrum $S_s(\nu)$ [17]

$$S_i(f) \propto \mathcal{R}^2 \{ S_d(f) + 2[S_s(\nu) * S_s(-\nu)] \}$$
(2.61)

where \mathcal{R} denotes the detector responsitivity. Since the mixing term is the convolution of the laser spectrum with itself, the lineshape detected by the ESA is symmetrical and has twice the spectral width of the original source spectrum for the case of Lorentzian lineshape. Due to the delayed self-homodyne mixing, the spectrum is centred at 0 Hz and the -3dB frequency corresponds to the FWHM of the optical source Δv . Figure 2.17 (left) shows the measured power spectrum of a linewidth corresponding to $\Delta v \approx 3$ MHz using delayed self-homodyne mixing. The degree of coherence function has been obtained with a similar setup by measuring interference fringe visibility for various path length differences. The calculated degree of coherence function $g(\tau_0)$ from (2.43) and (2.45) for $\Delta v = 3$ MHz as well as the equivalent measured interference fringe visibility are displayed in Figure 2.17 (right).



Figure 2.17: Delayed self-homodyne power spectrum of the DFB source with 3 MHz linewidth (left) and the measured and calculated degree of coherence function for $\Delta v = 3$ MHz (right).

The linewidth is determined with $\Delta \nu \approx 3$ MHz which corresponds to a coherence length of $L_c \approx 21.7$ m in SMF ($n_{gr} = 1.4677$). Theoretical and measured values agree well and suggest that the laser lineshape is indeed Lorentzian. These results are the prerequisite for the noise power spectral density considerations and measurements for a singlemode laser source presented in section 2.5.2.

This directly modulated DFB source has initially been operated and tested in the I-OFDR setup but has been discarded due to the strong signal fluctuations owing from interference from reflections and Rayleigh backscattering. Despite the inadequacy for I-OFDR measurement, this source has been characterized. Due to its singlemode emission and relatively narrow linewidth, it is most suitable for the spectral noise characterization presented in section 2.5.2. Singlemode laser sources can generally be used for I-OFDR measurement but commercially available sources are designed for telecommunication applications and exhibit relatively narrow linewidths to reduce the chromatic dispersion influence. Using a singlemode laser with considerably broader linewidth may be an option.

The motivation for considering a *superluminescent diode (SLD)* has been the very broad spectral width of tens of nm and the resulting very short coherence lengths in the order of only a few tens of

¹ Electrical spectrum analyzer FSP30 from Rohde & Schwarz with a frequency range from 9 kHz to 30 GHz.

micrometers. Using a SLD source basically eliminates all interference issues and would be the ideal choice in terms of interference. Such devices are available at the desired wavelength at $\lambda = 1310$ nm with output power up to tens of mW. A SLD¹ has also been tested in the I-OFDR setup but the measurement performance was found to be inferior compared to using a FP laser source. The main reason was the decrease of measurement sensitivity due to the lower modulation signal power in the FUT. The input power into the FUT was only about $I_0 \approx 5$ mW compared to about $I_0 \approx 22$ mW of the FP laser. Additional care has to be taken since fibre-coupled SLDs in the O-band are typically available with standard fibres (non-polarization-maintaining fibres) only. This may lead to signal drift (changes of the extinction ratio) when the SLD output fibre that is connected to the EOM is moved. This results in evident changes of the system transfer function (nonlinear behaviour). Also, SLDs at 1310 nm have typically lower degree of polarization which reduces the efficiency of the EOM. The very broad linewidth of the SLD may be a limitation for certain long-distance sensing applications due to chromatic dispersion issues, especially if the source spectrum does not match the zero dispersion region of the sensor fibre. Also, SLDs are prone to external optical feedback. An additional optical isolator should be ideally inserted between the SLD and the EOM to prevent strong reflections coupling back into the diode. Comparison measurements between the SLD and the FP laser in the setup showed considerably increased sensitivity and signal stability using the FP laser. In order to increase the signal power in the fibre and also rule out polarization issues, direct modulation of the current of the SLD using an external bias tee has been conducted. This approach has been implemented within the 'Digital OFDR' project by the fibrisTerre GmbH for a limited frequency range up to $f_{m,max} = 400$ MHz. The absolute frequency range, however, is limited not only by the required extremely wideband design of the bias tee and required modulation voltage amplifier but also by the diode itself. Most manufacturers specify the maximum modulation frequencies with several hundreds of MHz. The necessary direct modulation approach with relatively high modulation currents up to 300 mA is expected to decrease the lifetime of the optical source in comparison to the operation of a semiconductor laser in CW mode and using an external EOM for modulation. Performance comparisons of a directly modulated SLD with the I-OFDR setup using a FP laser source and an EOM showed inferior performance in terms of signal stability but almost comparable sensitivity. However, since a wider frequency range with higher modulation frequencies $f_{m,max}$ is intended, the direct modulation approach using the SLD has been abandoned for further extensive testing. Lifetime concerns were also an issue that led to this decision.

Fabry-Pérot laser

A Fabry-Pérot laser allows various modes to resonate and to be amplified in the gain window of the laser medium and therefore emits numerous longitudinal lasing modes. Although the linewidth of the single modes is much smaller, the spectral width of a FP laser is generally given as the FWHM of the envelope of all emitted laser modes. All I-OFDR backscatter measurement results in this thesis have been obtained using a FP laser module by Anritsu². Figure 2.18 shows the measured power spectrum of the FP laser for the laser operation settings (280 mA laser current and thermistor resistance settings of $R_{th} = 10.86 \text{ k}\Omega$) obtained by an optical spectrum analyzer³ (OSA).

¹ Experiments have been conducted with Exalos EXS13G1-2111 SLD with typical parameters: $I_{out} = 26$ mW and 44 nm spectral width. ² Anritsu AF3B Butterfly module, maximum output power I = 100 mW around $\lambda = 1310$ nm wavelength (http://www.anritsu.com/en-

AU/Products-Solutions/Products/FP-LD-series.aspx)

³ Optical spectrum analyzer Advantest Q8347 with a wavelength resolution of 0.01 nm.



Figure 2.18: Power spectrum of FP laser measured with an OSA (280 mA laser current and $R_{th} = 10.86$ k Ω).

About p = 40 individual laser modes with specific wavelengths λ_i and different optical powers contribute to the total output power of about 98 mW for these settings. The spectral characteristic of this FP laser source is reproducible and has been stable over 4 years of operation of the laser source. The approximate wavelengths and optical powers of the single modes can be determined but their linewidth or lineshape cannot be resolved because of the limited wavelength resolution of the OSA of 0.01 nm. The coherence length of the single laser modes and the precise coherence function or interferogram of the source can therefore not be calculated from the low-resolution OSA results. The obtained spectral information of wavelength and power of the single lasing modes is used in this section and section 2.5.2 for the calculation of interference and noise properties of the source.

In order to estimate the impact of interference of this source, interferograms (similar to coherence function) have been measured for various path length differences. The I-OFDR setup has been used to measure the interference fringe visibility during the tuning of the optical path length differences in a Michelson interferometer setup with the reflections R1 and R2 at the distances z_1 and z_2 as shown in Figure 2.19.



Figure 2.19: Schematic for the measurement of the interferogram (interference fringe visibility).

The detected interferograms exhibit, as it could be expected for a multimode laser, periodic power maxima of the interference fringes. Figure 2.20 (left) shows the recorded interferogram during tuning of the optical path differences $\Delta L = 2 \cdot (z_1 - z_2)$ from $\Delta L = -2$ mm to $\Delta L = +7$ mm by linearly straining the fibre with a PC-controlled step motor setup (section 4.1.1). In order to estimate the coherence length or degree of coherence function of the source, such interferograms have been recorded for various path length differences. Alternatively, the interferogram can be approximately calculated from the source spectrum measured by the OSA (Figure 2.18) by applying a Fourier transform to the measured spectrum.

To obtain comparable values for interferometric power changes (constructive and destructive interference), the spectral optical power values $S_{FP}(\lambda_i)$ of the OSA measurement are treated as p single frequency sources ($\tau_{coh} = \infty$) and are superimposed as a function of path length difference. The resulting interferometric power variation $I_{if}(z)$ as a function of optical path length difference ΔL in SMF is calculated as

$$I_{if}(\Delta L) = \sum_{i=1}^{p} S_{FP}(\lambda_i) \cdot \cos\left(4\pi \cdot \frac{n_e}{\lambda_i} \cdot \Delta L\right)$$
(2.62)

The resulting calculated interferogram is less accurate than the measured one since the spatial resolution of the OSA is limited and the exact lineshapes and wavelengths of the single lasing modes cannot be resolved. Figure 2.20 (right) shows the interferogram calculated from the source spectrum for the same path length difference variation as the directly measured interferogram in Figure 2.20 (left). Although power characteristics of the measured interferogram are more precise, the periodicity of the interference power maxima dz can be more accurately obtained from the calculated interferogram since the optical path length change (applied elongation) cannot be exactly transferred to the fibre core when straining the fibre. The intermediate distance between neighbouring interference maxima or its periodicity in SMF in reflection is $dz \approx 2.95$ mm (Figure 2.20) which is a function of the wavelength spacing between the single longitudinal modes of $\Delta\lambda \approx 0.198$ nm. This value is later used in section 2.5.3 to optimize the interference averaging during the backscatter measurement.



Figure 2.20: Measured interferogram (left) and calculated interferogram from the source spectrum using equation (2.62) (right) for optical path difference ΔL in reflection in a SMF.

It was also observed that the visibility of the interference fringes strongly depends on the laser current and temperature settings (therminstor resistance R_{th} of the laser module). Various operation point settings (laser current and laser temperature) result in high fringe visibility up to tens of meters path length difference, whereas other current and temperature settings show very low degrees of coherence and interference cannot be observed after few metres. Figure 2.21 shows the measured maximum fringe visibility using the setup in Figure 2.19 for various optical path length differences ΔL for two different laser operating settings (laser current and temperature).



Figure 2.21: Measured degree of coherence (maximum fringe visibility) for coherent setting (290 mA laser current, $R_{th} = 10 \text{ k}\Omega$) and incoherent setting (280 mA laser current, $R_{th} = 10.86 \text{ k}\Omega$) of the FP laser.

The more 'coherent' operating point setting (laser current 290 mA and $R_{th} = 10 \text{ k}\Omega$) shows significant interference even at 50 m path length difference and a coherence length (equivalent to the 1/e drop of the maximum interference fringe visibility) of about 10 m. The 'incoherent' operating point setting (laser current 280 mA and $R_{th} = 10.86 \text{ k}\Omega$) exhibits a much shorter equivalent coherence length of approximately 15 cm. Since incoherent detection is important for optimal I-OFDR results, this incoherent operating point (280 mA laser current, $R_{th} = 10.86 \text{ k}\Omega$, $I_{out} = 98 \text{ mW}$) is set for the measurements presented in this thesis. No changes of the spectral properties or optical power output have been observed during 4 years of laser operation.

The linewidth and lineshape of the single lasing modes is also an important parameter when it comes to the estimation of phase-to-intensity noise which will be presented in section 2.5.2. In order to determine the linewidth and shape of the single FP laser modes, heterodyne mixing using the relatively narrow linewidth DFB laser source as a local oscillator (LO) has been conducted. Both sources emit in the same wavelength region. The DFB laser source has been tuned in wavelength close to the wavelengths of the FP lasing modes by tuning the temperature of the DFB source. The local oscillator wavelength is set to a wavelength just below the FP laser mode. The resulting mixing products fall within the detection bandwidth of the photo detector and are measured by the ESA. The wavelength tuning has been monitored by means of an OSA measurement. Figure 2.22 (left) shows the measurement.



Figure 2.22: Measurement setup for heterodyne mixing of DFB and FP laser (left) and OSA measurement (right).

The heterodyne mixing products of the two sources are measured using the wide bandwidth photodetector and the ESA. The power spectrum of the photodetector current reduces similarly for the source spectra to equation (2.61) to the following expression [17]

$$S_i(f) \propto \mathcal{R}^2 \{ S_d(f) + 2[S_{L0}(\nu_{L0}) * S_s(-\nu)] \}$$
 (2.63)

If the linewidth of the LO is insignificantly small compared to the emission spectrum to be analyzed, the lineshape spectrum of the local oscillator $S_{LO}(\nu)$ can be approximated with a Dirac function. In this case [17], equation reduces (2.63) to

$$S_i(f) \propto 2\mathcal{R}^2 I_{\text{LO}} S_s(\nu - \nu_{\text{LO}}) \tag{2.64}$$

where $I_{\rm LO}$ is the optical power of the local oscillator.

The single FP laser modes are also beating with each other and result in heterodyne mixing products. Since the single laser modes are separated in wavelength by $\Delta\lambda \approx 0.198$ nm, corresponding to about 35 GHz frequency separation, their mixing products fall outside the detection bandwidth of the photodetector and do not contribute to the detected spectrum. Several laser modes of the FP laser for the incoherent operation settings have been mixed with the 3 MHz wide DFB laser spectrum and are displayed in Figure 2.23. The linewidth of the DFB laser is orders of magnitude smaller than the measured spectra. The detected mixing spectra can therefore be considered to approximately describe the actual emission spectra of the FP modes.



Figure 2.23: Spectral shape of single FP lasing modes measured by heterodyne mixing with the DFB laser.

Judging from the lineshapes of the few measured FP lasing modes, it is expected that all FP modes have similarly irregular spectra with FWHM linewidths in the order of several hundreds of MHz to 1 GHz. Operating the FP laser in the 'coherent' settings (290 mW laser current, $R_{th} = 10 \text{ k}\Omega$) results in relatively narrow spectra which explains the observed long coherence lengths in Figure 2.21. The coherence length for each lasing mode at the incoherent setting is therefore significantly reduced in comparison with the coherent operation point settings.

The important information obtained from the spectral measurements is that the FP laser modes cannot be approximated to be of Lorentzian lineshape. They are, however, very stable and reproducible for the FP operation settings (laser current and temperature). The spectral information is used to calculate the interferogram and obtain information for the optimization of the interference compensation technique in section 2.5.3. Delayed self-homodyne measurements can be conducted to identify 'incoherent' laser operation settings that are favourable for backscatter measurement.

2.5.2 Phase-to-intensity noise

Various noise sources contribute to the total noise associated with optical detection. The most dominant noise sources may be thermal noise, shot noise, intensity noise and phase-to-intensity noise. Since electrical filtering by the VNA around the modulation frequency f_m is conducted in I-OFDR, only the spectral noise power around the modulation frequency f_m is the SNR-determining value. The various noise sources, apart from the phase-to-intensity noise, are here only discussed in brief.

The intensity noise of the investigated optical sources can here be considered negligible compared to other noise sources. Thermal noise and shot noise exhibit approximately white noise characteristics. This means that the power spectral density is approximately constant throughout the frequency spectrum. The thermal noise is generated in the receiver electronics and can be considered the dominant noise source when low backscatter powers are detected since it is independent of the detector photocurrent. This noise source is specific to the photodetector and amplifier used in the setup. The photocurrent shot noise usually becomes the dominant noise source when high optical powers have to be measured since it is a function of the photocurrent.

For the specific case of the I-OFDR, however, the *phase-to-intensity* noise exceeds the shot noise level. The time-delayed mixing of the optical source spectrum with itself due to power originating from various locations in the FUT results in a much higher phase-to-intensity noise spectrum. An optical source is characterized by its amplitude noise and its phase noise which originates from random frequency fluctuations of the laser source. As shown in section 2.5.1, the conversion from optical phase noise to intensity noise can be observed when the source spectrum is mixed with a time-delayed version of itself at an optical detector. This noise can have a deteriorating effect in optical fibre communication systems at the presence of partial reflections causing multiple reflections in an optical data transmission optical fibre system [67],[64]. Also in optical fibre sensing can the phase-to-intensity

noise be a performance-limiting factor. The resolutions of interferometric sensors, where optical phase shifts are to be measured precisely, may suffer from phase noise-induced signal fluctuations [63].

Also for backscatter measurement using I-OFDR, this effect may be significant. The time-delayed mixing components may originate from distributed Rayleigh scattering along the fibre but also from multiple reflections in the FUT. Compared to the OTDR, the resulting phase-to-intensity noise in I-OFDR plays a more important role since the whole FUT is filled with the CW optical carrier as well as the power-modulated signal component during the measurement. Both components contribute to the phase-to-intensity noise in different qualities. In pulse domain reflectometry other noise sources are usually dominant since only a single pulse propagates at the time and time-delayed mixing can only occur within the pulse length in the fibre. This is less problematic in terms of phase-to-intensity noise.

The phase-to-intensity noise power spectrum is not flat but exhibits significant spectral dependencies that are a function of the optical source spectrum and also depend on the properties of the FUT itself. This noise component is also a function of the modulation frequency f_m and can be the SNR-limiting factor in an I-OFDR setup. It is qualitatively and quantitatively investigated in this section. Concluding from measurement results and simulations results, general recommendations for source spectral properties in power-modulated optical systems are derived. Signal-to-noise spectra in dependence on the FUT characteristics are calculated. The power modulation and bandwidth-limited detection of the VNA are incorporated into the calculations.

The photocurrent power spectrum due to the conversion of phase noise to optical intensity noise for the general case of a two-path interferometer with arbitrary time delay and equal powers in both arms has been derived for the coherent case as well as for the incoherent case by Moslehi [68]. It is shown that the noise power spectral density (NPSD) for the coherent case exhibits strong frequency dependence and strongly depends on the optical phase relation of the interfering waves. For the incoherent case, the NPSD results in the same delayed self-homodyne characteristic, as shown in equation (2.61) and Figure 2.17. The optical NPSD for a CW Lorentzian lineshape signal into a Mach-Zehnder interferometer for the incoherent case ($\tau_0 \gg \tau_{coh}$) is given [68] as

$$S_{I_{cw}}(f) \approx \frac{I_0^2}{8} \cdot \frac{\tau_{coh}}{1 + (\pi \cdot f \cdot \tau_{coh})^2} = \frac{I_0^2}{8\pi} \cdot \frac{\Delta \nu}{f^2 + (\Delta \nu)^2} \qquad \left[\frac{W_{(opt)}^2}{H_Z}\right]$$
(2.65)

The second term of the expression describes the Lorentzian lineshape function. I_0 is the input optical power into the interferometer with a coupling ratio of 0.5 of each coupler. This expression is valid for equal powers in the single interferometer paths and fully polarized light with the states of polarization (SOP) in both paths aligned. The equivalent electrical NPSD for the specific case of the I-OFDR setup without the modulation (CW only) is derived from equation (2.65). The expression is adapted in the following and extended to describe the I-OFDR system including the amplitude modulation component in order to identify critical system parameters and give recommendations for I-OFDR system design, sensor fibre design or choosing the appropriate measurement frequencies. Figure 2.24 shows the schematic of the setup used for the NPSD measurement. For validation reasons (sufficient power and control of the SOP), the equivalent photocurrent NPSD is measured by means of a Mach-Zehnder interferometer using the I-OFDR components (EOM, wideband photodetector) and the ESA.



Figure 2.24: Mach-Zehnder setup for the measurement of the NPSD of a CW signal with power modulation.

The setup allows for superimposing the modulation power component of the frequency f_m onto the CW source signal and time-delayed detection of the signal (equivalent to an I-OFDR measurement with two reflections in the FUT). The incoherent case ($\tau_0 \gg \tau_{coh}$) is assumed. The ESA measures, just as the VNA, the modulation signal as well as the noise that falls within the adjustable detection bandwidth *BW* around the modulation frequency f_m . The NPSD is therefore defined for a specified detection bandwidth *BW*. Equation (2.65) is adapted for the parameters of the measurement setup in Figure 2.24 (electrical power as measured by the ESA) in dBm (electrical) in order to directly compare the measured and calculated NPSD results:

$$S_{P_{cw}}(f) \approx \frac{BW \cdot (I_0 \cdot \mathcal{R})^2}{32\pi \cdot 50\Omega} \cdot \frac{\Delta \nu}{f^2 + (\Delta \nu)^2} \qquad \left| \frac{W_{(el)}}{Hz} \right|$$
(2.66)

 \mathcal{R} is the responsitivity of the photodetector¹ in V/W and the 50 Ω ESA input impedance has been added. The phase-to-intensity noise conversion has a strong polarization dependency. The case of fully polarized light and the SOP of both paths perfectly aligned would result in maximum phase-to-intensity noise conversion as described in equation (2.65). Orthogonal polarization states of fully polarized light in both paths would result in zero phase-to-intensity noise. Unit polarization vectors may be introduced here for the single path components. The measurements and calculations, however, are here conducted and described for the case of unpolarized light (randomly polarization scrambled light). Only half of the optical power contributes to phase-to-intensity noise for unpolarized light or randomly polarized (polarization-scrambled) light [67], [64], [69]. This effective reduction of the input power to $I_0/2$ is incorporated in equation (2.66). The NPSD measurements are conducted with randomly polarization-scrambled light in one of the paths and averaging a great number of ESA measurements. The polarization effect on the NPSD is independent of the interferometer delay and also occurs for the 'incoherent interference' at $\tau_0 \gg \tau_{coh}$.

The expression in equation (2.66) for the introduced measurement setup is generally valid for the special case of the combination of two equal but time-delayed power components of random polarization state in a Mach-Zehnder setup. For the case of the I-OFDR approach, it is more convenient to calculate the NPSD as a function of the optical powers values I_r , that originate from a reflection in the fibre (r as reflection index), as they are detected by the photodetector. The detected powers I_r are described in equation (2.34) by the reflectivities R_r multiplied by the incident optical power I_0 (fibre attenuation neglected). Compared to the Mach-Zehnder configuration with two couplers (0.5 coupling ratio), the incident powers I_r have to be multiplied by 4 to obtain the same results. The NPSD for two reflections with the incident powers I_1 and I_2 is then defined as

$$S_{P_{cw}}(f) = \frac{BW \cdot \mathcal{R}^2}{2\pi \cdot 50\Omega} \cdot I_1 \cdot I_2 \cdot \frac{\Delta \nu}{f^2 + (\Delta \nu)^2} \qquad \left[\frac{W_{(el)}}{Hz}\right]$$
(2.67)

The NPSDs have exemplarily been measured with the setup in Figure 2.24 and are calculated as above using equivalent parameters. Figure 2.25 shows the calculated as well as the measured NPSD for the settings $I_1 = I_2 = 65 \,\mu\text{W}$ and the settings $I_1 = 65 \,\mu\text{W}$ and $I_2 = I_1/4$. The delay τ_0 corresponds to an optical path length difference of $\Delta L = 189 \,\text{m}$. The thermal noise $S_{P_{th}}(f)$ is the other dominant noise source and is here plotted as measured by the ESA at $BW = 300 \,\text{kHz}$. For comparison reasons, $S_{P_{th}}(f)$ is also added to the calculated NPSD. The shot noise and other noise sources have been measured to be negligible for this setup and the I-OFDR system and are therefore not further considered.

¹ The responsitivity of the photodetector with integrated amplifier is about 2.55·103 V/W at 1310 nm (Femto HAS-X-S InGaAs).



Figure 2.25: Simulation and measurement of $S_{P_{cw}}(f) + S_{P_{th}}(f)$ for the settings $I_1 = I_2 = 65 \ \mu\text{W}$ and the settings $I_1 = 65 \ \mu\text{W}$, $I_2 = I_1/4$; $\Delta \nu = 5 \ \text{MHz}$, $BW = 300 \ \text{kHz}$, $\Delta L = 189 \ \text{m}$.

The measured results agree well with the simulated values. For the general case with multiple reflections $n \ge 3$ in the FUT, all detected powers I_r interfere incoherently with another. The above equation can be expanded equivalent to the interference term in equation (2.44), where all n reflection components interfere with another. The indices i and e ($i, e \subseteq r$) denote the ith and eth reflection in the fibre. The $S_{P_{cw}}(f)$ for $n \ge 3$ can then be described by

$$S_{P_{cw}}(f) = \frac{BW \cdot \mathcal{R}^2}{2\pi \cdot 50\Omega} \cdot \sum_{i=2}^n \sum_{e=1}^{i-1} I_i \cdot I_e \cdot \frac{\Delta \nu}{f^2 + (\Delta \nu)^2} \qquad \left[\frac{W_{(el)}}{Hz}\right]$$
(2.68)

for $|\tau_i - \tau_e| \gg \tau_{coh}$, as exemplarily shown in Figure 2.26.

$$I-OFDR$$

$$I_{1};\tau_{1}$$

$$I_{2};\tau_{2}$$

$$I_{3};\tau_{3}$$

$$I_{n};\tau_{n}$$

$$I_{n};\tau_{n}$$

$$I_{n};\tau_{n}$$

$$R_{1}$$

$$R_{2}$$

$$R_{3}$$

$$R_{n}$$

$$S_{P_{n}w}(f) \propto I_{2} \cdot I_{1} + I_{3} \cdot I_{1} + I_{3} \cdot I_{2} + \dots + I_{n} \cdot I_{1} + I_{n} \cdot I_{2} + I_{n} \cdot I_{3} + \dots + I_{n} \cdot I_{n-1}$$

Figure 2.26: Schematic of FUT with multiple reflection components.

Due to the double summation of the interference terms, the NPSD does not increase linearly with the number of reflections (equal detected powers assumed) but with the factor n(n - 1)/2.

When a CW source is amplitude-modulated, as it is the case during an I-OFDR measurement, the modulation power also induces a phase-to-intensity noise around the modulation frequency f_m . This modulation NPSD component $S_{P_{mod}}(f, f_m)$ around f_m is a function of the detected modulation power and therefore depends on the modulation depth m and the transfer function of the FUT. $S_{P_{mod}}(f, f_m)$ is a function of the absolute value of the FUT transfer function which is defined here as the transfer function coefficient $G(f_m) \propto |H(j\omega)|$. The modulation NPSD $S_{P_{mod}}(f, f_m)$ around the modulation frequency f_m of an amplitude-modulated CW source with the modulation depth m can then be described for each modulation frequency f_m by replacing f with $|f - f_m|$

$$S_{P_{mod}}(f, f_m) = \frac{m^2}{4} \cdot S_{P_{cw}}(|f - f_m|) \cdot G(f_m)$$
(2.69)

where $f_m \subseteq f$ with $f_m \neq 0$. The noise power of the amplitude modulated optical power is reduced by $m^2/4$ in electrical power relative to the CW noise power. $S_{P_{mod}}(f, f_m)$ exhibits the same spectral characteristic as $S_{P_{cw}}(f)$ (convolution of the laser lineshape with itself) but decreased power depending on m and the transfer function. The transfer function coefficient $G(f_m)$ describes the relation of the detected modulation power (sum of absolute values according to equation (2.58)) in relation to the

total reflected power that is incident at the photodetector. $G(f_m)$ can be calculated for a given number of *n* reflections with the corresponding powers I_r at the positions z_r as

$$G(f_m) = \frac{\left|\sum_{r=1}^{n} I_r \cdot e^{-j2\pi \cdot f_m \cdot 2 \cdot z_r \cdot n_{gr}/c_0}\right|^2}{\left[\sum_{r=1}^{n} I_r\right]^2}$$
(2.70)

The total NPSD $S_{P_{tot}}(f, f_m)$ of an amplitude-modulated CW source is the sum of the CW NPSD from equation (2.68) and the modulation NPSD component $S_{P_{mod}}$ from equation (2.69). Other noise sources such as the thermal noise $S_{P_{tb}}(f)$ may also be added to the total NPSD:

$$S_{P_{tot}}(f, f_m) = S_{P_{cw}}(f) + S_{P_{mod}}(f, f_m) + S_{P_{th}}(f) + \cdots$$
(2.71)

Thermal noise is the dominant white noise source and has been measured with about -125 dBm/Hz. Shot noise and intensity noise do not a have a measurable influence in this application but could analogously be added to the total noise.

The measurement signal is the detected modulation signal power $P_{mod}(f_m)$, which is basically the absolute value of the transfer function of the FUT as detected by the ESA or VNA. Possible deviations of the actual I-OFDR system transfer function are neglected. On the assumption that the backscattered signal originates from n single reflections in the fibre, $P_{mod}(f_m)$ can be calculated as

$$P_{mod}(f_m) = \frac{\mathcal{R}^2}{50\Omega} \cdot \left[\left| \sum_{r=1}^n I_r \cdot \frac{m}{2} \cdot e^{-j2\pi \cdot f_m \cdot 2z_r \cdot n_{gr}/c_0} \right| \right]^2 \quad [W_{el}]$$
(2.72)

The spectral power measurement by the ESA around the modulation frequency f_m is similar to the measurement performed by the VNA. The same electrical power spectrum comprising the sum of the total NPSD $S_{P_{tot}}(f, f_m)$ and the detected modulation signal $P_{mod}(f_m)$ is detected within the filter bandwidth BW. $S_{P_{tot}}(f, f_m)$ is a function of the filter bandwidth setting BW, whereas the narrow bandwidth $P_{mod}(f_m)$ can be considered to be independent of BW. Such a NPSD of a power-modulated CW source in a two-path interferometer has been simulated and measured with the setup in Figure 2.24 for random polarization (averaging ESA measurement while randomly scrambling the SOP in one signal path). Figure 2.27 shows the calculated and simulated NPSD $S_{P_{tot}}(f, f_m) + P_{mod}(f_m)$ for the settings of equal detected powers ($I_1 = I_2 = 65 \mu$ W) at $f_m = 421$ MHz and different detected power values ($I_1 = 65 \mu$ W, $I_2 = I_1/4$) at $f_m = 490$ MHz.



Figure 2.27: Calculated and simulated NPSD for $I_1 = I_2 = 65 \,\mu\text{W}$ at $f_m = 421 \,\text{MHz}$ and $I_1 = 65 \,\mu\text{W}$, $I_2 = I_1/4$ with $f_m = 490 \,\text{MHz}$ ($m = 0.5, \,\Delta\nu = 5 \,\text{MHz}^1, \,\Delta L = 189 \,\text{m}$).

The modulation frequency $f_m = 421$ MHz corresponds approximately to a maximum transfer function $|H(j\omega)|$ of the FUT. The maximum of $S_{P_{mod}}(f, f_m)$ is therefore about 12 dB lower than $S_{P_{cw}}(f)$ since $G(f_m) \approx 1$ and $m^2/4 = 1/16$. The thermal noise spectrum of the photodetector is also plotted in the figure and is added to the simulation results for direct comparison with the measurement results. The measured and calculated signal and noise power levels show good alignment. The derived equations (2.67) to (2.72) can therefore be used to calculate NPSD and signal powers.

The relative intensity noise (RIN) is an important parameter that is related to the system signal-tonoise ratio (SNR). The RIN is commonly defined as the mean square power fluctuation $\langle \Delta I(t)^2 \rangle$ (per Hz bandwidth) in relation to the averaged squared optical power $\langle I_0(t) \rangle^2$

$$RIN = \frac{\langle \Delta I(t)^2 \rangle}{\langle I_0(t) \rangle^2} \qquad \left[Hz^{-1} \right]$$
(2.73)

Since the intensity noise has a strong spectral dependency, it is useful to describe the *RIN* as a function of the optical NPSD in equation (2.65)

$$RIN(f) = \frac{\langle S_{I_{cw}}(f) \rangle}{\langle I_0(t) \rangle^2} \quad \left[Hz^{-1} \right]$$
(2.74)

The relevant parameter for I-OFDR measurement, however, is the modulation signal-to-noise ratio $SNR_{mod}(f_m)$ which is primarily a function of the measurement frequency and strongly depends on the filter bandwidth BW. $SNR_{mod}(f_m)$ is calculated as the ratio between the detected modulation signal power from equation (2.72) and the NPSD from equation (2.71) around the modulation frequency as

$$SNR_{mod}(f_m) = \frac{P_{mod}(f_m)}{S_{P_{tot}}(f_m)}$$
(2.75)

Equation (2.71) and equation (2.75) are used to exemplarily calculate the NPSD and SNR for a specific modulation frequency at a given filter bandwidth of BW = 1 kHz as it would be measured by the VNA during an I-OFDR scan. Figure 2.28 shows qualitatively the impact of the source linewidth on the NPSD and indicates the resulting SNR, as it would also be measured with the VNA. A filter bandwidth of BW = 1 kHz is chosen for the simulations since this is also the bandwidth used for most I-OFDR measurements presented in this thesis. Since the filter bandwidth is small compared to the laser linewidth ($BW \ll \Delta \nu$), the SNR can be directly determined as the relation between the detected modulation power $P_{mod}(f_m)$ and the calculated $S_{P_{tot}}(f_m)$.

¹ Another DFB laser of identical type (AOI-DFB-1310-BF-31-A5-FC/APC, $\lambda = 1310$ nm) with $\Delta \nu = 5$ MHz had to be used for this measurement because of damage of the laser used for previous measurements.



Figure 2.28: Simulation of frequency-modulated NPSD including thermal noise ($S_{P_{tot}}(f, f_m)$) for different laser linewidths; two reflections, $I_1 = I_2 = 65 \ \mu$ W, $\Delta L = 200 \ m$, $f_m = 421 \ MHz$, $BW = 1 \ kHz$, m = 0.5.

The noise peak power of a Lorentzian lineshape source $S_{P_{CW}}(f = 0)$, equation (2.66), for equal optical power values is inversely proportional to the source linewidth Δv

$$S_{P_{cw}}(f=0) \propto \frac{1}{\Delta \nu}$$
(2.76)

However, as it can be seen in the simulation results above, the resulting signal-to-noise ratio is also a function of the measurement frequency f_m as well as other measurement parameters and the FUT itself ($SNR_{mod} = f(\Delta v, f_m, m, G(f_m), BW$)). The resulting SNR over the measured frequency range of an I-OFDR scan is a function of the NPSD caused by the CW component as well as the detected signal power at f_m with $G(f_m) \propto |H(j\omega)|$, as described in equation (2.72). Figure 2.29 (left) shows the measured PD thermal noise and the simulation results of the dominant noise components over the measurement frequency range. The PD thermal noise and phase-to-intensity noise of the CW component are independent of the detected modulation signal power $P_{mod}(f_m)$. The NPSD caused by the modulation component is, however, a function of the modulation frequency and properties of the FUT as expressed in equation (2.70). The single noise components ($S_{P_{tot}}(f, f_m), S_{P_{cw}}(f), S_{P_{mod}}(f, f_m), S_{P_{th}}(f)$) are also plotted in Figure 2.29 (left). The resulting $SNR_{mod}(f_m)$ for all modulation frequencies f_m are exemplarily simulated using equation (2.75) for different source linewidths as they would be detected during an I-OFDR sweep. Figure 2.29 (right) shows the $SNR_{mod}(f_m)$ results for two equal power reflections ($I_1 = I_2 = 65 \mu$ W) and the incoherent case ($\Delta L = 100$ m).



Figure 2.29: Simulation of spectral noise components: modulation signal power $P_{mod}(f_m)$ for $\Delta v = 10$ MHz (left) and the simulated SNR_{mod} , as measured with an I-OFDR for different laser linewidths in the incoherent case (right); $I_1 = I_2 = 65 \ \mu$ W, $BW = 1 \ k$ Hz, m = 0.5, $\Delta L = 100 \ m$.

It can be concluded that broader linewidth results in mainly higher SNR over the sweep frequency range. The SNR at lower frequencies is mainly limited by the CW NPSD component $S_{P_{CW}}(f)$. Also, minima of the transfer function at frequencies in the order of and exceeding the laser linewidth exhibit

decreased SNR. Care has therefore to be taken when operating the measurement system at specific measurement frequencies f_m , as proposed for the dynamic approach in chapter 5. These calculations can be used to estimate the SNR for certain modulation frequencies or generally designing a frequency-modulated measurement setup and choosing a laser source.

The phase-to-intensity noise can actually have a sensitivity-degrading effect when conducting an I-OFDR measurement in a configuration as shown in Figure 2.24. Figure 2.30 shows two I-OFDR measurement results of a FUT with two strong reflections for the incoherent case ($\Delta L \approx 400$ m), the DFB laser ($\Delta v \approx 3$ MHz) as a source and VNA bandwidth setting of BW = 30 kHz. One measurement is obtained for the SOP of both paths aligned in order to ensure maximum phase-to-intensity noise conversion. The other measurement is conducted with the same settings but orthogonal SOP exhibits significantly reduced phase-to-intensity noise.



Figure 2.30: I-OFDR measurement with the DFB laser for the incoherent case: for SOP aligned and orthogonal SOP; $I_1 \approx I_2 \approx 100 \ \mu$ W, $\Delta \nu \approx 3 \ M$ Hz, $\Delta L \approx 400$, m = 0.5, BW = 30 kHz, $f_{m,max} = 10 \ M$ Hz.

The sensitivity of the polarization-aligned measurement is visibly lower than that for the reduced interaction at orthogonal SOP. This result shows that phase-to-intensity noise can be a limiting factor for backscatter measurement and polarization changes have a crucial impact on the NPSD also for the incoherent case.

For the case of a multimode FP laser, which is used for all I-OFDR measurements in this thesis, the NPSD and SNR cannot be described with the introduced equations. It has been shown in Figure 2.23 that the single lasing modes of the FP laser exhibit non-Lorentzian lineshapes. The mixing of the backscattered and backreflected powers from the FUT can also be assumed to be incoherent for general I-OFDR measurements. The resulting NPSD could be approximated with delayed self-homodyne mixing of the CW component and the frequency-shifted delayed self-homodyne component proportional to the transfer function coefficient $G(f_m) \propto |H(j\omega)|$.

Using the investigated FP laser has significant advantages over the DFB laser in terms of phase-tointensity noise. First of all, the linewidths of the lasing modes are much broader, resulting in increased SNR. Another important advantage of using a multimode laser over a singlemode laser is that the measurement signal is directly proportional to the modulation signal power $P_{mod}(f_m)$ but the phaseto-intensity noise is reduced for the same output power due to the multimode emission: For a singlemode laser, the NPSD (equation (2.66)) is proportional to the square of the input power I_0

$$S_{P_{cw}}(f) \propto I_0^2 \tag{2.77}$$

whereas for a multimode laser, the input power I_0 (the signal carrier) is the sum of the p single lasing mode powers I_s (s is the index of the longitudinal mode) with

$$I_0 = \sum_{s=1}^p I_s$$
 (2.78)

Since the frequency separation of the single lasing modes of the FP is with about 35 GHz (calculated from the OSA measurement in Figure 2.18) greater than the detection bandwidth, the detected NPSD originates only from the sum of the mixing components of the single lasing modes with themselves:

$$S_{i(FP)}(f_m) \propto \sum_{s=1}^{p} I_s^2$$
 (2.79)

The relation between equation (2.77) and equation (2.79) describes the improvement of the SNR of a multimode laser compared to a singlemode laser of equal emission power

$$\Delta SNR = \frac{I_0^2}{\sum_{s=1}^p I_s^2} = \frac{\left(\sum_{s=1}^p I_s\right)^2}{\sum_{s=1}^p I_s^2}$$
(2.80)

This SNR improvement factor ΔSNR for the used FP laser is calculated from the powers I_s of the single lasing modes measured with the OSA (Figure 2.18) and results in an improvement of $\Delta SNR \approx 14.8$ dB. The SNR can therefore be considerably increased when using a multimode laser source compared to the same signal power in a single lasing mode.

Figure 2.31 shows exemplarily the ESA measurement of the modulated DFB and FP sources for equal powers and the incoherent case but with the SOP in both paths aligned. The simulated result $S_{P_{tot}}(f, f_m) + P_{mod}(f_m)$ from the equations (2.71) and (2.72) for the DFB laser agrees well with the measured trace.



Figure 2.31: Simulated and measured NPSD for the DFB ($\Delta v = 5 \text{ MHz}$) and measured NPSD for the FP; $I_1 = I_2 = 65 \mu W$, BW = 300 kHz, m = 0.5, $\Delta L = 189 \text{ m}$, $f_m = 421 \text{ MHz}$, calculation of SNR for BW = 1 kHz.

Using the FP laser with multimode emission and broader linewidth of the single modes clearly improves the SNR. The measurement could only be conducted with 300 kHz bandwidth. The equivalent $SNR_{mod}(f_m)$ for 1 kHz bandwidth is about 51.7 dB for the DFB laser and about 73 dB for the FP laser. The total SNR improvement of about 21.3 dB when using the FP laser compared to the DFB laser can be largely attributed to the multimode emission (calculated $\Delta SNR \approx 14.8$ dB) as well as the impact of the broader laser linewidth. The SNR improvement due to different laser linewidths cannot be calculated as directly proportional to the spectral width relation ($\Delta v_{\rm FP}/\Delta v_{\rm DFB}$) since the NPSD is a superposition of the $S_{P_{cw}}(f)$ component as well as the $S_{P_{mod}}(f, f_m)$ component (equation (2.71)). Moreover, the spectra of the single FP modes cannot be treated as Lorentzian-shaped. The SNR improvement due to a higher spectral width of the FP source of about 6.5 dB is also a function of f_m (generally decreased SNR with increased f_m equivalent to the results in Figure 2.29).

Rayleigh backscattering

Not only reflections but also *Rayleigh backscattered power* from a fibre can be significant and equally results in beating with itself and other reflection components from the FUT. The detected phase-to-intensity noise spectrum originating from Rayleigh backscattering can be treated as for the delayed self-homodyne mixing in equation (2.61) and can be considered to be independent of the SOP and degree of polarization (DOP): The SOP of the signal propagating along a fibre typically changes with distance due to internal and external effects. Rayleigh scattering from a long fibre can therefore be assumed to have random polarization state when arriving at the detector. This means that delayed self-homodyne mixing of the Rayleigh backscattered power can be considered to be independent of the DOP of the source as well as the SOP and changes thereof. Only half of the Rayleigh backscattered power contributes to the phase-to-intensity noise [67], [64], [69] compared to fully polarized light and SOP aligned.

Due to the double summation in equation (2.68), the Rayleigh backscattering power I_{RB} results in approximately half the NPSD compared to the NPSD caused by two reflections of equal reflectivities $R_1 = R_2$ with the same total reflected power $I_{RB} = I_0 \cdot (R_1 + R_2)$. Using equation (2.67) for two equal reflections shows that $S_{P_{cw}}(f) \propto [I_0 \cdot (R_1 + R_2)]^2$. Rayleigh scattering can be described as an infinite number $(n \to \infty)$ of reflections I_r along the fibre with a total backscattered power of I_{RB}

$$I_{RB} = \sum_{r=1}^{n} I_r$$
 (2.81)

The double summation in equation (2.68) for Rayleigh backscattered power I_{RB} for $n \to \infty$ therefore leads to half the NPSD:

$$S_{P_{cw}}(f) \propto \sum_{i=2}^{n} \sum_{e=1}^{i-1} I_i \cdot I_e \quad \text{and} \quad \lim_{n \to \infty} S_{P_{cw}}(f) \propto \frac{I_{RB}^2}{2}$$
(2.82)

The NPSD of optical power originating from reflections in the fibre as well as Rayleigh backscattered power can be approximated by using equation (2.68) with reflected powers as well as the Rayleigh scattering component.

The Rayleigh backscattering itself may have significant power and can be calculated using equation (1.7). Exemplarily, for a 10 km long SMF and an assumed input power into the fibre of $I_0 = 20$ mW, the detected Rayleigh backscattering power is $I_{RB} \approx 1.9 \,\mu\text{W}$ ($\alpha = 0.33 \,\text{dB/km}$, $\lambda = 1310$ nm, data from Table 1.1).

Summary

The NPSD of a backscatter signal caused by an amplitude-modulated CW input signal into the FUT is a function of various parameters: the optical source spectrum, measurement parameters and system parameters as well as the FUT itself determine the SNR as a function of f_m . Depending on the source spectrum and the FUT, the phase-to-intensity noise can be the dominant noise source already at detected signal powers of a few μ W. Reflections and distributed Rayleigh backscattering contribute to this noise source in different qualities. Possible variables determining the NPSD and the SNR of an I-OFDR backscatter measurement result are summarized in Table 2.1. The coherent case can be generally ruled out for I-OFDR.

Reflections in the FUT	Reflections in the FUT	Distributed Rayleigh		
(coherent case)	(incoherent case)	backscatter		
 delay τ₀ → phase of the electric fields → H(jω) modulation frequency f_m modulation depth m linewidth Δν / lineshape polarization 	 delay τ₀ → H(jω) modulation frequency f_m modulation depth m linewidth Δν / lineshape polarization 	 modulation frequency f_m modulation depth m linewidth Δν / lineshape 		

Table 2.1. Devenue atoms and warinkless	fthe LOEDD set	a sund the FUT with in	fluence on the NDCD	and CND
Table 2.1: Parameters and variables of	ij the I-OFDR setu	p ana the FUT with in	iffuence on the NPSD	ana Sivik.

In conclusion, it has been shown that choosing a source with a broader linewidth generally improves the SNR of an I-OFDR sweep result. Further increase of the SNR can be achieved by using a multimode laser instead of a singlemode laser. The SNR improvement factor is $\Delta SNR \approx 14.8$ dB for the used FP laser. This is one reason for choosing the multimode FP laser over a singlemode laser. The other reasons are the favourable coherence and interference properties. General expressions for the calculation of the signal-to-noise ratio of an amplitude-modulated sensor signal that is dominated by phase-tointensity noise have been derived. These calculations may also be useful for the system design of other amplitude-modulated sensing applications, especially when narrow linewidth lasers are used.

2.5.3 Interference compensation

As indicated in the previous section, another systematic difference between the I-OFDR approach and the OTDR technique concerning the measurement signal stability is that interference is not limited to the pulse length (OTDR) but is determined by the emission spectrum of the optical source that is used for signal generation.

For telecommunication OTDRs using long optical pulses, corresponding to pulse lengths of $\Delta p = 100$ m or more, the coherence length L_{coh} is typically shorter than the pulse length. In that case, the interference impact between the distributed Rayleigh scattering in the fibre is negligible. For shorter pulses in the order of the coherence length, the amplitude uncertainty of the backscatter signal is increased due to coherent interaction within the full length of the pulse. The overall lower backscatter signal level for short pulses (proportional to equation (1.7)) as well as the statistically reduced intensity averaging of the various phase differences between the single scattering centres increases this backscatter uncertainty effect. This Rayleigh backscattering noise (also referred to as fading noise or coherent speckle) results in considerably increased power fluctuations for high spatial resolution OTDRs using laser sources. This effect is especially degrading in coherent OTDRs where fading noise reduction has been proposed by averaging temperature of the coherent source [70].

The case is different for the I-OFDR approach where the interferometric interaction is not limited by the pulse length but depends on the coherence function (or interferogram) of the source. When using a coherent source the backscatter trace of a spatially resolved measurement exhibits strongly varying power over distance. These power variations are stable if the temporal delay between the scattering centres is not changed due to external impact (strain, temperature) or wavelength changes of the source. These interferometric power variations of a spatially resolved backscatter measurement can be minimized by spectral averaging (tuning the wavelength of the source during averaging multiple I-OFDR sweeps). Distributed scattering centres or single reflections therefore interfere with different phase relation to each other. Averaging a great number of measurements of different wavelength settings considerably reduces the interference impact.

The prerequisite for effective averaging is that a number of different interference states (equally distributed from destructive to constructive) between two locations in the fibre at z_1 and z_2 occurs at least once $(\pm \pi \text{ or } \pm \lambda/2)$. The most efficient averaging effect and correct backscatter power detection can be achieved when the wavelength tuning envelope $\Delta\lambda$ equals exactly (or multiples of) the optical path difference corresponding to an integer multiple of the wavelength λ between two interfering scattering centres. There is no obvious parameter $\Delta\lambda$ for a singlemode laser but when observing the interferogram of the FP source, it is clear that the optical path difference ΔL for that wavelength tuning envelope $\Delta\lambda$ should ideally correspond to the periodicity of the interference maxima of the interferogram dz, Figure 2.32 (left). This periodicity of $dz \approx 2.95$ mm in reflection in SMF originates from the FP cavity length and is directly linked to the wavelength separation $\Delta\lambda \approx 0.198$ nm of the single lasing modes of the measured FP spectrum, Figure 2.32 (right).



Figure 2.32: Calculated interferogram with periodic power periodicity $dz \approx 2.95$ mm (left) and measured spectrum of the FP laser with wavelength separation $\Delta\lambda \approx 0.198$ nm (right).

Scattering centres at multiples of the optical path difference dz result in the highest interferometric power fluctuations. Their optical phase relation can be most efficiently averaged when $\Delta\lambda$ corresponds to $dz \approx 2.95$ mm (better: integer multiples of $\Delta\lambda$). The efficiency improvement of this averaging, optimized for the periodic interferogram maxima, is highest for low integer multiples of dz and decreases with increasing relative distance (number of maxima). Higher order maxima (multiples of dz = 2.95 mm) experience already multiple phase relations from destructive to constructive. Using this exact wavelength tuning envelope $\Delta\lambda$ would therefore have the most pronounced impact for multimode lasers with low coherence of the single lasing modes and only few interference maxima contribute to the interferometric power fluctuations. Pulse domain techniques with a pulse length of only a few multiples of dz would more significantly benefit from this proposed optimization.

In order to calculate the necessary wavelength tuning range $\Delta \lambda$ of the light source, the interference averaging distance dz is here defined as a multiple k ($k \in \mathbb{N}$) of the emission wavelength of the source λ_0 in the fibre:

$$dz = k \cdot \frac{\lambda_0}{n_{\rm gr}} \tag{2.83}$$

The absolute phase difference of the interferometer within dz has to be at least a full wavelength λ_0 during the tuning. For the round trip in reflection that corresponds to $\lambda_0/2$. This required wavelength difference $\lambda_0/2$ has to be exactly the number (k) of full wavelengths within dz multiplied by the effective wavelength tuning range of the source $\Delta\lambda$:

$$k \cdot \Delta \lambda = \frac{\lambda_0}{2} \tag{2.84}$$

The necessary wavelength tuning range for all states of interference within dz in reflection can therefore be calculated from equation (2.83) and equation (2.84) using

$$\Delta \lambda = \frac{\lambda_0^2}{2 \cdot n_{\rm gr} \cdot dz} \tag{2.85}$$

With $\lambda_0 = 1309 \text{ nm}$ and dz = 2.95 mm, the wavelength tuning range is calculated to be $\Delta \lambda \approx 0.198 \text{ nm}$. This value corresponds exactly to the measured spectral separation of the single FP lasing modes and could also be obtained from a spectral measurement using an OSA, see Figure 2.32. In order to obtain optimal averaging and minimize interference fluctuations, the source wavelength has to be tuned by $\Delta \lambda = 0.198 \text{ nm}$ or integer multiples of $\Delta \lambda$. The following calculations are therefore based on a wavelength tuning range of $\Delta \lambda = 0.198 \text{ nm}$.

Wavelength tuning can be achieved by tuning the laser diode current or by tuning the temperature of the laser. The wavelength change of a single lasing mode of the FP spectrum has therefore been measured with the OSA as a function of the FP diode temperature (thermistor resistance settings R_{th}) and as a function of the laser diode current. Figure 2.33 shows the measured resistance-wavelength dependencies and the laser current-wavelength dependencies with a linear fit.



Figure 2.33: Wavelength dependency on thermistor resistance R_{th} (FP temperature corresponding to $\Delta T \approx 2.6$ K between 10 k Ω and 11.2 k Ω) (left) and wavelength dependency on the laser current (right).

The temperature-wavelength dependency shows linear behaviour¹ with a slope of 0.084 nm/K (14.7 GHz/K) and the laser current-wavelength dependency exhibits a linear slope of about 1.3·10⁻³ nm/mA or 2.3 GHz/mA (about 4.1·10⁻³ nm/mW or 7.2 GHz/mW). Tuning of the laser temperature is clearly advantageous since a relatively large tuning range $\Delta\lambda$ can be induced by relatively small temperature changes and the absolute output power of the laser remains relatively constant. The wavelength dependency on the thermistor resistance settings is assumed linear for limited temperature ranges with about -1.8 $\cdot 10^{-4}$ nm/ Ω (linear fit from Figure 2.33). The temperature controller has a voltage-controlled temperature control input with a transmission coefficient of $R_{th}/\Delta U = 2 \ k\Omega/V$. The equivalent temperature tuning range for the calculated wavelength tuning range $\Delta\lambda \approx 0.198$ nm is $\Delta T \approx 2.37$ K and the resistance tuning range is $\Delta R_{th} \approx 1100 \Omega$ which corresponds to a required optimal voltage tuning range of $\Delta U_{opt} \approx 0.55$ V. The temperature tuning is achieved by modulating the temperature control input of the temperature controller with a signal generator². The voltage tuning has been conducted during averaging multiple I-OFDR measurements using a continuous triangle modulation with a peak-to-peak voltage ΔU . This results in averaging of multiple measurement results of different interferometric phase relations. The peak-to-peak modulation voltage can be set in steps of 0.1 V. In order to measure the highest interference suppression, the Rayleigh backscattering fluctuation has been measured along a 1925 m long SMF for different laser operating point settings: 'coherent' setting, 'incoherent' setting and wavelength tuning around the 'incoherent' settings for different ΔU from 0.1 V to 0.9 V in steps of 0.1 V. Temperature tuning with a higher envelope would drive the laser into a more coherent operating point. Figure 2.34 (left) shows the backscatter plots for the three cases: 'coherent' setting; 'incoherent' setting and wavelength tuning with $\Delta U = 0.5$ V. All backscatter traces have been obtained after 3 minutes of

¹ Temperature dependency of the resistor calculated from FP laser data (thermistor nominal resistance $R_0 = 10 \text{ k}\Omega$ at laser diode nominal

temperature $T_0 = 25^{\circ}$ C and energy constant of $B_{val} = 3900 \pm 100$ K): $T(R_{th}) = B_{val} \cdot T_0 / (T_0 \cdot \log(R_{th}/R_0) + B_{val})$

² Digital function generator PCGU1000 by Velleman[®].

averaging. The differences in backscatter fluctuations are therefore not due to additional noise power but originate from coherent interaction of the distributed Rayleigh backscattering itself. The efficiency of the interference compensation has been determined by calculating the standard deviation of the Rayleigh backscattering fluctuation σ_{RBS} along the fibre for the different laser operating point settings and different modulation voltages $\Delta U ~(\propto \Delta \lambda)$. Figure 2.34 (right) shows the calculated standard deviation values of the Rayleigh backscattering fluctuations σ_{RBS} as a function of ΔU .



Figure 2.34: Measured Rayleigh backscattering fluctuation in a 1925 m long SMF for coherent, incoherent and wavelengthaveraged ($\Delta U = 0.5 V$) laser settings, $t_{meas} = 3 \min$, $\Delta f = 37.5 \text{ kHz}$, $f_{m,max} = 100.31 \text{ MHz}$ (left) and standard deviation of Rayleigh backscattering fluctuations σ_{RBS} for different triangle-modulated wavelength tuning voltages ΔU (right).

The standard deviation of the backscattering fluctuations for the FP laser in coherent settings (290 mA, $R_{th} = 10 \text{ k}\Omega$) is with $\sigma_{RBS(coh)} \approx 0.811$ dB considerably higher than for the FP laser in incoherent settings $\sigma_{RBS(incoh)} \approx 0.188$ dB (280 mA, $R_{th} = 10.86 \text{ k}\Omega$). Figure 2.34 (right) shows that the interference-averaged results exhibit further reduced values of σ_{RBS} with a local minimum around $\Delta U \approx 0.5...0.6 \text{ V}$. This behaviour was expected from the calculation of the optimal wavelength tuning envelope using equation (2.85) or the measured mode separation using the OSA results, corresponding to $\Delta U_{opt} \approx 0.55 \text{ V}$. The wavelength tuning optimization calculated from the spectral characteristics of a multimode laser source (or measured/calculated interferogram) can therefore be considered to be a relevant parameter. This optimization would be even more pronounced for lower coherent multimode sources with fewer interference maxima dominating the power fluctuations. All further backscatter measurements in this thesis are conducted with the FP source for 'incoherent' settings and interference averaging using the optimized wavelength tuning range corresponding to $\Delta U = 0.5 \text{ V}$.

Determining backscatter fluctuations of a relatively low-scattering silica fibre with evenly distributed scattering centres is a suitable way to quantify the backscatter interference fluctuations and optimize the tuning modulation. Another important topic of this thesis is the precise backscatter measurement in MM perfluorinated (PF) POF for sensing applications by evaluating backscatter changes and position shifts of the strong scattering centres in this fibre type. This fibre type and sensing applications are introduced in more detail in section 3.1 and chapter 4. This PF POF type exhibits a much greater irregularity of relatively strong scattering centres along the fibre but the interference effect is expected to have a reduced impact on the backscatter trace due to the multimode propagation and the associated averaging owing from the differential mode delays. However, it is shown here that it is crucial also for the sensing principles in POF (proposed in chapter 4) to use the optimized spectral averaging technique. The following measurements exemplarily show the impact of the interference on the backscatter measurement result of such a MM PF POF and the improvement using the interference compensation technique. Figure 2.35 shows two measurement traces respectively for the FP laser in 'coherent' setting (left), the FP laser in 'incoherent' setting (centre) and the FP laser in 'incoherent' setting and spectral averaging applied with $\Delta U = 0.5 \text{ V}$ (right). Each measurement is obtained after 1 minute of averaging.



Figure 2.35: Two I-OFDR measurements of a POF section respectively with the FP laser operating point for 'coherent' settings (left); 'incoherent' setting (centre) and 'incoherent' setting with spectral averaging (right); $t_{meas} = 1 \text{ min}$, $\Delta f = 700 \text{ kHz}$, $f_{m.max} = 400 \text{ MHz}$, $\alpha_K = 2$.

These results qualitatively visualize the reduced interference impact in MM fibres. The signal-degrading interference is considerably reduced when the laser is operated in a setting with short coherence length and additional spectral averaging is conducted.

In summary: Interference between closely spaced scattering centres is a relevant issue in I-OFDR as well as high spatial resolution OTDR. This effect can be efficiently compensated for static measurements by averaging measurements for different wavelength settings. The most efficient wavelength tuning range $\Delta\lambda$ (tuning voltage ΔU) of a multimode (FP) laser can be derived from a spectral measurement of the source or a measured interferogram. Integer multiples of the wavelength separation $\Delta\lambda$ between the single lasing modes exhibit the highest interference compensation effect.

2.5.4 Choice of source and conclusion

Concluding the spectral characterization of the laser sources in terms of coherence, interference and noise, the multimode FP laser exhibits favourable characteristics compared to a singlemode laser source. The broad spectrum of the single FP laser modes results in reduced coherence length of the single lasing modes. Additionally, the distribution of the output power to a great number of single lasing modes leads to reduced interference for most path length differences, see Figure 2.32 (left). It is demonstrated in section 2.5.3 that the interference impact can further be reduced by additional effective averaging due to wavelength tuning of the emission spectrum during a static measurement. The optimum wavelength tuning value can be easily obtained from the source spectrum. Operating the I-OFDR in these conditions ensures high signal stability which is essential for the precise backscatter measurement and sensing applications. It is further shown in section 2.5.2 that the multimode emission also has advantages over singlemode emission regarding the SNR. The signal power distribution between numerous modes of the FP laser leads to an improvement of the signal-to-noise ratio of $\Delta SNR = 14.8$ dB compared to singlemode emission.

Strictly considering the spectral properties of a source for use in I-OFDR, a *broadband SLD* would be the component of choice. However, the practical implementation into the system as well as lifetime and stability concerns led to abandoning this approach. Direct modulation of the source as opposed to using an external EOM would be necessary to obtain acceptable SNR levels. This proved to be instable and difficult to implement over the required wide frequency range. Direct modulation of the SLD with very high currents is also considered to be a lifetime concern as compared to CW operation of a laser module.

A singlemode DFB laser has also been considered but had to be excluded, mainly for coherence reasons. The relatively narrow bandwidth resulted in strong interference and intolerable signal instability of the backscatter traces. Theoretically, a broader linewidth singlemode laser would be suitable for use in an I-OFDR system. Also, the SNR improvement effect due to multimode emission as well as the interference averaging effect of a multimode laser clearly puts an FP laser in advantage.

The multimode *Fabry-Pérot laser* delivers high output power and can easily be modulated using a standard EOM, which allows basically unlimited signal generation bandwidth far into the GHz range.

Operation of this laser over several years did not lead to measurable ageing effects or changes of the optical spectrum. The incoherent laser operation settings did not change and could easily be recalibrated by measuring for example the delayed self-homodyne source spectrum. The investigated FP laser diode is therefore considered as the optimal choice for the proposed I-OFDR technique and is used as the optical source for all experiments presented in this thesis.

2.6 Active reflection suppression

It has been shown in section 2.4.2 (Figure 2.16 (right)) that the dynamic range of the I-OFDR setup introduced in section 2.3 is fundamentally limited to about 40 dB. Small scattering events cannot be resolved at the presence of strong reflections. Some OTDRs solve the problem of receiver saturation and dead zones by electronically gating the photo detector signal for the time frame of the optical signal arriving from the reflection in the fibre. An equivalent of a temporal gating technique is not possible in the frequency domain and strong reflection signals will always limit the dynamic range of the I-OFDR result. In the following, it is suggested to reduce this fundamental drawback of the frequency domain approach compared to the time domain detection by proposing an active reflection suppression technique. This approach involves the generation of another harmonic signal for each measurement frequency f_m with exactly the same amplitude but phase-shifted by exactly π relative to the dynamic range-limiting reflection signal. The two signals will cancel each other when being superimposed. It has to be assumed that the system acts as a linear and time-invariant system. The impact of interference (section 2.5) and other nonlinearities of the measurement system such as transfer function stability (Figure 2.9, section 2.3.1) are considered to be negligible.

In order to implement this technique, a setup with two signal generators is required. The signal generators have to be able to generate sinusoidal signals with the same frequency but different amplitude and phase for each measurement frequency f_m . Figure 2.36 shows the possible implementation for the electrical addition of a suppression signal in order to cancel a disturbing signal. Figure 2.37 shows an example of an optical implementation of the suppression technique.



Figure 2.36: Electrical implementation of the suppression technique.



Figure 2.37: Optical implementation of the suppression technique.

The technique is in the following explained for the optical implementation as shown in Figure 2.37. The signal descriptions of the electrical implementation can be considered analogous. During frequency sweeping of the I-OFDR system, the harmonic voltage modulation signals

$$u_m(f_m, t) = A \cdot \cos\left(2\pi \cdot f_m \cdot t\right) \tag{2.86}$$

are generated for all modulation frequencies $\omega = 2\pi \cdot f_m$ with an amplitude A. The optical carrier signal $I_0(t)$ is proportionally modulated in amplitude using an external EOM and coupled into the FUT. The amplitude modulated optical power signal $x_m(f_m, t)$ can be described as

$$x_m(f_m, t) = I_0(t) \cdot [1 + u_m(f_m, t)]$$
(2.87)

Since bandlimited detection around the modulation frequency f_m is conducted and the modulation voltage and optical powers are proportional, the detected and filtered baseband voltage signals are also proportional to the input modulation $x_m(f_m, t) \propto u_m(f_m, t)$.

It is assumed that a single strong reflection at the position z in the fibre limits the sensitivity of the backscatter trace by exceeding the dynamic range of the system so that weak distributed Rayleigh scattering of the fibre cannot be detected as shown in Figure 2.16 (right). The signals received at the input port $u'(f_m, t)$ are linear superpositions of the weak backscatter signal $u_r(f_m, t)$ and the strong disturbing signals $u_d(f_m, t, \tau_d)$ originating from the reflection:

$$u'(f_m, t) = u_r(f_m, t) + u_d(f_m, t, \tau_d)$$
(2.88)

The delay τ_d is the value that the signal $u_m(f_m, t)$ experiences when propagating along the electrical and optical signal paths to and from the reflection at the distance z in the fibre before its detection as $u_d(f_m, t, \tau_d)$. τ_d can be precisely determined from the reflection peak delay of a non-calibrated measurement of the FUT h'(t):

$$h'(t) = \mathcal{F}^{-1}\{H'(j\omega)\}$$
(2.89)

Also the reflection power P_d of the disturbing signal only is derived from the reflection peak height of the time domain plot h'(t) as described in section 2.3.2. The value P_d is later used to calculate the necessary amplitude of the generated suppression signal.

The disturbing signal $u_d(f_m, t, \tau_d)$ from the reflection only, that is detected at the input port for all modulation frequencies is described by

$$u_d(f_m, t, \tau_d) \propto P_d \cdot \cos\left(2\pi \cdot f_m \cdot (t + \tau_d)\right) \tag{2.90}$$

with the amplitude ($\propto P_d$) and the phase ($\propto \tau_d$) depending on the reflection power and distance. The frequency responses of both signal paths (measurement path and suppression path) will have to be calibrated against another to obtain optimal suppression of $u_d(f_m, t, \tau_d)$. The signal conversion parameters (e.g. modulation voltage to optical power modulation and back to voltage) are comprised in the calibration transfer functions. These calibration terms will be inserted and introduced later in this section when defining the suppression signal. In order to completely suppress the disturbing signal $u_d(f_m, t, \tau_d)$, another suppression signal $u_s(f_m, t)$ has to be generated and superimposed with the measurement signal $u'(f_m, t)$ for each modulation frequency f_m . In case of the optical implementation of the suppression technique (Figure 2.37), this signal is modulated onto the optical carrier signal $I_0(t)$

$$x_{s}(f_{m},t) = I_{0}(t) \cdot [1 + u_{s}(f_{m},t)]$$
(2.91)

The phase and the amplitude of the necessary signal $u_s(f_m, t)$ are in the following determined. The suppression signal, as detected at the PD ($\propto u_s(f_m, t)$), is required to have the same frequency f_m and identical amplitude as $u_d(f_m, t, \tau_d)$, but a phase difference of exactly π at the signal detection side (after detection: $u_s = -u_d$). This necessary time difference $\Delta \tau_{\pi}$ (corresponding to a phase difference of π) between the detected suppression signal $u_s(f_m, t)$ and the detected disturbing signal $u_d(f_m, t, \tau_d)$ is also a function of the modulation frequency f_m (half the period):
$$\Delta \tau_{\pi} = \frac{1}{2 \cdot f_m} \tag{2.92}$$

In order to compensate for path length differences of the two signal arms, also the delay of the suppression signal path τ_s has to be determined. This can be done by conducting a calibration measurement $H_s(j\omega)$ of the suppression signal path only by generating $u_{s cal}(f_m, t)$.

$$u_{s \ cal}(f_m, t) = A_s \cdot \cos(2\pi \cdot f_m \cdot t) \tag{2.93}$$

 $u_{s_cal}(f_m, t)$ is multiplied with the optical carrier $I_0(t)$ using the second EOM. A_s is the suppression path modulation amplitude. The suppression signal path delay τ_s of the transmitted calibration signal can be obtained from the calculated time domain trace $h_s(t)$ of the measured suppression signal calibration transfer function $H_s(j\omega)$:

$$h_{s}(t) = \mathcal{F}^{-1}\{H_{s}(j\omega)\}$$
(2.94)

The necessary time difference $\tau_{diff}(f_m)$ of the generated suppression signals $u_s(f_m, t)$ relative to the generated measurement path signals $u_m(f_m, t)$ can then be calculated using

$$\tau_{diff}(f_m) = \tau_d - \tau_s + \frac{1}{2 \cdot f_m}$$
(2.95)

One might describe the suppression signal $u_s(f_m, t, \tau_{diff})$ simply as a function of absolute phases and phase differences derived from the suppression calibration measurement transfer function $H_s(j\omega)$ and $u_d(f_m, t, \tau_d)$ but the knowledge of the absolute signal delays τ_d and τ_s enables active compensation of possible delay changes (for example due to temperature changes or strain in the FUT). Tracking the changes of the detected signal during the measurement¹ allows determining delay drifts and real-time compensation by adapting $\tau_{diff}(f_m)$.

Suppression signal calibration

In order to optimally suppress the disturbing signal, not only the delay differences of the two signal paths have to be determined. Also the transfer functions of the signal paths and their deviations in phase and amplitude have to be calibrated for each modulation frequency f_m .

The transfer function of the suppression path $H_s(j\omega)$ and the suppression path delay τ_s are known. Also the transfer function of the measurement path has to be measured to define the ideal predistorted suppression signal. The measurement path calibration transfer function $H_{cal}(j\omega)$ can be determined as described in section 2.3.1. The time delay τ_{cal} of the calibration measurement and the detected calibration power P_{cal} is obtained from the position and peak height of the time domain response $h_{cal}(t)$

$$h_{cal}(t) = \mathcal{F}^{-1}\{H_{cal}(j\omega)\}$$
(2.96)

The suppression signals that have to be generated to be added to (or coupled with) the signal from the fibre $u'(f_m, t)$ for all modulation frequencies, have to be pre-distorted in phase and amplitude to compensate for the different transfer functions of the two signal paths before detection. This predistorted transfer function, or complex correction term $a(f_m)$, is

$$a(f_m) = \frac{P_d}{P_{cal}} \cdot \frac{H_{cal}(j\omega)}{H_s(j\omega)} \cdot e^{j\omega(\tau_s - \tau_{cal})}$$
(2.97)

The complex correction term $a(f_m)$ incorporates the transfer functions of the measurement signal path $H_{cal}(j\omega)$ and the suppression signal path $H_s(j\omega)$. The respective detected power differences of the calibration measurement a_{cal} and the disturbing signal P_d have to be compensated in order to

¹ A technique to calculate changes of the reflectivity and distance of reflections in the fibre from partial results of a frequency sweep is introduced in chapter 5. This technique can easily be implemented to compensate phase and amplitude of u_s for changes of τ_{diff} during the measurement.

arrive at an suppression signal amplitude equivalent to $u_d(f_m, t, \tau_d)$. Also the time delay offset owing from the delay differences of the suppression signal path and the calibration signal path ($\tau_s - \tau_{cal}$) has to be inserted. $a(f_m)$ accounts for the combined amplitude and phase deviations of the two transfer functions with zero time delay of its impulse response.

The suppression signal $u_s(f_m, t, \tau_{diff})$, that has to be generated in order to have equal amplitudes and phase differences of π compared to $u_d(f_m, t, \tau_d)$ for each modulation frequency, as defined by the delay difference τ_{diff} and the complex correction term $a(f_m)$, is described as

$$u_s(f_m, t, \tau_{diff}) = |a(f_m)| \cdot A_s \cdot \cos[2\pi \cdot f_m \cdot (t + \tau_{diff}(f_m)) + \operatorname{angle}(a(f_m))]$$
(2.98)

 $angle(a(f_m))$ denotes the angle (in radian) of the complex correction term. The resulting signal at the detection side is therefore

$$u_{tot}(f_m, t, \tau_s) = u_r(f_m, t) + u_d(f_m, t, \tau_d) + u_s(f_m, t, \tau_{diff})$$
(2.99)

and reduces to

$$u_{tot}(f_m, t, \tau_s) \approx u_r(f_m, t) \tag{2.100}$$

since $u_d(f_m, t, \tau_d) + u_s(f_m, t, \tau_{diff}) \approx 0$.

The algorithm has been explained as understandable as possible but its complexity can be reduced by using only the transfer functions of the signal paths. The suppression signal time delay τ_s does not have to be computed and the complex correction term $a(f_m)$ reduces to

$$a(f_m) = \frac{P_d}{P_{cal}} \cdot \frac{H_{cal}(j\omega)}{H_s(j\omega)}$$
(2.101)

The suppression signal can then be described as

$$u_{s}(f_{m}, t, \tau_{d}) =$$

$$|a(f_{m})| \cdot A_{s} \cdot \cos\left[2\pi \cdot f_{m} \cdot \left(t + \tau_{d} - \tau_{cal} + \frac{1}{2 \cdot f_{m}}\right) + \operatorname{angle}(a(f_{m}))\right]$$

$$(2.102)$$

The suppression signals are either superimposed in the electrical domain after detection by the photodiode as shown in Figure 2.36 or, as described above, in the optical domain shown in Figure 2.37. The impact of interference is minimized by choosing a source with low coherence length. However, care has to be taken when mixing the suppression signal with the backscattered signal $u'(f_m, t)$. A path imbalance between the optical backscatter path $\tau_{d(opt)}$ and the optical suppression path $\tau_{s(opt)}$ exceeding the coherence time τ_{coh} of the source before combining the signals at the optical coupler should be ensured:

$$\left|\tau_{d(opt)} - \tau_{s(opt)}\right| \gg \tau_{coh} \tag{2.103}$$

The active suppression technique has been described for the suppression of a single disturbing reflection only but can be theoretically used to simultaneously suppress multiple reflections in the FUT. For *n* reflections in the FUT with $r \in \{1, ..., n\}$ at the positions z_r , the suppression signal is a superposition of *n* harmonic suppression signals of different phases $(\tau_{diff,r} \propto \tau_{d,r} \propto z_r)$ and amplitudes $|a_r(f_m)| \cdot A_s$ depending on the delay $\tau_{d,r}$ and detected powers $P_{d,r}$:

$$u_s(f_m, t, \tau_{d,r}) = \sum_{r=1}^n |a_r(f_m)| \cdot A_s$$

$$+ \cos\left[2\pi \cdot f_m \cdot \left(t + \tau_{d,r} - \tau_{cal} + \frac{1}{2 \cdot f_m}\right) + \operatorname{angle}(a_r(f_m))\right]$$
(2.104)

By implementing the active suppression technique, the dynamic range of the I-OFDR can be theoretically increased. Simulation results with different transfer functions of the signal paths (including phase and amplitude noise) confirmed the validity of the proposed reflection suppression technique.

2.7 Technology comparison - advantages and limitations

The I-OFDR technique has been introduced and analyzed from the system point of view in this chapter. The two most important issues that have to be considered are system linearity and the avoidance of interference by choosing a source with an appropriate spectrum. Active compensation of interference effects is introduced by spectral averaging to minimize the nonlinear interference impact on the backscatter signal. Phase-to-intensity noise may also be a limitation under certain circumstances. The I-OFDR is compared in the following with two other important backscatter measurement techniques, swept wavelength interferometry (SWI) and OTDR. The comparison is made regarding systematic limitations, applicability for general backscatter measurement as well as backscatter sensing applications.

2.7.1 Comparison to SWI (coherent OFDR)

The swept wavelength interferometry or coherent OFDR was introduced in section 1.3. Due to the coherent detection mechanism, this technique is unrivalled regarding *sensitivity and spatial resolution* for short to medium fibre lengths. The dynamic range is given with 60 - 70 dB and a sensitivity of up to - 130 dB [35] (the manufacturer seems to use similar definition for dynamic range and sensitivity as defined for the I-OFDR in section 2.4.2). The definition for sensitivity and dynamic range is not given by the manufacturer but comparison measurement indicated that these definitions are comparable with those introduced in section 2.4.2. The SWI has also an advantage compared to OTDR and I-OFDR in terms of measurement time. A backscatter trace with a high SNR can be obtained after several seconds. Precise and high-resolution strain and temperature measurement can be conducted over a limited fibre length [35].

The distance range of the only commercial device [35] can be extended to 2 km at reduced spatial resolution. The linear frequency tuning range of the laser is the major limiting factor for spatial resolution and distance range. Longer distance ranges result in lower spatial resolution. The theoretical distance range of the I-OFDR however, is only limited by the lowest possible modulation frequency step Δf . The current laboratory setup covers about 10.2 km in SMF ($\Delta f = f_{m,min} = 10$ kHz using equation (2.9)) but can be extended without reducing the spatial resolution by using lower bandwidth components.

As the SWI is also a frequency domain measurement technique, the linearity of the system is crucial. Huge effort is made to maintain linearity of the system by calibrating source wavelength, linearity of the wavelength sweep and using polarization diversity detection. Nonlinearities during the frequency sweep caused for example by movement of the fibre might lead to distortions of the time domain trace after conducting the FFT. Measuring dynamic systems with SWI (for example measuring vibrations) may cause more complications than step-wise measurement of the frequency response.

The most significant constraint of the SWI technique is that correct results can only be obtained when single mode propagation is ensured. *Multimode propagation* leads to corrupted signals (changes of backscattered power) when the modal excitation is changed during a measurement or between two measurements, for example when strain sensing is attempted. The backscatter signature is not reproducible and exhibits differences in backscattered power and position. The system accuracy is degraded and strain measurement evaluation fails. SWI would be the technology of choice if very high-resolution measurement in SMF in the mm-range or below is required and the high instrument costs or limited fibre lengths are not an issue. For cm-resolution and general backscatter measurements in SMF, I-OFDR or OTDR would be an option. For correct measurement of MM fibres, especially when mode coupling occurs, incoherent backscatter techniques such as OTDR and I-OFDR are more suitable.

2.7.2 Comparison to optical time domain reflectometry (OTDR)

OTDR is the most widely used technique for fibre inspection and fibre characterization and has also been used for the majority of the proposed distributed backscatter and loss-based sensor applications. Since it is the time domain equivalent of the investigated I-OFDR and the alternative for similar measurement applications, it is compared and analyzed in greater detail in this section. The I-OFDR targets both, general backscatter measurement of long fibres as well as precise and high-resolution measurement for distributed sensing applications. Its performance and limitations are therefore discussed with respect to the common direct detection OTDRs as well as high-resolution photon counting OTDRs¹ (introduced in section 1.2.3).

The most significant limitation of the I-OFDR approach is the *fundamental limit of the dynamic range*. A strong reflection in the fibre would always be the dominant signal in the frequency response and therefore limit the dynamic range of the measurement system. At the presence of a very strong reflection, the Rayleigh level and therefore optical loss might not be resolved. Also the SWI technique has the same limitation when strong reflections are present in the fibre. Due to the difference in the detection principle, this is less of a problem in pulse domain reflectometry. Most direct detection OTDRs are driven into receiver saturation when a strong impulse is detected and obtain full sensitivity after a certain dead zone. This nonlinear behaviour, however, disqualifies this technique if precise backscatter sensing is intended on, or directly after strongly reflecting events. Many OTDR devices, such as the photon counting OTDR used in this thesis, can be electronically gated to shift the measurement window away from the strong reflection and therefore maintain dynamic range. In I-OFDR, possible saturation due to strong reflection signals from the FUT is automatically prevented by the VNA since the power of the incoming signal from the photodetector is automatically attenuated to maintain linearity (detector linearity with changing power levels is assumed ($I < 240 \,\mu$ W)). The dynamic range of the specific I-OFDR setup has been determined to be about 40 dB (and 52 dB using the digital evaluation board instead of the VNA) but may be extended using the active reflection suppression technique proposed in section 2.6.

Interference and coherent noise have been identified as another potentially systematic drawback of the I-OFDR approach. Due to the continuous measurement signal in the FUT (CW carrier and modulation component), interference can originate from the whole fibre from regions within the coherence length of the optical source. However, it has been shown that interference can be efficiently suppressed by choosing an appropriate light source and by implementing interference averaging by means of wavelength tuning (section 2.5.3). Using OTDR, interference can only occur within the length of the optical pulse propagating along the fibre. Only adjacent scatter centres could contribute to power fluctuations of the backscatter trace. Still, interference seems to be the main reason for the strong power fluctuations of backscatter traces in POF when comparing individual measurements. Figure 2.38 shows a comparison of two backscatter traces, each of the same PF POF, obtained by MM photon counting OTDR (left) and the interference-averaged I-OFDR setup (right) for equivalent spatial resolution settings ($\tau_p \approx 2$ ns (instrument setting) and $f_{m,max} = 400$ MHz) after 3 minutes of averaging.

¹ Two different photon counting devices by Sunrise Luciol have been used for measurement: SMF OTDR (v-OTDR λ = 1313 nm, FP source) and MM fibre (v-OTDR, FP source with $\lambda \approx$ 1311 nm, 50 µm core diameter)



Figure 2.38: Two backscatter measurements of the same fibre (3 minutes measurement time) obtained by photon counting OTDR (left) and I-OFDR (right) for equivalent spatial resolution settings; $t_{meas} = 3 \min$, $\tau_p \approx 2 \text{ ns and } \Delta f = 700 \text{ kHz}$, $f_{m,max} = 400 \text{ MHz}$, $\alpha_K = 2$.

The backscatter peak power and the position of the backscatter peaks exhibit higher deviation between single OTDR measurements whereas the I-OFDR traces exhibit very high *signal stability*. The backscattered power variations in the OTDR plot may be partly due to interference effects within the pulse width due to the coherence of the FP laser source in the OTDR. The exact reason for the backscatter instability is, however, unknown. The high signal stability in I-OFDR has exemplarily been quantified in a SMF setup in section 2.4.1. The I-OFDR promises greater prospects for precise distance and power measurement than OTDR techniques. The backscatter traces of the I-OFDR also show increased sensitivity compared to the photon counting OTDR traces.

The I-OFDR approach exhibits systematic advantages for high spatial resolution measurement. Especially for *direct detection OTDR*, spatial resolution and dynamic range are mutually conflicting requirements. High spatial resolution means very short pulses and therefore detection of very low powers with fast photodetectors. Weak backscatter signals are difficult to recover from the increased noise associated with the required wideband photodetector. The advantage of the I-OFDR is that more optical power is sent into the fibre which increases the available light for detection. Also, due to the narrow bandpass filtered detection of the received signal for each measured frequency, the signal noise can be considerably reduced. The availability and implementation of low-noise and wideband components allows for high sensitivity measurement at spatial resolutions typically exceeding those of direct detection OTDRs.

The more advanced *photon counting OTDR technique* allows for higher spatial resolution compared to direct detection OTDRs. Due to its statistical nature of the photon counting mechanism, dynamic range and sensitivity cannot be directly compared with other backscatter measurement techniques. The *measurement time* may be considerably higher if longer fibres are measured or strongly scattering events dominate the backscatter trace. Longer averaging is necessary to achieve similar dynamic range in that case. This is also the reason why the *distance range* of photon counting OTDRs is rather limited to short fibre lengths. Extending the distance range can be achieved by measuring and overlapping several traces for different gating settings [29]. Very high sensitivity can be achieved for weakly scattering FUT using this technique.

Another advantage of the frequency domain approach is presented in chapter 5: partial results of a full frequency response measurement can be used to obtain important information of the FUT. This allows for precise dynamic measurement on reflective events in the FUT.

The advantages (+) and limitations (-) of the I-OFDR in comparison with OTDR in general are simplified and in the following summarized in note form:

- + No dead zones
- + High linearity and stability of the backscatter signal \rightarrow advantage for sensing applications
- + Band-pass filtering of the received signal (SNR improvement, 'pulse shape' stability)
- + Advantages of hardware implementation for high-resolution measurement
- + High distance and power precision
- + Additional sensing possibilities \rightarrow dynamic measurement (Chapter 5)
- (-) Interference not limited to the pulse width (problem solved for static measurements)
- System absolutely limited by dynamic range (but possible extension proposed by active reflection compensation)
- High linearity requirements for all components over an extended detection power envelope
- Maximum distance range is limited by the lowest modulation frequency step size, here $z_{max}(\Delta f = 10 \text{ kHz}) \approx 10.2 \text{ km}$ in SMF

3 POF and mode propagation influences in multimode fibres

The majority of distributed fibre optic sensor systems use a SMF as the sensor medium. Reasons are the possibilities of coherent detection principles, the very low optical loss as well as the absence of modal dispersion (signal spreading in time due to different propagation velocities of propagation modes in MM fibres). The impact of modal dispersion in MM fibres is explained in more detail in section 3.2.2. The motivation for considering also MM fibres in this work is the intended use of the I-OFDR as a versatile instrument for precise optical backscatter measurement and for distributed sensing applications in both, singlemode and multimode fibre networks. The other reason is the targeted application for distributed length change and strain measurement using the mechanically advantageous properties and the strain-backscatter dependency effect in MM perfluorinated (PF) gradient-index (GI) POF. These sensor principles are introduced and demonstrated in chapter 4. Mode propagation in MM fibres is therefore investigated in order to identify possible sources of error and estimate its magnitude when conducting precise backscatter measurements with the focus on the PF POF sensor.

Multimode propagation and mode coupling mechanisms in POF differ from the well-studied silica fibres. After a brief introduction of PF POF, its development, general properties and fabrication are summarized. The mechanisms and impact of mode coupling in POF are explained. Following, measurement results on differential mode delay (DMD) and its dependency on launch conditions into the fibre are presented in comparison to standard silica MM fibres. This chapter aims on the understanding of light propagation and interaction in MM silica fibres and PF POF as a prerequisite for analysing its impact on the measurement principles introduced later for strain and length change measurement in chapter 4 and chapter 5.

3.1 Perfluorinated POF

It has been shown that the backscatter level of strained step-index (SI) PMMA POF strongly increases with increasing strain [3], [4], [5], [6], [7]. The motivations for investigating the relatively new PF POF (first commercial availability in 2005 [71]) as a possible sensor fibre are the favourable optical properties (low loss and GI structure) and its suspected backscatter dependency on strain. PF POF exhibits considerably lower attenuation than PMMA POF (150-200 dB/km at 650 nm [72]) and the gradient-index structure promises improved spatial resolution and sensing performance. The extension of the maximum measurement distance from about 100 m for the PMMA POF to several hundreds of meters for PF GI POF as well as the continuously high spatial resolution owing to their gradient-index structure were the most promising aspects for distributed backscatter sensing.

3.1.1 Chemical structure

Before the emergence of PF POF, PMMA-based fibres have been the standard for certain short distance data transmission applications. The attenuation of PMMA in the visible and near infrared region largely originates from the overtone vibration absorption of the C-H bonds in the polymer [73] which ultimately limits the distance of a PMMA POF link. Figure 3.1 (left) shows 8 C-H bonds that are present in each MMA monomer. Partial or complete substitution of the hydrogen compound by heavier atoms has considerably reduced the attenuation of optical polymers. Replacing hydrogen with heavy hydrogen reduces the attenuation but such deuterated POF are sensitive to water vapour absorption leading to an increase of attenuation [74]. The replacement of hydrogen atoms by heavy fluorine atoms results in the shift of the C-F absorption bands away from the telecommunication window (850 nm to 1550 nm). the various fluorinated polymers (for example polytetrafluoroethylene (PTFE), Among tetrafluoroethylene-perfluoroalkyl vinyl ether (PFA), etc.) the lowest absorption of an optical fibre has been obtained using the cyclic transparent optical polymer poly(perfluorobutinylvinylether). This polymer is produced by Asahi Glass Company (AGC) from Japan and is commercially known as CYTOP. Figure 3.1 (right) shows its molecular geometry.



Figure 3.1: Molecular geometry of PMMA (left) and the low-loss CYTOP material (right).

The first gradient-index fibre based on a CYTOP-based PF POF with an attenuation of 50 dB/km at 1300 nm wavelength has been produced at Keio University [75]. CYTOP has since then been the base material for further research and has been used for fibre fabrication [76],[77],[78]. The attenuation at 1000 nm wavelength has been reduced to about 10 dB/km [73] and the theoretical lower attenuation limit of amorphous fluoropolymers has been calculated to be about 0.3 dB/km at 1300 nm, a value that is comparable to silica fibres [75],[79]. Figure 3.2 shows the measured and theoretical attenuation spectra of a CYTOP-based GI POF.



Figure 3.2: Comparison of measured and theoretical attenuation spectra of CYTOP-based GI POF and GI PMMA POF, adapted by permission from Macmillan Publishers Ltd: NPG Asia Materials (vol.1, no. 1, pp. 22-28), copyright (2009) [73].

This theoretical attenuation limit, however, has not been reached. Current limitations can be attributed to the manufacturing process and material contamination for example by impurities, material crystallization and scattering centres [74]. The water absorption ratio by weight of pure CYTOP is stated with < 0.01 % [80] and is far below that of PMMA (up to 0.4 %). However, environmental investigations in chapter 4 show that the water content in the fibre has a significant influence on the optical attenuation around 1310 nm wavelength and cannot be neglected.

3.1.2 Fibre fabrication

The fibre fabrication is summarized in more detail since the fibre backscatter characteristics and light propagation characteristics strongly depend on the manufacturing process. This is important for the backscatter sensing applications presented in section 4.2. The development of CYTOP-based fibres has been aimed from the beginning at manufacturing GI fibres to ensure low modal dispersion and high bandwidth. The first PF GI POF has been fabricated by means of a drawing process from a polymer preform. This preform has been realized by an interfacial gel polymerization method of a doped monomer and an undoped monomer [81], [75]. A doped hollow-core preform is collapsed during the drawing process. This approach has limited potential for low-cost and high volume production but high-purity fibres with the lowest achieved attenuation have been produced this way. This fabrication process has later been employed by Asahi Glass Company (AGC) to produce PF GI POF¹ [82]. The CYTOP material has a glass transition temperature of 108 °C but the long-term stability of the index profile of this fibre type has been specified with 70 °C. Aging tests at 70 °C for 10000 hours and heat-humidity

¹ AGC commercialized this fibre under the trade name LUCINA[®].

cycles confirmed the stable bandwidth and attenuation of this commercial gradient-index fibre [83]. Although this preform-drawn fibre is not primary subject of investigation, several results obtained with this fibre type are presented in this work.

White et al. [78] later developed an efficient extrusion process that is now being used for highvolume production of gradient-index PF POF. The melt streams of the doped CYTOP (core extruder) and the undoped CYTOP (cladding extruder) are joined together at a crosshead to form a coaxial melt flow. The gradient-index profile is obtained by diffusion of the core dopand into the cladding stream in a heated diffusion tube following the extruders. An overcladding (or reinforcement) layer can afterwards be added by another extrusion process. The co-extrusion process leads to increased attenuation compared to the preform method due to additional impurities and defects in the fibre core. PF GI POFs are now commercially produced with this technique¹. This fibre type as well as a specifically designed sensor fibre version (additional protective jacketing materials) is used for most investigations and measurements throughout this thesis. Figure 3.3 shows that the preform method enables production of lower attenuation fibres due to minimized contamination and inhomogeneities compared to the coextrusion process (preform fibre: 11.4 dB/km at 1072 nm and 28.7 dB/km at 1310 nm; GigaPOF 50SR: 38.4 dB/km at 1072 nm and 46.4 dB/km). The co-extruded fibre in Figure 3.3 (right) shows the typically occurring backscatter peaks caused by contamination of µm-sized particles during the production process. Both fibre types have core diameters of 50 µm.





Recently, a new 'double cladding' layer technique has been proposed for POF manufacturing in order to reduce the bending loss by increasing the difference between the refractive indices of the core and the cladding [84], [73]. This technique has lately been commercialized by AGC under the trade name FONTEX [85] and replaces the discontinued LUCINA fibre.

3.2 Light propagation in multimode fibres

In optical communication systems, dispersion is generally the limiting factor concerning the maximum bandwidth of optical fibre links. The widening of a pulse travelling along a fibre also has an impact on the performance of distributed optical fibre sensors. This effect leads, respectively, to a degradation of the spatial resolution and distance accuracy with increasing fibre length. The associated change of the fibre's transfer function due to DMD has to be considered when applying the dynamic measurement technique proposed in chapter 5 as well as the reflection suppression technique introduced in section 2.6. The most significant and relevant sources of dispersion are chromatic dispersion and modal dispersion. The impact of both effects is considered in this section.

¹ GigaPOF 50SR fibres by Chromis Fiberoptics, Inc. are used for measurements in this thesis.

3.2.1 Chromatic dispersion

The material dispersion of bulk CYTOP material has been measured to be around -54 ps/(nm·km) at 845 nm wavelength and -9 ps/(nm·km) at 1300 nm wavelength [86] and is lower than that of silica at shorter wavelengths. Figure 3.4 shows the wavelength dependency of the material dispersion for CYTOP, silica and PMMA calculated from their wavelength dependency of the refractive indices [87].



Figure 3.4: Comparison of material dispersion as a function of wavelength of CYTOP, silica and PMMA; from [88].

The total chromatic dispersion (material dispersion + waveguide dispersion) of GI PF POF has recently been measured with a value of -88 ps/(nm·km) at 845 nm [89] and is expected to be even lower at the relevant wavelength around 1310 nm. The fibre type¹ used for the experiments in this thesis is specified with a dispersion slope < 0.06 ps/(nm²·km) and the zero dispersion wavelength is stated for a wide wavelength range between 1200 nm and 1650 nm. Exact information on the zero dispersion wavelength and chromatic dispersion could not be obtained from the manufacturer. Also other measurements of the chromatic dispersion in this wavelength range have not been reported in literature. Since the sensing applications proposed in this work aim for a maximum fibre length of a few hundreds of meters only, the chromatic dispersion is assumed to have negligible influence on the measurement results and is therefore not further considered.

3.2.2 Modal dispersion and mode coupling

As opposed to signal propagation in SMF, where solely the fundamental mode carries the information, the signal in MM fibres might populate thousands of optical modes. The bandwidth of MM silica fibres as well as MM POF is therefore mainly limited by the modal dispersion originating from different group velocities v_{gr} of the propagating optical modes. This effect is called differential mode delay (DMD). Even though optimized parabolic gradient-index profiles are used to minimize the delay changes between excited higher order modes and lower order modes, the DMD between these components can be the bandwidth-limiting factor of an optical fibre link.

The mode coupling mechanisms in GI silica fibre and GI POF are different. GI silica fibres exhibit very little intergroup coupling (power exchange between different mode groups) due to their high purity and the high length scale of the refractive index perturbation induced during the drawing process [90]. The stable power propagation within each excited mode leads to a linear increase of pulse broadening with increasing fibre length. Extrinsic mechanical influences such as fibre bends can therefore severely alter the bandwidth and DMD of the fibre link by inducing intergroup coupling into higher order modes or decoupling of higher order mode groups. The launch condition of the source into the fibre (overfilled or underfilled, central coupling or off-centre coupling) as well as mechanical impact on the fibre determine the transfer function (and therefore the bandwidth) of the fibre.

Mode coupling in POF (all types: SI, GI, PMMA POF, PF POF) is generally much stronger than in silica MM fibres. It has therefore a crucial impact on the bandwidth of a POF link which has been measured

¹ GigaPOF[®]-50SR datasheet available at: http://www.chromisfiber.com/pdf/GigaPOF50SR.pdf.

to be higher than it could be expected in theory without considering the impact of coupling between different mode groups. The reasons for the increase of bandwidth have been analyzed and measured for various POF types. Mode coupling has been determined to be the decisive factor for strongly coupling POF types: [91], [92], [93] (SI and GI PMMA POF) and PF GI POF [94], [95], [89]. It has also been shown that differential mode attenuation can be the determining factor for low-coupling PMMA-based GI POF [96]. Strong mode coupling in PMMA-based GI POF has been identified as the reason to increase the bandwidth exceeding the theoretical values by far (3 GHz opposed to 0.43 GHz for 100 m GI PMMA POF [91]). The reason is the strong coupling of energy between guided mode groups on a small length scale. Random redistribution of energy between slower and faster mode groups along the fibre results in reduced delay differences compared to a fibre without mode coupling. Instead of a linear dependency of the pulse broadening (η) on the fibre length (L) given as

$$\eta \propto L^{\beta} \tag{3.1}$$

with $\beta = 1$ for no mode coupling present, the pulse broadening reduces to an almost square root dependency on *L* ($\beta = 0.5$) as expected from the diffusive theory of mode coupling [97]. The pulse broadening is defined by the relation

$$\eta = \sqrt{\tau_2^2 - \tau_1^2} \tag{3.2}$$

where τ_1 and τ_2 are the full widths at half maximum (FWHM) of the input and output pulses, respectively [91]. The coupling length of a fibre L_c is either defined as the fibre length at which the pulse broadening-length dependency changes from $\beta = 1$ to $\beta = 0.5$ [91] or as the length at which the relative energy population of each guided mode does no longer change with propagation length [92]. The bandwidths in presence and absence of mode coupling (B_{wc} and B_{w0}) can be described by

$$\left| \frac{L}{L_c} = \frac{B_{wc}}{B_{w0}} \right|$$
(3.3)

The coupling length of GI PMMA POF has first experimentally been determined by Shi et al. [91] with $L_c = 2.1 \text{ m}$ and $\beta = 0.6$. The coupling length of SI PMMA POF was determined to be about 15 m [92].

Mode propagation in PF GI POF

Due to the different fabrication processes of PF GI POF (preform fibres or co-extruded fibres) and considerably varying fibre purity (e.g. contamination and inhomogeneities), even between single fibre batches of the same manufacturer, the published mode coupling and bandwidth results differ considerably.

The preform drawing approach allowed for the production of high-purity fibres with low loss and little backscatter fluctuations (Figure 3.3). Recent batches of LUCINA fibre exhibit less mode coupling and decreased attenuation compared to co-extruded fibres. Investigations on mode coupling in this fibre at 1550 nm showed little mode coupling [98]. Bunge et al. [99] reported that more recent batches of preform PF POF show relatively weak mode coupling with coupling lengths in the range of 800 m to 1200 m at 1550 nm wavelength. Significant differences of this behaviour at 842 nm and 1550 m wavelength have not been observed. This preform fibre type is, however, not subject of this work.

Co-extruded PF GI POF generally exhibit stronger mode coupling which can have various intrinsic and extrinsic origins. Intrinsic coupling generally owes to fluctuations in density and concentration [92]. During the drawing process, thermally excited fluctuations of density and composition, as well as polymer orientation become frozen into the fibre when cooling down from the melt [100]. This results in very short length scale inhomogeneities down to the scale of millimetres and below, which causes intermodal coupling [94],[100]. The degree of mode coupling and the absolute attenuation of PF POF are considered to be mainly determined by extrinsic effects and perturbations. The intrinsic attenuation measured on CYTOP bulk samples has been determined to be varying from 5 dB/km for undoped

samples to 10 dB/km for doped samples [94]. Extrinsic sources such as voids, cracks, microbends, index profile variations and diameter variations formed during the drawing process are believed to have a dominant impact on mode coupling in strongly coupling fibres [100]. Additional extrinsic imperfections, mainly particles with sizes in the range of 1 μ m to 10 μ m, contribute to mode coupling [94]. These impurities can clearly been observed in the backscatter trace as strongly scattering events, Figure 3.3 (right). Improved drawing processes reduced impurity contamination of more recent fibre batches but relatively strong scattering centres can still be observed irregularly distributed along the fibre.

The intergroup coupling and short coupling lengths have been identified as the primary mechanism leading to the high bandwidth in GI PF POF. It has been shown that GI PF POF can support 10 Gb/s over 100 m and beyond [89], [101], [102], [103]. Polley et al. [95] demonstrated that strong mode coupling in co-extruded GigaPOF 50SR fibres (50 μ m core diameter), the same fibre used for the experiments in this thesis, is the reason for the bandwidth enhancement of PF GI POF links to 40 Gb/s over 100 m. Any launch condition up to an offset of 25 μ m including overfilled launch into a 200 m long fibre yielded equivalent performance indicating complete mode coupling [95]. Simulation results indicate that mode coupling is the primary factor for the low DMD of this fibre type and differential mode attenuation (DMA) has negligible influence [94], [95].

The strongly coupling co-extrusion fibres¹ have been chosen for the backscatter sensing applications proposed in chapter 4. Although their attenuation is higher than that of the preform fibres, they exhibit several favourable characteristics. One reason is the relative independence of modal excitation on the backscatter trace and lower DMD due to the stronger mode coupling. This is the prerequisite for precise distance and length change measurement in the fibre proposed in section 4.2. Another important reason is the presence of relatively strong scattering centres along the fibre (Figure 3.3 (right)) which is beneficial for the length change sensing technique. Also, the commercial availability and favourable mechanical properties necessary for strain measurement applications are reasons for using this fibre type which is therefore investigated in more detail. Its optical properties are listed in Table 3.1.

Parameter	Value
Core diameter	50 ± 0.015 μm
Numerical aperture (NA)	0.19 ± 0.015
Zero dispersion wavelength range	1200 – 1650 nm
Dispersion slope	≤ 0.06 ps/nm ^{2.} km
Attenuation α at 1310 nm	≤ 60 dB/km
Group refractive index n_{gr} at 1310 nm	1.3563 ³

Table 3.1: Optical properties of the studied PF POF type; data from the product datasheet².

3.2.3 Mode dispersion measurements and impact

As mode dispersion in MM fibres has been shown to be the main cause of pulse broadening and the accompanied decrease in bandwidth, its impact is analyzed in more detail. Standard MM silica fibres (OM2) as well as the PF GI POF are investigated in terms of bandwidth and differential mode delay (DMD). MM silica fibres are also considered since they may be used to interconnect remote PF POF sensor fibres with the I-OFDR measurement setup ensuring minimum optical loss. A very important issue for precise sensing applications using the techniques proposed in chapter 4 and chapter 5 are delay changes as well as the transfer function stability as a function of modal excitation. Since the fibre

¹ GigaPOF 50SR fibres are investigated for distributed strain and length change measurement in chapter 4.

² Data sheet GigaPOF-50SR available at: http://www.chromisfiber.com/pdf/GigaPOF50SR.pdf.

³ The group refractive index of the sensor fibre is determined to be $n_{ar} \approx 1.3563$ using the I-OFDR setup for $\lambda = 1310$ nm at $T \approx 24$ °C.

is intended for strain sensing, the modal power distribution is expected to be altered by mechanical impact (e.g. fibre bends) leading to changes of the transfer function of the fibre. These effects are expected to be less pronounced in PF GI POF due to the strong mode coupling and short coupling lengths as well as the limited sensor length up to several hundreds of metres. Standard silica MM GI fibres as well as the PF GI POF sensor fibre are in the following analyzed for DMD and DMD stability.

The I-OFDR setup in Figure 2.8 has been modified and is operated in transmission to directly measure the transfer function (equivalent to the bandwidth) of the FUT. Figure 3.5 shows this setup with a SM-to-MM mode converter¹ (MC) between the SM source input and the MM FUT.



Figure 3.5: Schematic of the modified I-OFDR setup for the measurement of the FUT transfer function in transmission.

This mode converter (MC) is a passive device and ensures stable and reproducible launch conditions² with all mode groups populated into standard multimode fibres (50 µm core diameter) as opposed to central launch from a SM fibre into a MM fibre exciting almost exclusively the fundamental mode. Transmission measurements of long standard MM GI fibres (OM2) as well as the PF GI POF are conducted for two cases: central coupling from SM to the MM FUT and launching fully filled mode distribution into the MM FUT using the MC. In case of long silica MM fibres, the high temporal resolution of the frequency domain approach enables detecting delay changes of single mode groups in the fibre. Figure 3.6 shows the impulse response calculated from the measured transfer function with the MC in the setup (fully filled mode distribution) and without the MC in the setup (central coupling SM to MM) for two different fibre lengths.



Figure 3.6: Time domain responses of silica OM2 GI MM fibres for central launch and fully filled mode distribution using the MC for 4750 m fibre length (left) and 13550 m fibre length (right).

It can be seen that central coupling of a single mode fibre to the FUT results in stable propagation of almost the entire power in the fundamental mode over long distances. Intergroup mode coupling is insignificant. When using the MC, all mode groups are populated which results in DMD that can clearly be resolved in the impulse response depictions in Figure 3.6. The transmitted optical power is delayed in this case (higher order mode groups generally exhibit different group velocity) which would result in

¹ Singlemode to multimode fibre converter: SMC13113111 by AC Photonics, Inc.

² The exact principle of the device is unknown. A measurement of the output mode field is presented in the device datasheet available at: http://www.acphotonics.com/products/product_files/Singlemode%20to%20Multimode%20Fiber%20Converter.htm

a measured but not existing elongation of the fibre. Experiments with a macrobend mode scrambler showed that coupling into higher order mode groups can be easily induced by external mechanical impact on the fibre. The resulting DMD and effectively induced delay changes will have a deteriorating effect on the backscatter measurement resolution and the precision of sensing applications in these fibres, even at shorter fibre lengths. Also the decoupling of higher order mode groups, for example due to fibre bends, would result in incorrectly detected length changes.

In order to give an approximate worst-case value for a detected delay change or length change, the temporal power shift has been calculated from the measurement results in Figure 3.6 for the two cases: central coupling exciting mainly the fundamental mode compared to fully filled mode distribution using the MC. The measured delay differences and length differences between the different excitations in reflection for both fibre lengths would result in about 0.6 ns or 12 cm per km fibre length (measured: 4 ns shift for 13550 m and 1.5 ns for 4750 m one-way transmission). These values are fibre-specific and specific to the modal excitation of the fibre. The strong DMD in these fibres and the stable mode propagation could be a serious limitation when attempting precise delay change measurement in long mechanically loaded MM silica fibres.

Modal bandwidth is a term used in optical communication and characterizes the signal transfer capacity of a fibre per distance unit. The modal bandwidth of multimode fibres can be directly measured in the frequency domain and is defined as the frequency at which the amplitude $(|H(j\omega)|)$ drops 3 dB below the zero frequency components of the transfer function $(|H(j\omega = 0)|)$. Conducting a frequency response measurement with the I-OFDR setup allows directly measuring the modal bandwidth by determining the -3 dB frequency of the calibrated I-OFDR transfer function. Figure 3.7 shows the equivalent frequency response result of the two fibres for the two cases: central coupling SMF to MM opposed to fully filled mode distribution using the MC.



Figure 3.7: Frequency response and 3 dB bandwidth for central coupling SM-MM and with MC for two different fibre lengths (GI MM silica fibre, OM2 grade).

For the case of fully filled mode distribution, the modal bandwidth decreases to 218 MHz for a 4750 m long fibre and to 81 MHz for a 13550 m long fibre. As expected for MM silica fibres, the measured -3 dB bandwidth for the two fibre lengths corresponds to a linear bandwidth-distance product ($\beta \approx 1$). That means that intermodal coupling in these fibres is insignificant and that the above calculated position deviation with fibre length between different launch conditions can be approximately linearly scaled with fibre length. Using MM fibres with higher modal bandwidth, such as OM3 or OM4 standard fibres, would show the similar dependency but far reduced DMD and reduced delay change dependency.

DMD also has an impact on the measurement result of the reflection peak, as it is proposed later in chapter 5. Any deviation from the ideal frequency response $(|H(j\omega)| = \text{const.})$ results in a deviation of the peak power reflected from a singular reflection event in the fibre. The absolute reflected power measurement relative to the Rayleigh level using the values simulated in Figure 2.15 cannot be correctly conducted when the dispersion is significant. This measured peak power deviation depends on the used fibre type and cannot be calculated for a general case. Due to the increasing 'partition' of

the single mode groups with distance and the expected not symmetric DMD in the fibre, it can be assumed that the measured reflection peak power is not linearly proportional to the fibre length. If these deviations of the fibre transfer function during the measurement cannot be calibrated, integration of the total power of the full reflection peak shape would result in more precise reflectivity results than just obtaining the peak power of the reflection peak.

For the PF GI POF, reduced dependence on the launch condition and increased modal bandwidth for long fibres (several hundreds of metres) is expected due to the strong mode coupling in this fibre type [94], [95]. In order to determine the impact of modal excitation or mode filtering in PF GI POF, the same experiment has been conducted with a 964 m long Chromis GigaPOF sensor fibre that is also used for all sensing applications introduced in the chapters 4 and 5. As expected, the mode dispersion is lower and the bandwidth is higher than in the used OM2 MM silica fibres excited with fully filled mode distribution. Figure 3.8 shows the frequency response (left) and pulse response (right) of the POF in transmission with central coupling from SM to MM and fully filled mode distribution using the MC. The pulse response, Figure 3.8 (right), shows an additional measurement of the pulse without the POF (reference).



Figure 3.8: Frequency response (left) and calculated pulse response (right) of 964 m PF POF in transmission for central coupling as well as fully filled mode distribution using the MC.

The frequency response and the pulse response are basically the same for central coupling and coupling of a fully filled mode distribution. The modal bandwidth is hardly dependent on the modal excitation and about 1.74 GHz for the 964 m fibre. The measured effective modal bandwidth is 1680 MHz·km for PF POF and about 1050 MHz·km for the OM2 fibre.

Impact on the PF POF backscatter trace

Another important issue is the reproducibility of backscatter measurements in PF POF for different launch conditions. This is especially important for the sensing applications proposed in chapter 4. In order to test the modal excitation conditions of the I-OFDR setup, test measurements equivalent to Figure 3.5 but with the MM circulator in the setup have been conducted to ensure that the circulator does not significantly alter the modal excitation. The MM circulator is therefore inserted into the setup at the position of the MC (for fundamental mode excitation measurement) and between the MC and the FUT for fully filled mode distribution. The measurements with the two configurations showed that the modal excitation remains basically unchanged by the presence of the circulator itself: entering the circulator with the fundamental mode only (central SM-to-MM coupling) as well as with a fully filled mode distribution leads to similar DMD results as shown in Figure 3.6 (right) after 13550 m propagation in the MM silica fibre.

To investigate possible deviations of the backscatter trace depending on the launch conditions, the backscatter measurement setup (Figure 2.8) has been altered by introducing the MC between the EOM and the MM optical circulator. Figure 3.9 shows the obtained backscatter traces for the two cases: fundamental mode excitation without the MC and fully filled mode distribution with the MC between the EOM and the MM optical circulator.



Figure 3.9: Backscatter traces of the same POF for central coupling and fully filled mode distribution using the MC in the I-OFDR setup; $t_{meas} = 7 \text{ min}$, $\Delta f = 500 \text{ kHz}$, $f_{m,max} = 2 \text{ GHz}$, $\alpha_K = 2$.

The backscatter measurements of PF GI POF for different modal excitations do not exhibit significant deviations. The single scattering peak positions and peak powers relative to the Rayleigh backscatter level agree well. Only the coupling from the MM silica fibre to the PF POF at 5 m distance leads to an increased reflection and higher optical loss due to imperfect matching of the fibre cores. The higher Rayleigh backscattering coefficient of the POF can be noted at the coupling between the MM silica fibre and the MM POF. Also various investigations on the backscatter properties of the PF POF showed no advantage when using the MC in the I-OFDR setup. The use of a MC between the modulator and the optical circulator is therefore unnecessary for backscatter measurement in PF GI POF. All backscatter measurements in MM fibres are therefore conducted without the MC in the setup.

3.3 Conclusion and choice of fibre type

For backscatter sensing in *MM PF POF*, the co-extruded GigaPOF fibre is chosen over the preformdrawn fibre. An important reason is the very strong mode coupling that has been observed in the coextruded fibres. This results in reduced DMD and makes these fibres relatively insensitive to changes of the modal excitation. Decoupling of mode groups due to mechanical impact or other causes of extrinsic modal excitation changes are immediately compensated for on a small length scale due to the strong mode coupling in this fibre [94], [95]. That enables precise length change measurement and ensures relative insensitivity to mechanical impact on the sensor fibre. Compared to the low-coupling and low impurity preform fibres (Figure 3.3 (left)), the attenuation values are inferior. However, the relatively strong backscatter fluctuations and the presence of scattering centres in the co-extruded fibre considerably improve the distributed length change measurement that will be introduced in section 4.2. Another important reason is the favourable mechanical property of this fibre type and the availability as a sensor fibre (section 4.1).

Mode propagation experiments on *MM silica fibres* show significant impact of modal excitation on the pulse shape end effective optical delay. For general backscatter measurement and distance sensing in silica fibres, SMF without the deteriorating DMD effects would be the medium of choice. If long MM fibres are required, as it may be the case for the connection of remote PF POF sensors to the I-OFDR device, care has to be taken concerning modal excitation and changes thereof. Length measurement deviations due to modal excitation changes are approximately linearly scaled with fibre length. The result of the peak power evaluation of a reflection in the fibre also depends on the fibre length. If the fibre properties and modal excitation of a very low-coupling MM fibre are known, the occurring DMD and related distortion of the transfer function may be compensated for a certain distance by appropriate calibration or pre-distortion of the measurement frequency sweep. This is also an important issue for the proposed sensing principle in chapter 5. The use of higher-bandwidth MM fibres (OM3 or OM4 standard) is an efficient way to reduce deteriorating DMD effects. Care should be generally taken to not induce unwanted mode coupling for example due to mechanical impact if long MM silica fibres are used for precise sensing applications.

4 Distributed strain measurement in polymer optical fibres

In this chapter the introduced PF POF is investigated for distributed detection of strain and measurement of length change along the fibre. The high spatial resolution, high signal stability and multimode compatibility of the I-OFDR technique are essential requirements for conducting precise measurements with the following introduced sensing techniques.

The effect of backscatter increase at strained fibre sections is investigated for distributed strain detection in section 4.1. In section 4.2, distributed length change measurement is demonstrated by using the distinctive scattering centres in the PF POF as reference for the measurement of optical delay changes along the fibre. Section 4.3 investigates cross-sensitivities, limitations and systematic influences on the measurement results. Their influence on both measurement techniques is discussed.

4.1 Perfluorinated POF for backscatter sensing

It has been shown that the backscatter level of strained SI PMMA POF increases with increasing strain [3], [4], [5], [6], [7] and can be used for distributed strain measurement of very high strain values up to 45 % using the OTDR technique. This effect was also expected in PF POF and is investigated in this section.

Until recently, PF POFs have only been available with a small overcladding diameter of 490 µm (Asahi Lucina as well as Chromis GigaPOF 50-SR). The overcladding and protective jacketing materials are important since they determine the mechanical properties of the fibre and protect the fibre from damage or macrobends when being integrated as a sensor into a structure. Preliminary strain measurement experiments with GigaPOF 50SR fibres (490 µm overcladding diameter) have been conducted using the OTDR technique and resulted in cross section constriction (necking) of the fibre. This necking occurred already when applying strain (length changes) exceeding about 2-3 % [104] and resulted in localized very high strain and optical loss. Due to a different overcladding material, early patches of the preform PF POF (Lucina) could be uniformly strained up to 100 % without considerable loss. These first commercially available fibres were delicate to handle, prone to kinking and therefore not suitable for mechanical sensing applications. Later, more robust versions with an overcladding diameter of 750 µm (Chromis GigaPOF 50/750 SR) were available and could be strained up to about 8 % before necking occurred [105]. These promising first results and the targeted use of this fibre type for practical sensing applications lead to the decision to obtain a more rugged custom-made sensor fibre which was specially designed and fabricated by Chromis Fibreoptics Inc. Figure 4.1 shows a crosssection view of the sensor fibre design.



Figure 4.1: Schematic of PF GI POF sensor fibre cross section.

This fibre with a 50 μ m core diameter, 750 μ m diameter polymer overcladding, 1200 μ m diameter of a low tensile strength and high-ductile linear low-density polyethylene (LLDPE) jacketing and a second jacketing layer of 2200 μ m outer diameter of a higher tensile strain low-density polyethylene (LDPE) promised greater strain rates without necking and was used for most measurements presented in this work. The fibre core and overcladding is identical with the GigaPOF 50SR fibre. Its optical properties have been summarized in Table 3.1. The mechanical properties of the fibre materials are discussed in section 4.3.

4.1.1 Strain-backscatter interaction in perfluorinated POF

Investigations of the backscatter signal and its dependence on strain, temperature and humidity have initially been obtained using a high-resolution photon counting OTDR and have been published in [6],[105],[7],[104]. The I-OFDR provides the high resolution and signal stability necessary for the precise characterization of the occurring effects and cross-sensitivities. Therefore, more precise and extensive results obtained using I-OFDR are presented in this chapter.

Strain-backscatter dependencies

As expected from the behaviour of PMMA POF, the backscatter level increase with strain is also measurable in PF POF. All backscatter measurements as a function of strain have been conducted with the same setup: the section of the POF to be strained is mechanically clamped at two points (compressed between 40 mm long clamping jaws). One end of the section is fixed whereas the second clamp can be linearly moved by a PC-controlled step motor setup with a step size of 6.25 μ m. Any strain value (or elongation up to $\Delta l = 1$ m) can be applied to the clamped fibre section while measuring the backscatter trace for the different strain (or elongation) settings.

Figure 4.2 (left) shows exemplarily a number of backscatter plots of the same PF POF section but for different strain values applied to the section of the length $L_0 = 1.5$ m between z = 61.5 m and z = 63 m. The measurement parameter is the change of the backscatter level of the strained fibre section as a function of the strain $\varepsilon = \Delta l/L_0$. This backscatter level change is evaluated in the following by comparing the mean backscatter level of the strained fibre section, here between 61.5 m and 63 m, relative to the same section of a reference measurement at 0 % strain. This backscatter level change in dB has been obtained for various I-OFDR backscatter measurements for different strain values during a step-wise elongation of the clamped fibre section. The backscatter level changes as a function of strain up to $\varepsilon \approx 5$ % are separately measured for 6 different fibre sections and are plotted as a function of the applied strain ε in Figure 4.2 (right).



Figure 4.2: Backscatter measurement: several traces of the same fibre with different strain values applied to the fibre section between 61.5 m and 63 m; $t_{meas} = 5 \text{ min}$, $\Delta f = 900 \text{ kHz}$, $f_{m,max} = 1999.8 \text{ MHz}$, $\alpha_K = 2$ (left) and strain-backscatter change characteristic measured for 6 different fibre sections and a continuous strain increase of 0.4 %/h (right); $t_{meas} = 5 \text{ min}$, $\Delta f = 900 \text{ kHz}$, $\alpha_K = 2$.

The strain-backscatter dependency in Figure 4.2 (right) is reproducible for independent measurements of different fibre sections but has a non-linear characteristic. The backscatter increase is only evident within a limited strain range between about $\varepsilon \approx 1.\%$ and $\varepsilon \approx 3.5\%$. The backscatter level has a maximum at a strain of about $\varepsilon \approx 3.5\%$ and decreases with further increase of applied strain. Also, it is shown later that the rate of the applied strain increase (here: 0.4 %/h) has a strong impact on the slope of the characteristic. The analyzed backscatter level change dependency is superimposed by a temporal relaxation dependency of the sensor response which also depends on the applied strain.

Temporal influences and relaxation

The backscatter level change exhibits a strong dependence on time. Figure 4.3 shows the relative backscatter change (continued measurement of Figure 4.2 (right)) of several individually strained fibre

sections during a linear strain increase to $\varepsilon = 5 \%$ from t = 0 h to t = 12.5 h. After the strain increase, a constant strain of 5 % is maintained from t = 12.5 h to t = 23 h. From t > 23 h, the strain is fully released and the backscatter level asymptotically falls to almost the initial backscatter level prior to straining the fibre.



Figure 4.3: Temporal dependency of the backscatter level for linearly straining the fibre from $\varepsilon = 0$ % to $\varepsilon = 5$ % (t = 0 h to 12.5 h), constant strain at $\varepsilon = 5$ % (t = 12.5 h to 23 h) and for the released fibre (t > 23 h).

After reaching a maximum at about 3.5 % strain (at $t \approx 8.5$ h), the backscatter level decreases with the same tendency up to t = 23 h although the strain increase is stopped at t = 12.5 h and held constant at 5 % strain from t = 12.5 h to t = 23 h. It can be assumed that the signal level decrease from about 3.5 % on during the continuous strain increase is partially due to the observed temporal relaxation effect. Straining the fibre with a different strain increase rate leads to a different characteristic due to the superposition of the temporal relaxation effect.

In order to investigate the backscatter level change and temporal relaxation for static strain and for different strain values, a long-term test has been conducted with 4 individual fibre sections permanently strained to $\varepsilon = 1.3$ %, $\varepsilon = 1.5$ %, $\varepsilon = 2.25$ % and $\varepsilon = 2.5$ %. All fibre sections have been strained from 0 % to the permanent values at t = 0 h. Figure 4.4 (left) shows the evaluation of backscatter level change relative to the reference measurement of 0 % strain during the first 17 hours after applying the strain and Figure 4.4 (right) shows the continued backscatter level change over an extended time period of 258 days.



Figure 4.4: Backscatter level change after straining the fibre to different values ($\epsilon = 1.3$ %, $\epsilon = 1.5$ %, $\epsilon = 2.25$ % and $\epsilon = 2.5$ %) up to 17 h (left) and continued over an extended period of time of 258 days (right).

As expected from the characteristic in Figure 4.2 (right), higher strain values result in increased backscatter levels. The temporal relaxation of the backscatter level exhibits different dependencies during the first 70 days after applying the strain for small strain values (backscatter level increase for $\varepsilon = 1.3$ % and $\varepsilon = 1.5$ %) compared to higher strain values (backscatter level decrease for $\varepsilon = 2.25$ %). After about 70 days, the relaxation behaviour converges and a gradual decrease of all backscatter levels can be observed. Low strain values result in a measurable backscatter change after

several days and might initially not be detected if only the backscatter level is evaluated. Also, higher strain values exhibit an initial backscatter increase during the first 3 h for $\varepsilon = 2.5$ % and about 20 h for $\varepsilon = 2.25$ % before backscatter decrease begins. The reasons for the signal relaxation the differences of the relaxation behaviour for different strain values are unknown. This sensor signal relaxation behaviour effectively makes it impossible to use the backscatter level change of this fibre type for direct strain measurement. A unique determination of the strain value from the backscatter level change is not possible. Strained fibre sections can, however, be localized when comparing backscatter levels with a reference measurement. This backscatter level dependency on strain has also been determined to be independent of the modal excitation of the sensor fibre: comparative measurements when exciting the fibre with different modal launch conditions (central coupling and fully filled mode distribution using the MC into the MM optical circulator) did not lead to measurable changes of the backscatter signal level of the strained sections.

Viscoelastic and cyclic behaviour

The sensor fibre may also be used to measure cyclic strain loads. In order to ensure measuring the correct length change value, it is crucial to determine the elastic strain limit of the fibre. A cyclic measurement of alternately straining and releasing a fibre section with increasing strain steps of $\varepsilon = 0.5 \%$ up to $\varepsilon = 10 \%$ ($0 \% - 0.5 \% - 0 \% - 1 \% - 0 \% \dots 9.5 \% - 0 \% - 10 \%$) has therefore been conducted using the automated step motor setup. Each strain value was held constant for 5 hours. Figure 4.5 (left) shows the applied strain and the actual measured length change by evaluating the spatial shift of a reflection peak in the fibre 'after' the strained section. From these measurements, the fully elastic strain limit for this fibre is determined to be about $\varepsilon \approx 2 \%$. Strain values exceeding about 2 % begin to show viscoelastic and plastic deformation (remaining length change). This behaviour can be largely contributed to the material properties of the jacketing materials and the overcladding material. Mechanical properties of the fibre are further discussed in section 4.3. The temporal relaxation of the backscatter level change can also be observed during the cyclic increase of strain, Figure 4.5 (left). As it could be expected from the results shown in Figure 4.2 (right) and Figure 4.4, the time-dependent backscatter increase occurs for smaller strain values up to $\varepsilon \approx 2.5 \%$.





Also the backscatter level change of a long-term cyclic load of the fibre is investigated: a fibre section has been alternately strained to 3 % and released to 0 % in cycles of 5 hours each. The measured backscatter level change of the strained section is shown in Figure 4.5 (right). The decrease of the backscatter level over time occurs over a much shorter timescale and reaches a smaller absolute value compared to the static strain results shown in Figure 4.4. This deviation presumably owes from the cyclic load effects and associated polymer mechanics during straining and relaxation of the fibre. The exact reasons for this behaviour are unknown.

Although direct strain measurement is not possible using backscatter level evaluation, the POF has a considerable advantage over silica fibres. It can be used for extremely high-strain sensing applications. PF POFs have the potential to survive and to measure extreme elongation: an early batch of AGC's PF POF could be uniformly strained to $\varepsilon \approx 100 \%$ [106],[107]. Figure 4.6 shows earlier OTDR backscatter plots of this fibre type for very high strain up to $\varepsilon = 100 \%$.



Figure 4.6: Backscatter traces obtained by photon counting OTDR of a 1 m long fibre section (from 17.5 m to 18.5 m) strained in steps up to 100 %.

More precise and high-resolution I-OFDR measurements could not be conducted with this fibre type since this fibre is no longer available and only a short section could be tested. The custom-made sensing fibre can also endure strain values exceeding 100 % but it cannot be uniformly strained beyond about 50 % due to strong fluctuations of the jacketing diameter along the fibre. Necking and very high localized strain occurs at higher strain values when clamping and elongating a fibre section. The fibre diameter considerably reduces at these sections where the strain is concentrated. This behaviour would be less problematic if the fibre was integrated into a structure and the true strain would be correctly transferred to the fibre. The integration of this sensor fibre into a geotextile has successfully been conducted without inducing additional optical loss along the fibre. This sensor textile is intended for the detection of the movement of soil. A field test with such a sensor textile and the I-OFDR as measurement system has been initiated.

Concluding this section, it can be stated that the nonlinear backscatter level change with strain as well as the temporal change of the backscatter level prevents using this effect for direct strain measurement. It is, however, a very useful characteristic for identifying and locating strained fibre sections in PF POF with cm-spatial resolution (better than the two-point resolution δz_{eff} of the I-OFDR system). Further investigations on cross sensitivities and mechanical properties of the fibre, also on the backscatter level are presented in section 4.3.

4.2 Distributed length change measurement

The typical backscatter signal of a PF POF exhibits a large number of scattering centres and backscatter fluctuations of different power that are randomly distributed along the fibre (Figure 4.7 (left)). The origin of these scattering centres was discussed in chapter 3. This characteristic fingerprint of the fibre is permanent and largely independent of the modal excitation of the fibre (Figure 3.9). It can therefore be used to measure optical delay changes along the fibre when comparing the backscatter signature of a new measurement relative to a reference measurement. Straining a section of the fibre leads not only to local backscatter increase but also to a spatial shift of the backscatter peaks 'after' the strained section towards greater distances. It is shown in section 2.4.1 for SMF that length changes along the Fibre can be measured using I-OFDR by evaluating the shifts of single reflection peaks. In case of the PF POF, the single backscatter fluctuations and scattering centres in the fibre due to inhomogeneities and contamination are weaker and of widely differing power, Figure 4.7 (left). A spatial shift, or length change, of a fibre section can therefore be most efficiently calculated by applying a cross-covariance algorithm to a fibre section (for example from z = 28 m to z = 30 m) of a reference measurement

 $h_{ref}(28 \text{ m} \le z < 30 \text{ m})$ and the corresponding section of a new measurement result $h_{new}(28 \text{ m} \le z < 30 \text{ m})$. The length of the correlated fibre section or 'correlation window' is defined as the correlation length l_c . The spatial shift is directly derived from the position of the maximum of the cross-covariance function of the correlated sections of the reference trace and the new backscatter trace as input. The calculated length change result $\Delta l(z_0)$ at the position z_0 represents an averaged value of the spatial shift within the 'correlation window' for $z_0 - l_c/2 < z < z_0 + l_c/2$:

$$\Delta l(z_0) = \operatorname*{argmax}_{z_0} \left[\operatorname{cov} \begin{cases} h_{ref} \left(z_0 - \frac{l_c}{2} < z < z_0 - \frac{l_c}{2} \right), \\ h_{new} \left(z_0 - \frac{l_c}{2} < z < z_0 - \frac{l_c}{2} \right) \end{cases} \right] \cdot \delta z_{res} - l_c$$
(4.1)

where, $cov(h_{ref}(z), h_{new}(z))$ denotes the cross-covariance function (using Matlab's '*xcov*' function) of the input vectors $h_{ref}(z)$ and $h_{new}(z)$, argmax is the argument of the maximum (position) and l_c is

an integer multiple of the spatial separation of the FFT bins δz_{res} (equation (2.21)) of $h_{ref}(z)$ and $h_{new}(z)$. This averaging of backscatter results within the length of a 'correlation window' l_c leads to more precise length change results than comparing the shift of weak single scattering points. The calculation of $\Delta l(z_0)$ along the fibre is conducted for z_0 in steps of $\delta z_0 \ll l_c$ (overlapping correlation windows) and results in a spatially more detailed length change evaluation. The application of this technique is shown for a step-wise strained fibre section in Figure 4.7. The left plot shows several I-OFDR measurements of a PF POF fibre with a 1 m long section between z = 26.9 m and z = 27.9 m elongated by steps of 5 mm up to 35 mm total length change by using the step-motor setup. The backscatter increase of the strained section is clearly visible in Figure 4.7 (left). The spatial shift of the scattering peaks can be noted 'after' the strained fibre section. Figure 4.7 (right) shows the length change result $\Delta l(z_0)$ along the fibre after conducting the cross-covariance evaluation using equation (4.1) with a correlation length $l_c = 2 \text{ m}$. 7 single backscatter traces of the fibre with length changes from 5 mm to 35 mm have been correlated with the same reference measurement $h_{ref}(z)$ and are calculated for z_0 in steps of $\delta z_0 = 2$ cm. The interpolation of $h_{ref}(z)$ and $h_{new}(z)$ between the IFFT bins using zero-padding (section 2.2.2) is here also necessary to obtain high position resolution results. The bin resolution (equation (2.18)) without zero padding would in this case be $\delta z_{bin} \approx$ 2.76 cm $(f_{m,max} = 2 \text{ GHz}, n_{gr} = 1.3563)$



Figure 4.7: I-OFDR measurements of a stepwise strained 1 m long POF section; $t_{meas} = 5 \text{ min}$, $\Delta f = 1 \text{ MHz}$, $f_{m,max} = 2 \text{ GHz}$, $f_{zp} = 50$, $\alpha_K = 2$ (left) and calculated distributed length change of the same fibre strained in 5 mm steps up to 35 mm; $l_c = 2 \text{ m}$, $\delta z_0 = 2 \text{ cm}$ (right).

The backscattered power results in Figure 4.7 (left) demonstrate that strained sections can be located with cm-resolution by evaluating the backscatter increase effect. The distributed length change can be measured with a resolution better than 1 mm, even at relatively small l_c of 2 m. The maximum deviation of $\Delta l(z_0)$ is measured to be smaller than 1 mm for distances z_0 further than l_c from the location of applied length change. The spatial resolution of the distributed length change results

 $\Delta l(z_0)$ can be approximately defined with $l_c + \Delta l(z_0)$: a singular length change event resulting in Δl at the position z can be determined without interfering with the calculation of equation (4.1) for results at the distances $z_0 = z - l_c/2$ and $z_0 = z + l_c/2 + \Delta l(z_0)$. Solutions for $\Delta l(z_0)$ with the correlation window $(z_0 - l_c/2 < z < z_0 + l_c/2)$ overlapping with the strained section result in intermediate or averaged length change results. That may give a better indication of the location of the strained section than $l_c + \Delta l(z_0)$, as it can be seen in Figure 4.7 (right).

The accuracy as well as the spatial resolution of the distributed length change measurement depend on the chosen correlation length l_c . They can be further improved by correlating longer fibre sections (increasing l_c) and increasing the measurement time. The length change resolution is also dependent on the degree of backscatter fluctuations along the fibre, the spatial resolution of the backscatter measurement, the signal stability and the backscatter signal-to-noise ratio. The latter might be limited by the dynamic range of the system or is a function of the system sensitivity (or t_{meas}). The resolution is considerably improved when interference between the scattering centres is suppressed by conducting spectral averaging during the measurement (section 2.5.3). Since the characteristic backscatter 'fingerprint' of the fibre is permanent, the correlation technique is insensitive to optical loss along the fibre. The algorithm is very robust against random disturbances such as fibre bends or extremely short strained fibre sections since the correlated fibre sections always contain multiple backscatter fluctuations.

As the investigated POFs exhibit irregularly distributed scattering centres with widely differing backscattered powers, stronger scattering centres have a dominant impact on the cross-covariance function and the calculated length change result $\Delta l(z_0)$. Strong scattering centres leading to high backscatter power may cause significant spectral leakage (decaying side lobes as in Figure 2.5 (right)) which superimposes neighbouring low-power scattering centres. This effect can be seen in the measurement in Figure 4.8. The spectral leakage influence around the strong scattering at $z \approx 100$ m might also stretch into correlation sections to both sides of the backscatter peak and corrupt the length change results $\Delta l(z_0)$. Applying a window function with high side lobe suppression ratio (large α_K , section 2.2.2) is therefore advisable at the presence of strong reflections in the fibre. Optionally, the reflection peak can be removed from the backscatter trace by subtracting its calculated frequency response component $H_r(f_m)$ from the total measured frequency response $H(f_m)$. The reflection frequency response $H_r(f_m)$ can be obtained by determining the exact reflection position and amplitude from the time domain measurement h(z). A detailed explanation of the calculation of the frequency response $H_r(f_m)$ of a single reflection in the fibre is explained in detail in section 2.3.2 using equation (2.58). The backscatter result without the disturbing reflection $h_{rem}(z)$ is obtained using equation (1.5) after calculating the IFFT of the reflection-subtracted frequency domain response $\mathcal{F}^{-1}{H_{rem}(f_m)}$ with

$$h(t) = \mathcal{F}^{-1}\{H_{rem}(f_m)\} = \mathcal{F}^{-1}\{H(f_m) - H_r(f_m)\}$$
(4.2)

This effectively removes the side lobes caused by the strong reflection and accurate correlation calculation can be conducted around the reflection peak. Figure 4.8 shows the backscatter responses of the FUT with a very strong scattering centre about 23 dB above Rayleigh level as directly obtained from the I-OFDR measurement h(z) (left) and after subtraction of the strong reflection $h_{rem}(z)$ (right).



Figure 4.8: Backscatter traces h(z) of PF POF with strong reflection at 100 m (left) and $h_{rem}(z)$ after removal of the reflection (right); $t_{meas} = 3 \min$, $\Delta f = 800 \text{ MHz}$, $f_{m,max} = 2 \text{ GHz}$, $\alpha_K = 1$.

The side lobes of the reflection are efficiently removed. Their considerable impact on the backscatter trace and the length change evaluation results in the vicinity of the reflection can be suppressed.

Femtosecond laser pulse-inscribed scattering centres

Some fibre types exhibit very weak backscatter fluctuations along the fibre so that a distributed length change measurement is not possible or too imprecise. In order to be able to also use other POF types or increase the length change resolution, the inscription of permanent scattering centres into the core of PF GI POF is proposed. Some first experiments on the inscription of scattering centres using focused femtosecond laser pulses above the structural modification threshold of PMMA POF and PF POF are presented in [8]. This inscription technique and setup is briefly explained and introduced in section 5.1.1. Here, only the results in PF POF are concluded. Figure 4.9 shows OTDR measurements of a PF POF fibre (GigaPOF 50/750SR) before and after inscription of scattering centres at the positions 23.5 m and 24.3 m. The scattering centre at 22.7 m is due to particle contamination in the fibre core. The laser irradiation has been focused through the 750 µm diameter transparent overcladding of this fibre type into the 50 µm diameter CYTOP core.



Figure 4.9: OTDR traces of PF POF before inscription (reference) and after inscription of scattering centres at 23.5 m and 24.3 m.

These first experiments demonstrate the possibility to create significant and stable scattering centres along the fibre with potentially low optical loss. Future POF with minimal particle contamination and relatively smooth and uniform backscatter fluctuation could be structured in such a way to achieve optimal length change results. The inscription of evenly distributed scattering centres of equal scattering power would deliver most reliable results with constant length change resolution along the whole fibre length. Since dispersion is not a serious issue in this fibre type (section 3.2) only the reduced SNR due to optical loss towards the end of the fibre would degrade the length change measurement resolution with increasing fibre length.

4.3 Cross sensitivities and limitations

The sensing techniques proposed in section 4.1 and in section 4.2 rely on the precise measurement of backscattered power levels and optical delay changes. Other influences on these measurement parameters as well as propagation loss along the fibre therefore have to be investigated in order to identify possible sources of measurement errors and estimate the impact of environmental changes on the sensor performance. As it is generally the case for fibre optic sensor systems, the most disturbing external influence is the temperature T which has a non-negligible impact on the optical delay in the fibre. Since the sensor medium is a polymer, also changes of the relative humidity RH and the associated absorption of water of the fibre have an impact on light propagation, scattering power and transmission loss. Optical delay, transmission loss, backscattered power and water absorption rate are a function of both, temperature and relative humidity/water content, and are analyzed in relation to another in section 4.3.1. The mechanical limitations of the sensor fibre are discussed in section 4.3.2.

4.3.1 Temperature and relative humidity influences

All temperature and relative humidity measurements have been conducted with a section of the PF POF placed in a climate chamber. Temperature as well as relative humidity in the chamber can be individually controlled. The fibre sections in the beginning of the sensor fibre (z < 40 m) and the end of the fibre (z > 92 m) are placed outside the chamber in a temperature-controlled laboratory environment with near-constant relative humidity ($RH \approx 55$ %, $T \approx 23$ °C), Figure 4.10 (left). This way, the impact of relative humidity changes and temperature changes can be retrieved in comparison to the constant climatic conditions from the measured backscatter traces. The backscatter traces in Figure 4.10 (right) qualitatively show the impact on fibre attenuation for two different temperatures and different RH settings. Quantitative values are presented in this section.



Figure 4.10: Measurement setup for temperature and relative humidity measurement (left) and backscatter traces of the fibre for different temperature and relative humidity settings in the chamber from z = 40 m to z = 92 m (right); $t_{meas} = 3 \min, \Delta f = 800$ MHz, $f_{m,max} = 2$ GHz, $\alpha_K = 2$;

Three different effects on the backscatter trace can be observed when temperature and relative humidity are changed: optical delay change (due to refractive index change or length change of the fibre), change of transmission loss and change of backscatter level. The results are discussed in the following. For comparison: standard silica fibres are specified with lower attenuation changes: humidity and temperature dependence ≤ 0.1 dB/km at 1300 nm for MM fibres¹ and ≤ 0.05 dB/km at 1310 nm for SMF².

Length change

The causes of delay changes as a function of temperature or relative humidity may not be exclusively caused by actual changes of the fibre length. However, since the measurement parameter is the length

¹ Corning® ClearCurve® MM fibre, datasheet at: http://www.corning.com/WorkArea/showcontent.aspx?id=61265.

² Corning[®] SMF-28[™] SMF, datasheet available at: http://ece466.groups.et.byu.net/notes/smf28.pdf.

or length change, deviations thereof are given in the following in equivalent fibre length changes. Temperature has the dominant impact but water absorption of the fibre additionally alters the detected length change as well as the length change dependency on temperature. Figure 4.11 shows the measured equivalent length change in % that is obtained from numerous single I-OFDR measurements every 15 minutes during the temperature change of the fibre in cycles between -20°C and +70°C. Figure 4.11 (left) shows the results for saturated RH = 30 % and Figure 4.11 (right) for saturated RH = 90 % respectively. The length changes are measured by evaluating position changes of a single backscatter peak in the fibre 'after' the climate chamber and normalizing it to the affected fibre length in the climate chamber (40 m < z < 92 m). The temperature increment for both cycles is 11.25 K/h.



Figure 4.11: Measured length change as a function of temperature at 30 % RH (left) and at 90 % RH (right)

The length change results show a similar behaviour for high and low water content in the fibre but an offset and a slightly higher slope for RH = 90 %. The plots in Figure 4.12 show the measured length changes as a function of the measured temperature in the climate chamber during the two full temperature cycles for different RH settings of 30 % and 90 %.



Figure 4.12: Measured length changes vs. Temperature of the full temperature cycles at RH = 30 % and RH = 90 % shown in Figure 4.11.

The characteristic is not linear but highly reproducible and has a coefficient of about $dL/(L \cdot dT) \approx 91 \cdot 10^{-6} \text{ K}^{-1}$ at RH = 30 % and $dL/(L \cdot dT) \approx 93 \cdot 10^{-6} \text{ K}^{-1}$ at RH = 90 % for the extended temperature range from -20 °C to +70 °C. The measured length changes show a relative humidity-dependent offset and a slightly deviating characteristic for different relative humidity settings. Hysteresis is not observed. The relative humidity-dependent slope difference and the offset detected for different water content in the fibre could be explained by mechanical impact (changes of the expansion coefficient $\alpha_L = dL/(L \cdot dT)$ and swelling of the fibre materials due to water absorption) as well as changes of the thermo-optic coefficient of the core material. It has to be noted that the first heating of the fibre over about 68 °C results in a permanent length offset. Figure 4.13 (left) shows a temperature cycle of a not annealed sensor fibre. Figure 4.13 (right) shows the length change result as a function of temperature in the chamber. The temperature cycle measurement has been conducted in a

temperature chamber without controlling the RH values. The relative humidity changes during the cycles between about $RH \approx 10$ % and $RH \approx 75$ %.



Figure 4.13: Measured length change in % during temperature cycles (left) and length change as a function of temperature during the same measurement cycle from t = 0 h to t = 38 h (right).

It can be seen that the length change experiences a permanent offset of about -0.13 % when first being heated above about 40 °C and up to a temperature of 68 °C. It is therefore advisable to anneal the fibre at about 70 °C before the first use as a length change sensor.

The detected length change is a superposition of mechanical and thermo-optic effects. The relevant material properties of the sensor fibre materials are summarized in Table 4.1. The mechanical properties of the overcladding material are not known.

	Young's modulus E _Y	Thermal expansion coefficient $\alpha_L = dL/(L \cdot dT)$	Water absorption	Maximum elongation
СҮТОР	1400–1600 MPa [80]	74·10 ⁻⁶ K ⁻¹ [80]	< 0.01 % [80]	162–192 % [80]
LDPE	200–400 MPa [108]	150–200·10 ⁻⁶ K ⁻¹ [108]	0.01–0.02 % [108]	600-650 % [108]
LLDPE	250–700 MPa [108]	200·10 ⁻⁶ K ⁻¹ [109]	0.01 % [108]	500 – 900 % [108]

Table 4.1: Overview of mechanical parameters of the sensor fibre materials (cross section of the fibre in Figure 4.1).

The exact values for E_Y and α_L are not know but it can be assumed that the LDPE/LLDPE jacketing materials are expected to have the largest impact on the mechanical elongation of the fibre due to their large cross sectional area compared to the core and overcladding cross sectional area, see Figure 4.1. The E_Y values of all fibre materials are in the same order of magnitude. The impact of the core and overcladding on the total fibre thermal expansion coefficient is therefore neglected when making a rough estimate of a resulting fibre expansion coefficient: The LDPE jacketing accounts for about 70 % of the cross sectional area and is assumed to be determining for the total expansion coefficient with a value of about $\alpha_{L_{fibre}} \approx \alpha_{L_{LDPE}} \approx 150 - 200 \cdot 10^{-6} \text{ K}^{-1}$. The thermo-optic coefficient of CYTOP however is negative and has been determined with $dn_{CYTOP}/dT \approx -50 \cdot 10^{-6} \text{ K}^{-1}$ at 1550 nm wavelength [110]. The resulting delay changes cannot be accurately calculated with the available data. The expected effective temperature dependency can be roughly estimated to be in the order of $\alpha_{L_{fibre}} + dn_{CYTOP}/dT \approx 100 - 150 \cdot 10^{-6} \text{ K}^{-1}$ at $RH \approx 30 \%$. Previous investigations of the observed length change dependence of a thinner GigaPOF 50SR fibre¹ with only 490 µm overcladding diameter (no LDPE/LLDPE jacketing) exhibited a lower dependence of $dL/(L \cdot dT) \approx 22 \cdot 10^{-6} \text{ K}^{-1}$ [6]. This difference of

¹ GigaPOF-50SR with the same fibre core as the sensor cable, datasheet available at: http://www.chromisfiber.com/pdf/GigaPOF50SR.pdf.

 $dL/(L \cdot dT) = f(\alpha, dn/dT)$ as well as the mechanical and thermo-optic coefficients of the fibre materials indicate that the thermal expansion of the sensor fibre itself (predominantly the LDPE/LLDPE jacketing) has a dominant influence on the measured length change.

In case of a sensor application with the fibre fully integrated into a structure with no degree of freedom in fibre axis (the fibre can only expand in length with the surrounding structure), the negative refractive index dependency on temperature might have a dominant impact on the optical delay change. The Young's modulus of the fibre is relatively small so that the structure or material surrounding the fibre can be considered to be the determining parameter for the overall expansion coefficient. The measured length change deviation with temperature for integrated sensor fibres is then expected to be smaller due to the lower thermal expansion of most structures and materials that might be monitored (e.g. concrete $14.5 \cdot 10^{-6} \text{ K}^{-1}$, most metals: < $50 \cdot 10^{-6} \text{ K}^{-1}$). In fully sensor-integrated applications, the opposite signs of the linear expansion coefficients of the structural material as opposed to the thermo-optic coefficient of CYTOP are beneficial due to their compensation effect. Using for example PVC ($\alpha_{L_{PVC}} \approx 50.4 \cdot 10^{-6} \text{ K}^{-1}$) as jacketing material would result in a reduced length change dependency of the fibre due to coefficients (linear expansion and thermo-optic) of similar magnitude but opposite sign. For comparison: the thermal expansion coefficient of standard SMF is about $\alpha_{L_{silica}} \approx 0.5 \cdot 10^{-6} \text{ K}^{-1}$ [111] and the thermo-optic coefficient is also positive with about $dn_{SMF}/dT \approx 10.10^{-6} \text{ K}^{-1}$ [112]. The Young's modulus of fused silica is $E_Y \approx 72 \text{ GPa}$. PMMA¹ has a Young's modulus of $E_Y \approx 1.8$ -3.1 GPa.

Transmission loss

The two other relevant fibre parameters, transmission loss and backscatter level, are also a function of both, ambient temperature and water content in the fibre. They also have a mutual influence and are therefore discussed together. Although the water absorption of the base material of the fibre core (CYTOP) is < 0.01 %, a relatively strong impact on the propagation loss of the fibre is observed. The diffusion and water absorption of the fibre core at room temperature is delayed by the protective LLDPE and LDPE jacketing of the investigated sensor fibre and takes weeks to reach equilibrium. For the fibre without the LDPE/LLDPE jacketing (GigaPOF 50SR with 750 µm overcladding diameter), a steady state of the measurable impact of relative humidity is reached after a few hours only. Changing the relative humidity settings at an elevated temperature of 70°C accelerates the water absorption. The optical loss is obtained from the backscatter measurement results by evaluating the changes of backscattered power in the fibre 'after' the climate chamber for z > 92 m, Figure 4.10. The measured backscatter change is normalized to one-way loss (in transmission) in dB/m. Negative values represent decreased transmission. Figure 4.14 (left) shows the change of optical loss (one-way) of the sensor fibre in the climate chamber at 70 °C during a stepwise increase of RH settings (30 % - 60 % - 90 %). Figure 4.14 (right) shows the measured length change over time during the stepwise decreased relative humidity settings (90 % - 60 % - 30 %) at a constant temperature of 70 °C. The measured length change as a function of relative humidity would be smaller at lower temperature, as shown in Figure 4.12.

¹ From "MIT Material Property Database", http://www.mit.edu/~6.777/matprops/pmma.htm



Figure 4.14: Optical transmission loss over time during relative humidity steps at constant temperature of 70 °C (left) and detected length changes during the relative humidity changes (right).

The optical loss is a direct function of relative humidity and is fully reversible at a similar time constant. A long-term humidity test of the fibre in water-saturated soil over almost 4 years shows comparable changes of optical loss values. The backscatter level of the fibre is almost unaffected by relative humidity and discussed in more detail regarding mutual influence with temperature at the end of this section.

The cause of the optical loss as a function of relative humidity, or water content, can be explained when analyzing spectral transmission measurements. A white light source¹ has been used to couple a broad optical bandwidth into the PF POF that is partly placed in the climate chamber (40 m < z 92 m), as shown in Figure 4.10. The transmitted optical power is measured for different saturated relative humidity settings and temperatures using the OSA. Figure 4.15 (left) shows the transmitted optical power spectrum for 25 °C and 70 °C at 30 % relative humidity. Figure 4.15 (right) shows the transmitted optical power spectrum for a constant temperature of 70 °C and relative humidity settings of RH = 30 %, RH = 60 % and RH = 90 % respectively.



Figure 4.15: Spectral transmission of the sensor fibre for RH = 30 % at 25 °C and 70 °C (left) and for relative humidity settings of RH = 30 %, RH = 60 % and RH = 90 % at elevated temperature of 70 °C.

These spectral transmission measurements clearly show the impact that the OH absorption peak around $\lambda = 1383$ nm has on the transmission also at the FP laser wavelength around $\lambda = 1310$ nm. Increased water content in the fibre leads to increased transmission loss. The absorption peaks around $\lambda = 1130$ nm originate from vibrational overtones of one of the CYTOP bonds that are affected by the presence of the OH groups in the polymer. Temperature also has a strong impact on transmission around the absorption peaks. The transmission loss at the measurement wavelength is a function of both, temperature and water content. Other suitable wavelength ranges for example around 1 µm are not affected by water content and temperature and might be a better choice when designing a

¹ Yokogawa AQ4305 with a wavelength range from 400 nm to 1800 nm: http://cdn6.us.yokogawa.com/uploaded/buaq4305e_2.pdf.

measurement system exclusively aiming for backscatter measurement and sensing applications in PF POF. However, compromises would have to be made when operating in this wavelength region: using alternative wavelengths may result in increased dispersion and higher attenuation in standard silica fibres.

The attenuation dependence on the wavelength, temperature and relative humidity could also be used for the *distributed detection of regions of increased humidity or elevated temperatures*. Measuring backscatter traces of the FUT at two different wavelengths would lead to unambiguous results: other sources of optical loss can be ruled out when comparing relative backscatter change results with backscatter change results measured at a second wavelength that is not affected by temperature and RH (for example around $\lambda = 1000$ nm, Figure 4.15). The discrimination of these effects for measurement of relative humidity and temperature is further discussed at the end of this section.

Figure 4.16 shows the impact of water content on the optical loss, obtained from the backscatter measurement results, as a function of temperature during two full cycles between -20 °C and +70 °C for low relative humidity of RH = 30 % (left) and high relative humidity of RH = 90 % (right).



Figure 4.16: Measured optical loss (one-way) during temperature cycles for constant relative humidity settings of RH = 30 % (left) and RH = 90 % (right).

The absorption loss considerably increases when exceeding temperatures of about 50 °C. The optical loss exhibits considerably higher values at high RH environments. When operating the measurement system around $\lambda = 1310$ nm and aiming for high-humidity environments at elevated temperatures, the decrease of distance range due to increasing absorption loss has to be considered. Figure 4.10 (right) shows the backscatter traces for extreme absorption loss differences at T = 25 °C at RH = 30 % in comparison to T = 70 °C at RH = 90 %.

Backscatter change

As mentioned earlier, the backscatter level of the fibre is almost unaffected by relative humidity or water content in the fibre. The maximum backscatter level change for humidity changes between RH = 30 % and RH = 90 % occurs at high temperatures of +70 °C but is below 0.13 dB. Humidity changes at lower temperatures lead to decreased backscatter level dependency. This RH dependency is much smaller than the backscatter increase effect used for the detection of strained fibre sections (compare Figure 4.2).

Temperature changes between -20 °C and +70 °C have a more significant impact on the backscatter level than relative humidity changes between 30 % and 90 %. Figure 4.17 shows the backscatter change during two full temperature cycles between -20 °C and +70 °C for RH = 30 % (left) and RH = 90 % (right) obtained by evaluating backscatter changes of the fibre section at the beginning of the climate chamber between z = 40 m and z = 41 m.



Figure 4.17: Measured backscatter change relative to T = 25 °C as a function of temperature for saturated relative humidity settings of RH = 30 % (left) and RH = 90 % (right).

The observed backscatter level decreases with increasing temperature and has a slightly stronger impact for higher relative humidity settings. This effect can be significant for the unlikely event of very high temperature differences up to about 0.55 dB between neighbouring fibre sections at T = -20 °C and at T = +70 °C at RH = 90 %. Backscatter level changes due to strain may in this case exhibit similar values (see Figure 4.4). Confusing the impact of strain and temperature on the backscatter level change can, however, be ruled out since the two effects have opposite signs with respect to the length change result: strain increase leads to increased backscattering (Figure 4.2) and positive length change, whereas temperature increase results in decreased backscattering (Figure 4.17) and increased length change (Figure 4.12). When measuring the distributed length change from the spatial backscatter signature shift along the fibre (Figure 4.7), these two effects can be distinguished. Interestingly, the backscatter level change as a function of temperature has opposite sign but similar magnitude in PMMA POF [6]. The reason for this difference is unknown.

Temperature and relative humidity influence various parameters of the FUT backscatter trace such as backscatter level, attenuation and optical delay (measured length change). The attenuation is also a function of the wavelength used for the measurement which allows for discriminating the impact of relative humidity and temperature. Distributed measurement of relative humidity and/or temperature is intended. At the measurement wavelength $\lambda \approx 1310$ nm, the backscatter level change effect due to temperature in PF POF is superimposed by the strong impact of attenuation along the fibre due to temperature and relative humidity changes. It is therefore difficult to distinguish between these two effects. However, the temperature influence and the influence of relative humidity could be separated when additionally measuring backscatter traces at a second wavelength that is not affected by absorption due to temperature or relative humidity, for example around $\lambda \approx 1000$ nm. It can be seen in Figure 4.15 that attenuation changes at 1310 nm can be attributed to either relative humidity changes or temperature changes, whereas the backscatter trace at $\lambda \approx 1000$ nm will not be affected by attenuation changes. The backscatter trace at $\lambda \approx 1000$ nm would show backscatter level change mainly due to the temperature influence. By evaluating both dependencies at the two wavelengths (attenuation change at λ = 1310 nm and backscatter level change at λ = 1000 nm) it would be possible to separate these two effects. Distributed measurement of humidity and temperature differences along the fibre could be conducted. Additional evaluation of optical delay changes along the fibre (measured length change) could further clarify if the measured backscatter changes are either caused by temperature or relative humidity.

4.3.2 Mechanical limitations and strain transfer

The small CYTOP core has a negligible impact on the total mechanical properties of the sensor fibre. The protective jacketing materials basically determine the mechanical properties of the fibre (cross section and material properties see Table 4.1 and Figure 4.1). In order to test the maximum strain limit, the sensor fibre has been elongated up to very high strain values using the step-motor setup while

obtaining the backscatter measurements with the I-OFDR setup every two minutes. The sensor fibre can endure very high strain of more than 100 % when being elongated at moderate strain increase rates. Figure 4.18 shows the measured strain ε_m (position change evaluation of a strong scattering peak 'after' the strained section using I-OFDR) as a function of the applied strain ε_a by the step-motor setup. This 673 mm long fibre section has been strained at a rate of 3 %/h up to 144 % (1638 mm) before rupture of the fibre occurred.



Figure 4.18: Measured strain from length change evaluation as a function of applied strain with linear fit and residuals in % (rupture at 144 %; strain increase rate of 3 %/h; $t_{meas} = 2 \min$, $n_{gr} = 1.3563$, $RH \approx 35$ %, $T \approx 22$ °C).

The residuals of a linear fit exhibit relatively small deviations from a linear characteristic. The positive residuals at 70 % strain and about 140 % strain are caused by temperature deviations of the laboratory environment. The positive and linearly decreasing residuals for low strain values up to about 3 % may be attributed to the different pretensions of the different fibre materials and mechanical settlement before reaching equilibrium and the strain is directly transferred to the fibre core. Care has therefore to be taken when precisely measuring low strain values. This behaviour is fibre-specific and has to be determined before attempting precise length change measurement. Optimization of the fibre materials and the extrusion process as well as annealing the fibre may reduce this deviation. If it is possible for the specific sensing application, it is advisable to install the fibre in pre-strained condition. The transfer of the externally applied strain to the fibre core is commonly described by the strain transfer coefficient C_{ε} and is defined as the relation of measured strain ε_m to applied strain ε_a

$$C_{\varepsilon} = \frac{\varepsilon_m}{\varepsilon_a} \tag{4.3}$$

 C_{ε} is obtained for the full strain range from 0 % to 144 % from the slope of the linear fit and is $C_{\varepsilon} \approx 0.9978$ (for $n_{gr} = 1.3563$). This measurement shows that very high strain values exceeding 100 % can be measured using this sensor fibre. The plastic deformation limit of the sensor fibre is theoretically limited by the maximum elongation of the fibre materials (LDPE: 600 % to 650 %; LLDPE: 500% to 900 % [108]). The maximum elongation of CYTOP is stated with 162 % to 192 % but higher elongation can be expected since the fibre core is an integral part of the fibre. The practical strain limit of the non-integrated or bonded fibre (as it is also the case for this measurement: clamped at two points and strained) is restricted by early necking of fibre sections due to strongly varying diameter changes of the jacketing materials. Higher strain values than 144 % as shown here are possible with the same sensor design if more care is taken to maintain a continuous fibre diameter during the LDPE/LLDPE jacketing extrusion process. The measurement of cyclic strain and mechanical relaxation exhibits a different behaviour. It is shown in section 4.1.1 (Figure 4.5) that fully elastic, cyclic and dynamic strain measurement with this fibre can only be conducted up to about 2 % strain. Higher deformations show viscoelastic and plastic behaviour. Designing a sensor fibre with highly elastic overcladding and jacketing materials would extend the elastic measurement range.

4.3.3 Mode propagation influences and interference

Mode propagation in PF GI POF has been investigated and discussed in chapter 3. Due to the very short coupling length L_c of this fibre type, changes of modal excitation do not lead to significant changes of the fibre's transfer function or pulse shape/delay in transmission (Figure 3.7). Also the comparative backscatter measurement with central coupling versus fully filled mode distribution coupling (using the MC) into the FUT (Figure 3.9) did not lead to significant delay changes. Only a short fibre section in the order of the coupling length L_c would contribute to an insignificant delay change far below the length change resolution (of about 1 mm) of the measurement principle introduced above. Since MM PF POF would only be used for high-strain measurement applications, possible external disturbances causing strong mode coupling or decoupling are likely to have a greater influence on the fibre length itself. Also the backscatter level change due to strain in the fibre is not affected by the modal excitation of the fibre.

Mode propagation effects are expected to be more significant *in long MM silica fibres* due to the very long coupling lengths resulting in stable mode propagation. Possible external perturbations causing coupling or decoupling of mode groups may lead to pulse shape deviations (transfer function distortions) and effective delay changes (Figure 3.6). Care has therefore to be taken when long MM silica fibres are used in a measurement setup. The use of high-bandwidth fibres (OM3 or OM4) is advisable and mechanical impact on long fibres, which may lead to mode coupling/decoupling, is to be avoided if a precise length measurement is intended. SMF however, are not affected by modal dispersion and are more suitable for length change measurement of long fibre sections.

Interference generally does have an impact on the backscatter trace of MM fibres as well as SMF when using laser sources in the setup. Employing a multimode FP laser with a relatively broad emission spectrum of the single lasing modes considerably reduces the interference impact on a backscatter trace compared to relatively narrow linewidth singlemode lasers. Spectral averaging by wavelength tuning during the measurement has been shown to effectively reduce remaining backscatter signal fluctuations (section 2.5.3, Figure 2.34 and Figure 2.35) caused by interference between Rayleigh scattering centres along the fibre. This considerably increases the precision of the length change evaluation using distributed scattering centres as a reference. By carefully choosing the laser source (multimode laser and incoherent operating point) and conducting optimized interference compensation, the impact of interference can efficiently be reduced.

4.4 Comparison to alternative techniques and conclusion

The reasons for the high measurement resolution of the proposed distributed length change evaluation technique in PF POF are the incoherent detection principle, the high signal stability of the I-OFDR approach and the high spatial resolution of the sensor system.

The *photon counting OTDR* technique has initially been used to measure PF POF for distributed detection of strained fibre sections [104] as well as distributed measurement of length change along the fibre [106], [7]. Apart from the increased spatial resolution, the I-OFDR also provides a more stable and reproducible backscatter trace which allows considerably increasing the length change resolution. Using high resolution photon counting OTDR, even long correlation lengths of $l_c = 15$ m resulted in deviations of the length change results up to 10 mm [7], whereas better than 1 mm length change resolution is achieved with correlation lengths of only $l_c = 2$ m using the I-OFDR setup.

The *coherent SWI* (section 1.3), the backscatter measurement technique with the highest spatial resolution and dynamic range, also employs a correlation-based principle to measure strain and temperature, but in the spectral domain. This approach features high strain and temperature resolution at unmatched spatial resolution in SMF. However, this technique cannot be correctly used in MM fibres. Only incoherent detection techniques can be effectively and reliably used for precise distributed backscatter measurement in MM POF.

Distinction and comparison to distributed strain measurement techniques

Various sensor systems for distributed measurement of strain have recently been commercialized (for example Brillouin strain sensors, SWI). All these systems have in common that they actually provide a strain value at positions according to their spatial resolution. This strain value is typically some kind of mean value or predominant value of the strain distribution within the spatial resolution limit of the measurement system. For many monitoring applications, especially for the targeted application as a high-strain sensor, the absolute length change caused by an event (opening of a crack, creeping slope,...) may actually be the more interesting measurement parameter. Continuously distributed strain measurement systems might fail to deliver correct absolute length changes when integrating the measured strain values over the fibre length. This may be especially the case when measuring sensor fibres with strongly varying strain profiles at length scales below the spatial strain resolution of the measurement system. Singular events of spatially confined elongations below the measurement resolution (e.g. due to cracks in a structure) might not be detected or their impact (length change) cannot be correctly derived. This deviation from the correct absolute length change adds up and increases with fibre length. For certain applications, absolute displacement measurement might therefore have an advantage over continuously distributed strain measurement systems and provide the more interesting information.

Conclusion

The combination of the two proposed techniques, the evaluation of backscatter level change with strain and the backscatter-correlation algorithm, allows for precise localization of strained fibre sections with a resolution δz_{eff} of a few centimetres as well as distributed length change measurement along the fibre with a resolution better than 1 mm. The influence of mode propagation has been shown to be negligible on backscatter levels as well as the length measurement in PF GI POF but might have to be considered when longer MM silica fibres are used to interconnect remote PF POF sensors. The impact of relative humidity and water content in the fibre is measured to be largely insignificant for precise length change measurement. The temperature sensitivity of the fibre itself (thermo-optic as well as expansion coefficient) is higher than for silica fibres and has to be considered when intending precise strain measurement. Its impact is $dL/(L \cdot dT) \approx 93 \cdot 10^{-6} \text{ K}^{-1}$ for the sensor fibre and $dL/(L \cdot dT) \approx 22 \cdot 10^{-6}$ K⁻¹ for the fibre (GigaPOF 50SR) without jacketing materials. The measured delay on temperature may be less evident when the fibre is integrated into a structure due to the negative thermo-optic coefficient of CYTOP. Another issue that has to be considered is the increase of attenuation (up to 30 dB/km) for high relative humidity at elevated temperatures T > 50 °C. Shifting the source wavelength from 1310 nm towards lower wavelengths would avoid this sensor lengthreducing effect.

5 Dynamic length and power change measurement using I-OFDR

The aim of a dynamic measurement is to determine a measurement parameter with a time-dependent value. This generally requires a measurement system that has a higher measurement repetition rate (or measurement repetition frequency f_{meas} , given in Hz) than the rate of the changing measurement parameter. The measurement technique introduced in this chapter allows for measuring fibre parameters with a measurement repetition rate up to $f_{meas} = 2 \text{ kHz}$.

Recent years showed an increasing demand and market for the monitoring of the dynamic behaviour of structures and components. Instant damage detection, modal analysis, creep or load cycle information are important for the evaluation of the integrity of a structure and can only be obtained using high-resolution dynamic measurement techniques. Fields of application can be found in civil infrastructure (bridges, buildings, railway dams, power lines and power distribution infrastructures,...), transportation (avionics, naval,...) or structural components such as wind turbine towers and blades. Fibre optic sensors may be advantageous in comparison with traditional sensing principles. For certain applications total length change of a structure or its total deformation is required. Embedded or surface-bonded length change sensors with arbitrary gauge length would be most beneficial for these applications. A solution for these applications based on I-OFDR is proposed in this chapter: dynamic and precise measurement of length changes of arbitrary gauge length as well as reflected power changes, or indirectly: optical loss. The most established fibre optic solution, the FBG [10], is basically limited in gauge length by the typical grating length of a few millimetres to centimetres. The gauge length of FBGs is basically limited to the grating length of typically a few centimetres. Efficient extension of the gauge length of FBGs is not that simple but packaging solutions have been proposed to extend the gauge length to decimetres or metres. Another established interferometric fibre optic technique for precise static and dynamic length change measurement and gauge lengths up to several meters is based on infibre Michelson interferometry [113]. Both systems provide precise and dynamic strain measurement but have limited applicability for certain applications, especially when very long-gauge measurement is required. Recently presented total length change sensors based on phase measurement techniques [114] provide dynamic and precise length change results of the whole fibre. These sensors simply measure the phase at a single frequency. Long-gauge measurements can be conducted with this sensor type but only one fibre per channel can be measured and only the entire fibre, not a single section of the fibre, can be monitored.

In this chapter, a dynamic approach for quasi-distributed measurement of length changes and optical power changes at multiple reflective events along the FUT is introduced. The possibility of the I-OFDR setup to measure phase and amplitude to a sinusoidal excitation for different frequencies allows extracting additional information without the necessity to perform an IFFT of the full frequency scan. High measurement repetition rates can therefore be achieved by calculating reflection position and reflected power changes from only a few frequency points of the full FUT frequency response. This technique allows for measuring multiple sensor sections of arbitrary gauge length (from centimetres to kilometres) using a single measurement channel.

A similar, simpler technique [115], using phase-sensitive detection has been proposed to evaluate the transmitted power of multiplexed optical fibre point sensors. The different sensor points are divided by directional couplers and the system is probed by a source that is sinusoidal power modulated at different frequencies. The transmitted signal is analyzed with a phase sensitive detector. The optical path length of each sensor path, and thus the relative phase to a reference for each sensor path and frequency has to be determined before the measurement. The phase information of the transmitted signals compared with the reference modulation at each frequency can then be used to solve a matrix to obtain the transmitted power of each point sensor path.

The technique proposed here allows for self-calibrated measurements of both, power changes and length changes in reflection. In section 5.1, the requirements on a sensor fibre and its design, the

insertion of reflective reference points, are explained. Section 5.2 introduces the measurement principle in detail. Section 5.3 deals with systematic limitations, possible systematic sources of error and their impact. A phase step compensation algorithm is introduced to ensure absolute and correct position measurement and a technique to recognise measurement failures is proposed and demonstrated. The capabilities of the proposed measurement technique are demonstrated in section 5.4 by means of laboratory tests measuring length changes and optical power changes. Also the practical applicability is demonstrated by reference to a field test with sensor fibres installed on a masonry building during a seismic shaking test.

5.1 Sensor fibre

The basic idea of the measurement principle is to calculate phase changes (respectively length changes) and optical power changes of the FUT from a small part of the full complex frequency domain response $H(f_m)$. The motivation is to increase the measurement repetition rate. The most straightforward sensor architecture would be in transmission using optical couplers to split the signal into multiple paths of different length and recombine them for detection at the photodiode. This results in very high signal levels and prevents multiple reflections between reflection points ('ghost reflections', see section 5.3.2) that might corrupt the sensor signal. A more applicable and flexible approach for actual sensing applications is the backscatter approach: strong reflections or scattering points are inserted along the FUT and can be used as references for phase and magnitude evaluation. Such reference points for length change and optical power change can be inserted into the FUT by different means. The easiest way to achieve high signals in reflection is to use strongly reflecting physical contact (PC) connectors (0° angle) at locations of interest. Such a sensor network can further be multiplexed using optical couplers as shown exemplarily in Figure 5.1.



Figure 5.1: Schematic of an implementation example of a quasi-distributed sensor network with multiple reflectors.

Using PC connectors as reflection points ensures relatively strong signals but also introduces mechanical discontinuities into the sensor fibre. Most measurements presented in this chapter are conducted with strongly reflecting PC connectors. Straining a PC connection may lead to opening of the connection or changes of the reflectivity of the connector. Special packaging of the reflecting connectors between the sensor sections might be necessary to ensure strain-relieved installation of the connectors. That might be impractical if a small form factor of the sensor fibre is important. Bulky fibre connectors cannot be used as reference reflectors for such applications. Sensor integration, for example into composite structures, often requires very small sensor fibre diameters. Maintaining the smallest possible diameter can only be achieved by intrinsic structuring of the fibre core, as it is done by 'inscribing' or 'writing' FBGs into a fibre.

5.1.1 Inscription of scattering centres using femtosecond laser pulses

Limitations due to sensor dimensions and mechanical restrictions can be avoided by inducing scattering damage in the core of the optical fibre. This way mechanical continuity along the fibre can be maintained and full use of the small form factor of the fibre for sensor integration can be exploited. In order to induce substantial scattering damage in the core of a standard SMF, focused femtosecond laser pulses at high pulse energies are applied. Point-to-point inscription of refractive index variations using ultrashort laser pulses has been conducted to write FBGs into SM silica fibres [116], [117]. The motivation in this thesis was to use focused femtosecond laser pulses at elevated pulse energies to
inscribe not only refractive index changes but substantial scattering damage into the fibre core which can be used as a reference point for the static and dynamic evaluation of distance changes or power changes. The physics of interaction of ultrashort laser pulses with high-bandgap materials such as silica and polymers has widely been investigated and strongly depends on the laser pulse duration, pulse energy and focusing of the laser beam. Depending on the material and pulse energy, the induced thermal energy may result in chemical modification, refractive index change, void formation or scattering damage. These processes are initiated by nonlinear absorption including multiphoton ionization and avalanche ionization [118]. Focused fs pulses allow for very precise material modification of a minimally effected zone due to nonlinear absorption, the short excitation compared to the electron-phonon-relaxation time and the minimized heat diffusion into surrounding material [119]. Extensive experiments on the inscription of scattering damage for quasi-distributed measurement of fibre curvature and temperature in PMMA POF using backscatter measurement techniques have been conducted [120],[8]. These results however, are not a topic of this thesis. The same technique and setup is used for the inscription of scattering points into PF POF with the purpose of creating backscatter variations to improve the resolution of the cross correlation length change measurement results introduced in section 4.2. Conceptual results are shown in section 4.2. Further technological explanations and experiments in PMMA POF have been published in [8].

All inscription experiments of scattering points have been conducted at the Heinrich Hertz Institute (HHI) located in Goslar using a femtosecond laser regenerative Spitfire system (Spectra-Physics). The amplifier emits pulses with 120 fs pulse duration at a centre wavelength of 800 nm and a tunable repetition rate up to 5 kHz. The laser beam has been focused into the fibre core by using a 32x objective with a NA of 0.6. The positioning of the fibre with respect to the focused laser beam is controlled by a 3-axis translation stage while monitoring the position of the fibre with a CMOS camera. This setup, shown in Figure 5.2, is otherwise used to write refractive index changes and FBGs into SMF at pulse energies below the structural modification threshold, usually below 0.3 μ J.



Figure 5.2: Setup for inscription of scattering points into the fibre core using focused fs laser pulses, from [8].

Using focused fs laser pulse irradiation well above the mechanical damage threshold has been conducted to inscribe strongly scattering 'micro voids' into the core of SMF and MM POF respectively. Figure 5.3 shows an I-OFDR backscatter plot of 4 single inscribed scattering points (at 5 μ J pulse energy) separated by 3 m distance each.



Figure 5.3: I-OFDR backscatter plot of 4 scattering points in SMF 28 fibre; $t_{meas} = 50 \text{ min}$, $\Delta f = 1 \text{ MHz}$, $f_{m,max} = 2 \text{ GHz}$, $f_{zp} = 20$, $\alpha_K = 3$.

A measurement example using the dynamic evaluation technique on the inscribed scattering points, shown in Figure 5.3, will be demonstrated in section 5.4.2. Another sensor fibre with 12 scattering points has been produced with the same setup and was used to quantify reflection position resolution and power resolution in section 2.4.1 (Figure 2.11).

The investigations on the inscription of scattering damage have only been conceptual but are a promising approach to efficiently produce intrinsic reference reflectors for static or dynamic quasidistributed measurement. Further experiments have to be conducted to optimize inscription parameters and increase the backscattered powers.

5.2 Measurement principle

5.2.1 Method and algorithm

The result of an I-OFDR measurement is the complex-valued frequency response of the FUT. Each measured frequency point (phase and absolute value) contains information of the whole FUT corresponding to the sum of the single frequency responses of all reflective events in the fibre as well as distributed backscattered power and noise power. The aim is to calculate position changes (from phase changes) and reflected power changes (from absolute value changes) of each reflection point in the FUT from a few values of $H(f_m)$. Reflective events or scattering originating from a singular point in the fibre ideally have, after calibration, a flat frequency response with a constant absolute value over the whole measured frequency range but exhibit periodically varying phase with a periodicity as a function of distance of the reflection. The detected phases $\varphi_r(f_m)$ are dependent on the modulation frequency f_m and the positions z_r of the single reflections:

$$\varphi_r(f_m) = 4\pi \cdot f_m \cdot z_r \cdot \frac{n_{gr}}{c_0}$$
(5.1)

The absolute value of the frequency response of a single reflection is a function of the reflected power. The idea of the proposed technique is that new positions and reflected powers of each reflection can always and uniquely be calculated from a few measured $H(f_m)$ values by relating the phase and absolute value dependencies of the single reflections for different measurement frequencies f_m . The initial position and reflected power of the reflectors must be exactly known and the number of measured frequency points must be at least the number of reflections in the fibre. In the following, this technique is explained for a simple example of two reflections points. The same measurement setup and configuration as introduced in chapter 2 (Figure 2.8) for general backscatter measurement is used. Only the software is adapted to conduct the dynamic evaluation. Figure 5.4 shows the schematic I-OFDR setup connected to the FUT with two strong reflections at the positions z_1 and z_2 originating from 0°-angle PC connectors. The reflection at the fibre end is reduced using an angle-polished connector (APC).



Figure 5.4: Schematic of the FUT with two reflections at the positions z_1 and z_2 .

The first step is to measure the full calibrated complex frequency domain response $H(f_m)$ of the FUT. Thereafter, the initial phase and magnitude values for each reflection $H_r(f_m)$ (position z_r and magnitude $P_r \propto$ detected power I_r) is determined as described in section 2.3.2 using equation (2.58). The calculated frequency domain components $H_r(f_m)$ of the two reflections are shown in Figure 5.5.



Figure 5.5: Calculated frequency domain data for the two reflections: $H_{r=1}(f_m)$ (left) and $H_{r=2}(f_m)$ (right).

The absolute values $|H_r(f_m)|$ are constant over the whole frequency range. The frequency domain response of the fibre without any reflection $H_0(f_m)$ is then calculated by subtracting the single reflection components $H_r(f_m)$ from $H(f_m)$. It is assumed that the reflectivities $R_r \ll 1$ so that the detected multiple reflections from the FUT ('ghost' reflections) can be neglected in the following calculations. Ideal values of the reflectivities R_r are discussed in section 5.3.2. The general description for *n* reflections is

$$H_0(f_m) = H(f_m) - \sum_{r=1}^n H_r(f_m)$$
(5.2)

The $H_0(f_m)$ component is very small compared to the strong reflections. In the case of very strong reflections the dynamic range of the measurement system is too small to resolve the Rayleigh backscattering of the fibre. In this case $H_0(f_m)$ represents the noise floor of the frequency response measurement. In the case of weaker reflections, $H_0(f_m)$ is composed of noise and the low-frequency Rayleigh backscattering component and other imperfections of the FUT. These components remain more or less constant when the fibre is strained but might limit the measurement precision when considerably exceeding the noise level and contributing to phase or power changes of $H(f_m)$.

Now $H_r(f_m)$, their absolute values $|H_r(f_m)|$ and their phase values $\varphi_r(f_m) r \in \{1, ..., n\}$ of all n reflections and each measurement frequency f_m as well as $H_0(f_m)$ are known and will be used for further calculations. In theory, new measurements of points of the frequency response of the FUT $M(f_k)$ at arbitrary frequencies f_k with $k \in \{1, ..., n\}$ and $(f_k \subseteq f_m)$ correspond to the sum of all reflection components $H_r(f_k)$ and $H_0(f_k)$:

$$M(f_k) = H_0(f_k) + \sum_{r=1}^n H_r(f_k)$$
(5.3)

Possible location changes (delay changes) of the reflectors or optical power changes at the reflection points cause changes in phase and absolute value of $H_r(f_k) = |H_r(f_k)|e^{-j\varphi_{rk}}$. For any of the *n* reflections, a possible position change Δz_r relative to the reference measurement would result in phase

changes $\Delta \varphi_{rk}$ at the modulation frequency f_k using equation (5.1), whereas detected power changes ΔP_r would result in an absolute value changes $\Delta |H_r(f_k)|$ ($\Delta I_r \propto \Delta P_r \propto \Delta |H_r(f_k)|$). $\Delta \varphi_{rk}$ and $\Delta |H_r(f_k)|$ are the parameters that have to be determined to calculate relative position changes Δz_r and power changes ΔP_r for each reflection.

Using the complex frequency response values of the reflections $H_r(f_m)$ derived from the time domain data and equation (2.58), one can define a complex-valued system of equations in the frequency-domain with n lines and n columns to calculate the particular phase φ_{rk} and absolute value $|H_r(f_k)|$ for each reflection and frequency f_k .

Only *n* frequency domain measurement points $M(f_{k=1...n})$ at the frequencies f_k are necessary to determine the phase and amplitude of all *n* reflections. The system of equations for the example of two reflections measured at arbitrary frequencies $f_{k=1}$ and $f_{k=2}$ ($f_{k=2} > f_{k=1}$) is retrieved from equation (5.3)

$$I \quad M(f_{k=1}) - H_0(f_{k=1}) = |H_1(f_{k=1})| \cdot e^{j(\varphi_{11})} + |H_2(f_{k=1})| \cdot e^{j(\varphi_{21})}$$

$$II \quad M(f_{k=2}) - H_0(f_{k=2}) = |H_1(f_{k=2})| \cdot e^{j(\varphi_{12})} + |H_2(f_{k=2})| \cdot e^{j(\varphi_{22})}$$
(5.4)

The phases and amplitudes of the single reflection components $H_r(f_k)$ of the FUT are the targeted solutions of the system of equations. The previously calculated component without any reflection $H_0(f_k)$ is ideally very small compared to $H_r(f_k)$ and does not experience significant change. The phase values φ_{rk} for each reflection are a function of the measurement frequency f_k and the positions of the single reflections z_r . To be able to solve the system of equations, all φ_{rk} have to be related to the phase values $\varphi_{rk=1}$ for a certain reference frequency (for example $f_{k=1}$). This is done by introducing a phase difference value Δ_{rk} . The phases of the reference frequency (here $f_{k=1}$) are hereafter named φ_r and the resulting phases φ_{rk} for the other frequencies f_k are calculated relative to the corresponding reference frequency using the phase difference value Δ_{rk} :

$$\varphi_{rk} = \varphi_r - \Delta_{rk} \tag{5.5}$$

Each Δ_{rk} is the calculated relative phase difference between the measurements at the frequency $f_{k=1}$ (the reference frequency) and the frequency f_k for the specific reflection position z_r and the frequency difference $\Delta f_k = f_k - f_{k=1}$:

$$\Delta_{rk} = 4\pi \cdot \Delta f_k \cdot z_r \cdot \frac{n_{gr}}{c_0}$$
(5.6)

The accuracy of the measurement can be further increased by using an over-determined system of equation with d (d > n) measured frequency points $M(f_k)$ $k \in \{1, ..., d\}$. The system of equations for the general case with n reflections in the fibre and d measured frequency points is

$$\begin{array}{lll} M(f_{k=1}) - H_0(f_{k=1}) &= X_{r=1} \cdot |H_{r=1}(f_{k=1})| \cdot e^{j(\varphi_1)} &+ \cdots + X_{r=n} \cdot |H_{r=n}(f_{k=1})| \cdot e^{j(\varphi_r)} \\ &\vdots &+ \ddots + &\vdots \\ M(f_{k=d}) - H_0(f_{k=d}) &= X_{r=1} \cdot |H_{r=1}(f_{k=d})| \cdot e^{j(\varphi_1 - \Delta_{rk})} &+ \cdots + X_{r=n} \cdot |H_{r=n}(f_{k=d})| \cdot e^{j(\varphi_r - \Delta_{rk})} \end{array}$$

This system of equations with the coefficient $X_r = 1$ describes the initial state of the systems as during the measurement of $H(f_m)$. New measurement results $M(f_k)$ of the FUT with changed reflection powers and reflection positions will result in changes of the phase and absolute values of the respective equation elements. These relative changes in phase and absolute value can be evaluated by solving the system of equations for X_r . Since the new measurement values $M(f_k)$ comprise all reflection components and the phase relations are defined by Δ_{rk} , the solutions of the system of equations X_r contain all phase and absolute value information of each reflection at the time of a new measurement.

(5.7)

The relative phase changes $\Delta \varphi_r$ for each reflection are calculated from the complex-valued results X_r of the new measurement relative to the initial value $X_r = 1$ using MATLAB[®] 'atan2' function which is defined from $-\pi$ to $+\pi$. The resulting phase changes $\Delta \varphi_r$ can be evaluated as a delay changes or position change Δz_r for each reflection:

$$\Delta z_r = \frac{\Delta \varphi_r}{4\pi \cdot f_{k=1}} \cdot \frac{c_0}{n_{gr}}$$
(5.8)

Since the initial position z_r is used as a starting value to calculate $\Delta_{rk} = f(z_r)$, a change of z_r introduces a small deviation from the correct Δ_{rk} when solving (5.7). The resulting error of Δz_r , however, can be eliminated by conducting a few iteration steps using a new $z_{r(new)} = z_r + \Delta z_r$ as a starting value to solve equation (5.7).

In case of a change of the detected optical powers ΔI_r , the absolute value results $|X_r|$ are not unit vectors $(|X_r| \neq 1)$ but differing from $|X_r| = 1$ proportionally to the changes of the detected powers $\Delta P_r \propto \Delta I_r$. The logarithmic relative power changes ΔP_r for each reflection can be calculated using

$$\Delta P_r = 10 \cdot \log_{10}(|X_r|) \quad [dB] \tag{5.9}$$

These changes of optical power relative to the reference measurement can be evaluated as a function of any optical power-modulating measurement parameter. Any of previously proposed measurement principles based on optical loss, absorption or light decoupling can be measured by evaluating the change of reflected power. This possibility to measure phase and reflected optical power simultaneously and independently for each single reflection provides a multitude of possible sensing applications. Since the VNA has a relatively constant phase resolution over the whole sweep range, the highest absolute resolution of both, phase and magnitude, is achieved by measuring frequencies f_k closer to $f_{m,max}$ for the evaluation.

The possibility to calculate phase changes (position changes) and absolute value changes (power changes) at n reflection points from only n frequency measurement points allows for high measurement repetition rates and therefore the measurement of dynamic parameters. Since the technique is based on an incoherent detection technique, also MM fibres can be measured the same way as SMF. Therefore, also the mechanical advantages of POF for high-strain sensing applications can be utilized. Measurement results demonstrating the capabilities of this approach in both fibre types are presented in section 5.4.

5.2.2 Phase step compensation

As for any direct phase measurement technique, coherent detection or based on power modulation of an optical carrier [114], the length change solution is only unique and correct for a limited phase range of $\pm \pi/2$ or $\pm \pi$. Simple phase evaluation cannot uniquely determine absolute (or relative) distance changes. Also with the technique proposed here, possible position (phase) changes equivalent to $|\Delta \varphi_r| > \pi$ would result in a phase failure corresponding to multiples of $\pm 2\pi$ and an additional deviation resulting from incorrect phase relations Δ_{rk} . Since the measurement is conducted at various frequencies, a compensation algorithm, that can recognize and compensate possible phase steps, can be easily implemented into the dynamic evaluation algorithm. Phase steps occur when distance change ranges Δz_{max} equivalent to $\Delta z_r(|\Delta \varphi_r| = \pi)$

$$\Delta z_{max} = \frac{(|\Delta \varphi_r| = \pi)}{4\pi \cdot f_{k=1}} \cdot \frac{c_0}{n_{gr}}$$
(5.10)

around the reference frequency $f_{k=1}$ are exceeded.

This can be compensated for by calculating a second solution of a system of equations with the same input. The same measurement results $M(f_k)$ serve as input, but the system is solved for a different

frequency $f_{k,g} \neq f_{k=1}$ as the basis for defining Δ_{rk} . That delivers phase change results $\Delta \varphi_{r,g}$ (for $f_{k,g}$) differing from the solution $\Delta \varphi_{r,1}$ calculated for $f_{k=1}$. Different measurement frequencies result in different phases depending on the position change of the reflections. This phase difference between a solution for a higher frequency and a solution for a lower frequency can be used to detect and compensate for possible phase steps. In order to demonstrate this technique, a dynamic measurement during considerable delay changes exceeding the equivalent of Δz_{max} has been conducted by heating a 3 km long SMF section (delay change due to thermal expansion and thermo-optic refractive index change). The phase changes $\Delta \varphi_{r,g}$ and $\Delta \varphi_{r,1}$ are calculated from the same measurement results $M(f_k)$ and undergo several phase steps during the measurement. The resulting distance changes Δz_r for both solutions, calculated using equation (5.8), are identical but the phase difference between the high frequency solution and the low frequency solution $\Delta \varphi_{r,tot} = \Delta \varphi_{r,g} - \Delta \varphi_{r,1}$ is a function of position change (or delay change respectively) and the frequency difference $(f_{k,g} - f_{k=1})$ used for solving the systems of equations:

$$\Delta \varphi_{r,tot} = \Delta \varphi_{r,g} - \Delta \varphi_{r,1} = \Delta z_r \cdot 4\pi \cdot \frac{n_{gr}}{c_0} \cdot \left(f_{k,g} - f_{k=1} \right)$$
(5.11)

For the solution based on $f_{k=1} = 1.96$ GHz, a phase step corresponding to Δz_{max} occurs at $\Delta \varphi_{max}$

$$\Delta \varphi_{max} = \Delta \varphi_{r,tot}(\Delta z_{max}) = (\pm \pi) \cdot \frac{f_{k,g} - f_{k=1}}{f_{k=1}}$$
(5.12)

with a periodicity of $2\Delta\varphi_{max}$. The results of this phase difference $\Delta\varphi_{r,tot}$ are shown in Figure 5.6. As indicated, $2\Delta\varphi_{max}$ corresponds to about 1.29° for this measurement example ($f_{k=1} = 1.96$ GHz and $f_{k,g} = 1.9642$ GHz). Simple subtraction of the calculated phases ($\Delta\varphi_{r,g} - \Delta\varphi_{r,1}$ ranging from $-\pi$ to $+\pi$) might lead to opposite signs due to a 'delayed' phase step for the solution based on $f_{k,g}$. This can be compensated by implementing some simple logic operators for the evaluation of the measured phase differences $\Delta\varphi_{r,tot}$.



Figure 5.6: Measured relative phase change difference $\Delta \varphi_{r,tot}$ with indications for phase steps of $\Delta \varphi_{max}$; $f_{k=1} = 1.96$ GHz, $f_{k,g} = 1.9642$ GHz, $\Delta f = 1.4$ MHz, d = 6, averaged three times, $f_{meas} \approx 24$ Hz.

The absolute position change for each reflection can always and uniquely be determined from $\Delta \varphi_r$ and $\Delta \varphi_{r,tot}$. This algorithm works efficiently in real time measurement applications. Its implementation is demonstrated in and shows the not compensated length change measurement result (solution of a single system of equations) and the phase step compensated solution using the proposed technique.



Figure 5.7: Length change results: phase step compensated solution and not compensated result; $f_{k=1} = 1.96 \text{ GHz}$, $f_{k,g} = 1.9642 \text{ GHz}$, $\Delta f = 1.4 \text{ MHz}$, d = 6, averaged three times, $f_{meas} \approx 24 \text{ Hz}$.

The measurement algorithm is implemented into the iteration algorithm to also compensate for the correct phase changes without reducing the measurement speed of the system. Using this technique, the allowed measurement range can be extended exceeding Δz_{max} . A frequency difference of, for example $f_{k,g} - f_{k=1} = 1$ MHz, allows for calculating unique solutions ($|\Delta \varphi_{r,tot}| < \pi$) for each reflection equivalent to position changes of $\Delta z \approx \pm 51$ m in SMF. If necessary, this limit can be easily increased by choosing smaller frequency differences for the compensation calculation. Practically unlimited extension of the measurement range can be achieved by solving the system of equations for a third frequency and additionally relating its phase change solutions. The phase step compensated solution is therefore always unique and correct and may be used for absolute length measurement.

5.3 Systematic sources of error

In this section, the possible and evident impact of internal and external disturbances and systematic sources of error on the dynamic measurement technique are discussed. Basically, every deviation from the assumptions made for the dynamic evaluation technique may result in a measurement error. Causes may be deviations from the linearity of the system itself (section 5.3.1). This may be due to rapid changes and a resulting 'distortion' of the reflection frequency response during data acquisition (sequential measurement of $M(f_k)$). Another reason for a deviation from the system linearity is due to interference between reflected electric fields. Other sources of error may be ghost reflections owing from multiple reflections in the fibre (section 5.3.2), significant and not compensated changes of the FUT caused by appearing reflections (section 5.3.3) or reflection frequency response distortions due to dispersion in the fibre (section 5.3.4). Techniques for measurement fault recognition as well as for dispersion compensation are proposed and demonstrated.

5.3.1 System linearity

The fundamental requirement for mathematically correct frequency domain reflectometry in general and for the proposed measurement principle in particular is the *linearity and time-invariance of the measurement system*. This implies linearity and stability of the measurement system transfer function over the measured frequency range but also a stable transfer function of the measurement system during the sweep time. As demonstrated in chapter 2, the frequency domain measurement approach generates far more reproducible and accurate measurement results than using pulse reflectometry due to the precise generation and control of each spectral component of the 'pulse' and narrow bandwidth filtering of the detected signal. However, changes of the measurement system or FUT result in a distortion of the system transfer function and affect the solution of the system of equations. The laser source, the temperature and current controller, EOM and signal generation by the VNA are very stable. It has been shown in section 2.3.1 that the changes of the system transfer function are small when the magnitude of optical input power is changed by orders of magnitude. The measurement results that will be presented in section 5.4.1 can be understood as a proof that the system linearity is not affected by moderate optical power changes.

Interference has been identified as a cause of nonlinearity in section 2.2.4. Phase changes of the optical carrier between reflections located too close to another can cause interferometric power changes superimposed on the measurement result. The coherence and interference issue for different light sources and compensation techniques for static measurement have been discussed in section 2.5.1. The possibility of spectral averaging by tuning the wavelength of the source and averaging the measurement result for various phase relations works well for static measurements but is not an option if dynamic measurement at high repetition rates is intended. The only way to prevent interference influence is to ensure a path length differences between single reflections in the FUT clearly exceeding the coherence length of the source. It has to be noted that measurable interference also occurs at path length differences exceeding the definition of the coherence length in the fibre, equation (2.47). For precise optical power change measurement with the described setup using the FP source, the distance between single reflections in the fibre should be at least 1 m in reflection to completely rule out interference influences.

Another potential source of error are temporal changes of the FUT or the system transfer function due to the sequential measurement of $M(f_k)$. Generally, substantial changes of the FUT at a time scale smaller than the measurement time $(1/f_{meas})$ can result in a 'distortion' of the measured frequency response and a deviation from ideal system linearity. Moderate changes of phase and detected power or gradual changes thereof do not lead to a measurable error. However, abrupt changes of the phase or optical power of considerable magnitude during the acquisition of $M(f_k)$ may have an impact on the measurement result. Causes may for example be *abrupt mechanical impact* and associated length or power change. This impact cannot be generally or reasonably quantified since it depends on too many parameters (z_r , P_r , f_k , d, n, Δz_r , ΔP_r) in an overdetermined system of equations. However, the occurrence of a measurement error due to such rapid temporal changes or distortion of the transfer function can be identified by using the fault recognition algorithm that will be introduced in section 5.3.3.

5.3.2 Multiple reflections

As it is the case for any other backscatter measurement system, multiple reflections between the single reflectors in the sensor fibre lead to 'ghost reflections'. These 'ghosts' originate from optical power that is detected by the PD after being reflected multiple times between strong reflections in the fibre. 'Ghosts' would be visible at multiples of the distance between two reflections in the fibre. If these ghost reflection components are significantly above the noise level, they would contribute with their phase and absolute value to the frequency response and the measurement results $M(f_k)$ leading to deviations when evaluating the length and power measurement. In the following, recommendations for choosing optimal reflectivities are given to minimize the impact of the 'ghost reflections' on the measurement result. Assuming equal reflectivities R and no optical loss between the single reflectors (equation (2.34)), the logarithmic optical power relation ΔP_g between a single detected reflection peak (reflected once: $I_r \propto I_0 \cdot R \cdot R \cdot R$) is given by

$$\Delta P_g = 10 \cdot \log_{10} \left(\frac{I_0 \cdot R}{I_0 \cdot R \cdot R \cdot R} \right) = 10 \cdot \log_{10} \left(\frac{1}{R^2} \right) \qquad [dB]$$
(5.13)

The dependency of the direct reflection power relative to the ghost power is calculated in Figure 5.8 as a function of the reflectivity using equation (5.13).



Figure 5.8: Simulation: directly reflected power relative to ghost power ΔP_g as a function of the reflectivity R.

As a guideline to optimize the reflectivity for sensing purposes, R should not exceed about 0.01. This value ensures a high reflection signal but the ghost reflection components are 40 dB below the reflection itself. This power difference corresponds to the total dynamic range $2D \approx 40$ dB of the I-OFDR system (Figure 2.16). The ghost power is then below the noise level and its impact on the measurement results can therefore be neglected. However, care has to be taken to not exceed the linear power range of the PD. If higher reflection powers are required, the ghost reflections could be incorporated into the calculations by calculating their phase and amplitude values from the changes of the directly reflected values and iteratively solving the system of equations with the information of the ghost reflections. Using this technique is not necessary for the measurements conducted in this thesis and is therefore not elaborated in detail. In order to completely avoid ghost reflections, the single sensor sections may also be measured in transmission or in reflection using optical couplers to divide (and recombine) the measurement signal paths.

5.3.3 Changes of the FUT and fibre breaks

The dynamic measurement approach is based on the knowledge of the number and precise initial positions of the single reflectors in the FUT when constructing the system of equations (5.7) used for calculation of X_{r} . Changes of the reflection position and the reflected power can always be tracked and calculated. However, the occurrence of an additional reflection somewhere in the fibre (for example caused by a fibre break or the degradation of a previously 'invisible' optical connector) would result in a significant phase and amplitude offset of $M(f_k)$ for each frequency. The assumptions made for solving the system of equations and tracking the positions and powers of the reflectors do not hold true in this case. The calculated powers and positions of all reflections would suddenly shift to false values by an unpredictable offset. Such false results due to changes in the FUT could be mistaken for correct measurement results and cannot be recognized as false results without conducting a full backscatter trace measurement of the FUT. As previously mentioned, another cause of measurement failure may be rapid and significant phase change or power change during the measurement of $M(f_k)$. However, only significant phase and intensity changes at timescales shorter than the measurement time $1/f_{meas}$ may seriously distort the transfer function and impact the measurement. Quantifying this impact is neither trivial nor useful since it depends on multiple factors and values when solving the complex system of equations (5.7) and cannot be used to inversely calculate correct results.

A reliable approach to detect measurement failures due to such 'distorted' results of $M(f_k)$ due to the appearance of an additional reflection or due to rapid significant changes of the FUT itself is therefore proposed in the following.

Fault recognition algorithm

A straightforward approach to identify false measurement results and significant changes of the FUT that deviate from the assumptions made for the dynamic reflection evaluation can be implemented into the measurement algorithm. This is achieved by separately solving systems of equations with measurement results of different frequencies as input. Typically, an overdetermined system of

equations with d > n frequency results $M(f_k)$, as described in equation (5.7), is solved to increase the measurement resolution. If all assumptions made for the construction of the system of equations (number and positions of reflections) are correct, separate solutions of two systems of equations with different frequency inputs (for example $M(f_{k=1...5})$ and $M(f_{k=6...10})$) from the same sweep result $M(f_{k=1...10})$ would deliver similar results for length change and power change:

$M(f_{k=1\dots 10})$	\rightarrow	$\Delta z_r; \Delta P_r$
$M(f_{k=1\dots 5})$	\rightarrow	$\Delta z_{r;low}$; $\Delta P_{r;low}$ (for lower frequency inputs)
$M(f_{k=6\dots 10})$	\rightarrow	$\Delta z_{r;high}; \Delta P_{r;high}$ (for higher frequency inputs)

with $\Delta z_r \approx \Delta z_{r;low} \approx \Delta z_{r;high}$ and $\Delta P_r \approx \Delta P_{r;low} \approx \Delta P_{r;high}$.

If a significant reflection component appears during the dynamic measurement or the transfer function is 'distorted' by rapid changes during the sweep, the assumptions made are not correct any longer. The solutions of two separate systems of equations with different frequency results as input $(\Delta z_{r;low}; \Delta P_{r;low} \text{ and } \Delta z_{r;high}; \Delta P_{r;high})$ would give significantly deviating results $(|\Delta z_{r;high} - \Delta z_{r;high})$ $\Delta z_{r;low} \gg 0$ and $|\Delta P_{r;high} - \Delta P_{r;low}| \gg 0$). By monitoring these mutual deviations of the partial frequency solutions against a certain error margin, such an event can be immediately recognized. A demonstration measurement with the setup depicted in Figure 5.9 (left) is conducted. The FUT consists of a 1x4 optical coupler with 2 Fresnel reflections (R1 and R2) originating from two open fibre ends. A third Fresnel reflection (R3) is suppressed by a variable optical attenuator (VOA) in line with R3 at the fibre end. Figure 5.9 (right) shows the corresponding I-OFDR backscatter trace of the FUT with two strong reflections R1 and R2 used for the dynamic evaluation and a second trace of the FUT with the fault reflection R3 at 18.6 m induced during the dynamic evaluation. The initial backscatter measurement of $H(f_m)$ is conducted for the case of two reflections only. The system of equations is constructed for measuring phase and magnitude of these two reflections. An additional fault reflection is then induced during the continuous dynamic evaluation by reducing the attenuation of the VOA in line with the third Fresnel reflection (R3).



Figure 5.9: Setup used to induce a fault reflection during the measurement (left) and I-OFDR plots of the initial backscatter trace used for defining the system of equations and the corrupted backscatter trace by an additional reflection introduced during dynamic evaluation (right); $t_{meas} = 5 \text{ min}$, $\Delta f = 1 \text{ MHz}$, $f_{m,max} = 2 \text{ GHz}$, $f_{zp} = 20$, $\alpha_K = 3$.

The appearance and presence of the third reflection peak R3 (\approx 8 dB below R1) causes significant changes of considerably deviating magnitude for the partial solutions $\Delta z_{r;low}$, $\Delta z_{r;high}$ as well as $\Delta P_{r;low}$ and $\Delta P_{r;high}$. Figure 5.10 shows all measured dynamic length change results Δz_r and power change results ΔP_r and the deviations of the partial solutions ($\Delta z_{r;high} - \Delta z_{r;low}$ and $\Delta P_{r;high} - \Delta P_{r;high}$) for the correct assumptions of two reflections (t = 0...16 s and t > 24 s) and the the presence of the not considered reflection R3 during t = 16 s...24 s.



Figure 5.10: Dynamic measurement results of all length changes (left) and all power changes (right) for correct assumptions of two reflections (t = 0...16 s and t > 24 s) and false results during presence of a third reflection (t = 16 s...24 s); d = 10, $f_{k=1} = 1.848$ GHz, $f_{k=6} = 1.853$ GHz, $f_{meas} = 20$ Hz.

Externally induced position changes Δz_1 and power changes ΔP_1 at the first reflector by straining the fibre before R1 by hand are correctly calculated for t = 0...16 s and t > 24 s. The results $\Delta z_{r;low}$, $\Delta z_{r;high}$ as well as $\Delta P_{r;low}$ and $\Delta P_{r;high}$ are of similar magnitude and their differential magnitudes $(\Delta z_{r;high} - \Delta z_{r;low} \text{ and } \Delta P_{r;high} - \Delta P_{r;low})$ are approximately zero. During the simulated fibre break (induced 'fault reflection' during t = 16 s...24 s), the calculated length and power change results Δz_r and ΔP_r show an offset which could be mistaken as a correct measurement result due to strain in the sensor sections and associated change of the reflected powers. The calculated differential results $\Delta z_{r;high} - \Delta z_{r;low}$ and $\Delta P_{r;high} - \Delta P_{r;low}$, however, show significant deviation from zero which clearly indicates a fault in the FUT during the measurement. If such a failure is triggered, a full frequency scan of the FUT is necessary to analyze the cause of the fault. This way fibre breaks or other failures in the FUT can be recognized and repaired or simply incorporated into a resumed dynamic measurement.

Basically any change that leads to a deviation of the expected transfer function can be recognized. That includes the appearance of additional reflection components but also rapid and significant changes of the FUT during the measurement of $M(f_k)$ as discussed in section 5.3.1. Due to the delayed measurement of the higher frequency components, the solutions of $\Delta z_{r;high} - \Delta z_{r;low}$ and $\Delta P_{r;high} - \Delta P_{r;low}$ exhibit deviations from zero as shown in Figure 5.10. Any failure, for example due to sudden power or phase changes much faster than the measurement repetition rate (sweep time to obtain $M(f_k)$), can be identified. This fault recognition algorithm is implemented into the measurement algorithm without decreasing the measurement repetition rate. If deviating results are detected, appropriate measures can be taken.

5.3.4 Dispersion influences

The dynamic measurement technique is ideally applied in a SMF network. The absence of modal dispersion and the low chromatic dispersion in standard SMF allows for long-gauge measurement without deteriorating the frequency response of the single reflections. The laser emits within the stated zero dispersion wavelength region of the fibre¹ between 1304 nm < λ_0 < 1324 nm. All assumptions made in equation (2.58) can therefore be considered to be correct and equation (5.7) can be used without alteration. In case of extreme applications where very high local strain is expected, MM PF POF might be the medium of choice. It is shown in section 3.2.3 that modal dispersion can have a significant impact on the transfer function of a long fibre. This is especially evident for low-coupling MM silica fibres. Changes of the modal excitation or mode coupling can seriously distort the transfer function of a reflection. Also, reflections in the same fibre at different distances will have different transfer functions. It is also shown in section 3.2.3 that, due to the strong mode-coupling in PF POF, modal excitation changes basically do not change the transfer function of a PF POF section.

¹ Corning[®] SMF-28[™] SMF, datasheet available at: http://ece466.groups.et.byu.net/notes/smf28.pdf.

However, if a dispersive element in the FUT distorts the calibrated transfer function of a reflective event, the assumptions made in equation (2.58) for the proposed technique do not hold true any longer. That means that the reflection frequency response $H_r(f_m)$ is a function of the distance z in the fibre. Figure 5.11 shows exemplarily that the ideal transfer function $|H_r(f_m)|$ of a single reflection calculated from equation (2.58) deviates from a dispersed transfer function after propagating through a 964 m long PF POF. The absolute values $|H_r(f_m)|$ are not identical over f_m and minor phase deviations might occur over f_m due to non-symmetric distortion of the 'pulse'. These deviations from the ideal $H_r(f_m)$, as calculated in equation (2.58), have to be included into the calculation of equation (5.7) to obtain correct results.



Figure 5.11. Ideal transfer function and the calibrated dispersed transfer function $|H_r(f_m)|$ after 964 m PF POF (left) and the time domain equivalent (right).

In the case of a non-ideal (dispersed) reflection in the fibre, its transfer function $H_r(f_m)$ in the fibre can be directly retrieved from the time domain data h(z) calculated from the initial full frequency response measurement. As presented in [121], filtering of the single reflections $h_r(z)$ in the time domain delivers high-resolution results when measuring length change and power change simultaneously. After conducting the IFFT ($h(z) = \mathcal{F}^{-1}{H(j\omega)}$), the single reflection components $h_r(z)$ are individually retrieved from h(z) by setting all h(z) values apart from the region around the reflection position z_r to zero. The time domain data of the FUT without the reflections $h_0(z)$ is then calculated equivalently to equation (5.2) by subtracting the single reflection components $h_r(z)$ from the full time domain response h(z):

$$h_0(z) = h(z) - \sum_{r=1}^n h_r(z)$$
(5.14)

In the following, the time domain components of the FUT $h_0(z)$ and $h_r(z)$ are transferred back into the frequency domain using a fast Fourier transform (FFT). The resulting frequency domain reflection components $H_r(f_m)$ and $H_0(f_m)$ contain the dispersed (distorted in absolute value and phase) transfer functions of each reflection. These correct reflection transfer functions are equivalently used to solve equation (5.7) and calculate correct phase and absolute value changes. This way, dispersion along the FUT can be individually compensated for. Prerequisite is that the dispersion, and therefore the individual reflection frequency responses, are constant during the measurement. Sudden and extreme changes of the transfer function of the fibre due to induced mode coupling or mode filtering would result in incorrect results for all measurement points. This effect, however, would only have a measurable influence if long silica multimode fibres are used. The very short coupling lengths in PF POF lead to immediate redistribution of the mode groups. Therefore, only a very short fibre length would contribute to a negligible error. External mechanical influences that may cause such strong mode coupling effects are likely to have a greater impact on the measured position change and power change itself. The presence of a dispersed reflection signal can be easily identified in the initial backscatter trace. By comparing for example the expected effective spatial resolution δz_{eff} (compare equation (2.22) and Figure 2.6) with the actual FWHM of each reflection in the time domain plot h(z), the necessity for time domain filtering instead of ideal reflection transfer function assumption (equation (2.58)) can be identified.

5.4 Measurement results

5.4.1 Laboratory results

In order to investigate and demonstrate the capabilities of the proposed technique, several tests with different measurement setups and fibre types have been conducted and are presented in this section. Both, SMF and MM fibres (silica as well as PF POF), are used. Only the optical circulator is exchanged to adapt the setup to SMF or MM fibres.

Since only a few frequency points $H(f_k)$ need to be measured to calculate a result, the measurement repetition can be much higher than conducting a full scan of $H(f_m)$. By altering the measurement parameters such as filter bandwidth of the VNA or the overdeterminacy of the system of equations (d > n), the measurement resolution or measurement repetition rate f_{meas} can be adapted to the application requirements: high resolution or high repetition rates. Wide filter bandwidth settings of the VNA and no overdeterminacy of the systems of equations (d = n) yield the highest measurement repetition rates. f_{meas} can be further increased by sweeping a greater number (i.e. several hundred) of frequency points than needed for calculating a single solution. The sweep result can then be split into a greater number of single systems of equations which are solved separately for different input frequencies and deliver unique solutions. This way, the time loss between single measurements due to communication and data transfer between the PC and the VNA is reduced for the same number of measurement results. The highest possible measurement repetition rate using the VNA connected via GPIB is demonstrated in the figure below. A 50 µm core diameter PF GI POF section is clamped and alternately strained and relieved at a frequency of about 0.7 Hz using the step motor setup [122], Figure 5.12 (left). Figure 5.12 (right) shows the measured length change result $\Delta l = \Delta z_2 - \Delta z_1$ of the reflection at the distance z_2 relative to the reflection at the distance z_1 at the maximum measurement repetition rate of $f_{meas} \approx 2$ kHz.



Figure 5.12. Schematic of the strain setup using PC-controlled step motor (left) and length change measurement of a PF POF section (right); $f_{meas} \approx 2$ kHz, d = 2, $f_k = 2.1$ GHz...2.9985 GHz, $\Delta f = 1.5$ MHz, BW = 30 kHz.

Very precise length and power change evaluation can be achieved by decreasing the filter bandwidth of the VNA and increasing the overdeterminacy of the systems of equations. Figure 5.13 shows a result for the same setup as above but for a high-resolution measurement at a lower measurement repetition rate of $f_{meas} = 10$ Hz.



Figure 5.13: High-resolution measurement of a strained PF POF; $f_{meas} = 10$ Hz, d = 300, $f_k = 2.46...2.9085$ GHz, $\Delta f = 1.5$ MHz, BW = 10 kHz.

The motivation to use a PF POF as a sensor fibre is the suitability for very high strain sensing applications exceeding the strain limits of silica fibres. For the measurement of low strain values standard silica SMF provides the best performance due to minimum dispersion and optical loss.

In order to demonstrate that the technique is capable of measuring multiple sensor sections independently and simultaneously, a laboratory setup has been built [123]. Figure 5.14 shows this setup of four silica SMF sections that are separated by strongly reflecting PC connectors every 15 m. The four sensor sections are glued under pre-strain onto both sides of a 5 mm thin wooden panel. One end of the panel is fixed so that the two sensor fibres bonded on one side of the panel experience elongation whereas the two sensor fibres bonded onto the opposite side will experience relaxation (negative length change) when the panel is deflected in one direction.



Figure 5.14: Schematic and photographs of the demonstrator setup with 4 fibre sections, separated by the reflectors R1 to R4, surface-glued onto the panel.

The length changes between the single reflectors are measured during deflection of the panel. Figure 5.15 (left) shows length change results of the panel in static condition for t < 0.8 s, then deflected in one direction for t = 0.8 s to t = 3.2 s followed by a free damped oscillation for t > 3.2 s. This demonstration measurement shows that multiple fibre sections can be monitored simultaneously and independently and that the length change values agree well in magnitude and sign. Each length change result can be distinctively allocated to the respective sensor section. The measurement in Figure 5.15 (right) shows a high-resolution measurement of the same setup at a low repetition rate of $f_{meas} \approx 1$ Hz. Starting from 34 seconds, the panel is alternately being deflected to one side and released to the initial condition. The standard deviation of the length change results of all four sensor sections is below 1 μ m.



Figure 5.15: Dynamic measurement with two strained/compressed fibre sections in static condition (t < 0.8 s), deflection in one direction (t = 0.8 s to t = 3.2 s) and free damped oscillation for t > 3.2 s, at $f_{meas} \approx 25$ Hz (left) and high-resolution measurement for small deflections in one direction, $f_{meas} \approx 1$ Hz, d = 40, $f_k = 2.808$ GHz...2.9952 GHz, $\Delta f = 5$ MHz, averaged 30 sweeps, BW = 2 kHz (right).

In order to demonstrate the capability of simultaneous and undisturbed power change measurement, another experiment with an additional fibre for refractive index measurement has been conducted. In parallel to the panel setup in Figure 5.14 (reflections R1 to R4), another SMF with an open 0°-angled end (R5) is inserted using a bidirectional optical coupler, Figure 5.16.



Figure 5.16: Schematic of the demonstration setup for combined length change and refractive index measurement.

The sensor sections between the reflections R1 to R4 experience length changes when the panel is deflected, whereas reflection R5 experiences both, position change and optical power change. The position change of R5 is applied by clamping a fibre section and using the step motor setup to alternately elongate and release the fibre section 'before' R5. The optical power change at R5 is implemented as a refractive index change sensor by immerging the open 0°-angled fibre end into water and changing its index of refraction by step-wise adding a sugar solution. The absolute value $|X_5|$ of the solution of equation (5.7) is a function of the reflectivity R of the fibre end and thus a function of the refractive index of the medium at the fibre end n_m [17]. The reflectivity R_r for normal incidence of light can be calculated from the Fresnel equation

$$R_r = \left(\frac{n_e - n_{m,r}}{n_e + n_{m,r}}\right)^2$$
(5.15)

The reflectivities R_r from a new measurement can be expressed as a product of the reflectivities $R_{r(ref)}$ of the reference measurement and the absolute values $|X_r|$ of the solution from equation (5.7):

$$R_r = R_{r(ref)} \cdot |X_r| \tag{5.16}$$

If the refractive indices at the fibre ends at the time of the reference measurement $H_{ref}(f_m)$ are known, the new refractive indices $n_{m,r}$ can be calculated by inverting equation (5.15) and inserting the measurement results from equation (5.16):

$$n_{m,r} = n_e \cdot \frac{1 - \sqrt{R_{r(ref)} \cdot |X_r|}}{1 + \sqrt{R_{r(ref)} \cdot |X_r|}}$$
(5.17)

 $R_{r(ref)}$ are the calculated theoretical reflectivities of the known refractive indices of the reference measurement $n_{m,r,(ref)}$ using equation (5.15) where $n_e = 1.45284$ is calculated from the Sellmeier equation [124] for silica at $\lambda = 1310$ nm and the specific group refractive index $n_{gr} = 1.4677$ of the SMF using

$$n_e = n_{gr} + \frac{dn_e}{d\lambda} \cdot \lambda \tag{5.18}$$

Figure 5.17 shows the length change results of the combined length change and refractive index measurement obtained with the described setup. The length changes Δl of the sections between R1 to R4 are caused by forced oscillation of the wooden panel, whereas the position change of R5 is induced by alternately straining and releasing the clamped fibre section.



Figure 5.17: Length change measurement of the oscillating panel (fibre sections between R1 to R4) and the strained/released fibre section before R5 [125]; $f_{meas} = 21$ Hz.

At the same time, the refractive index of the water solution at reflection 5 has been step-wise increased by adding a sugar solution. Figure 5.18 shows the refractive index evaluation calculated from the optical power change measurement at reflection 5 using equation (5.17). A magnetic stirrer is used to accelerate reaching a concentration equilibrium in the beaker. The small peaks at the beginning of each index change step represent correct refractive index results (actual concentration values) when adding the sugar solution before a concentration equilibrium is reached. The measurement has been conducted with $f_{meas} = 21$ Hz.



Figure 5.18: Refractive index measurement stepwise increased index at open fibre end (R5) conducted simultaneously to the length change results in Figure 5.17; $f_{meas} = 21$ Hz.

These strain and refractive index measurements demonstrate that both measurement parameters (delay changes and reflected optical power changes) can be obtained simultaneously and independently without mutual influence. To give an estimation of the measurement resolution of

sensor principles evaluating optical power changes, a measurement with a configuration according to Figure 5.14 with 4 sensor points has been conducted. The standard deviation of the reflected power measurement of the four reflections at $f_{meas} = 21 \text{ Hz}$ is in the order of $\sigma_{P_r} \approx 0.004 \text{ dB}$. This corresponds to a standard deviation of $\sigma_{n_m} \approx 5.8 \cdot 10^{-5}$ for the refractive index measurement of water.

5.4.2 Dynamic measurement using fs laser-inscribed sensing points

The inscription of scattering centres into the core of a SMF using focused femtosecond laser pulses has been introduced in section 5.1.1. The dynamic evaluation technique is demonstrated in the following on a fibre with the 4 inscribed scattering points shown in Figure 5.19 (right) [65]. As indicated in Figure 5.19 (left) the fibre section between z_1 and z_2 as well as a section between z_2 and z_3 has been strained and released simultaneously but with different magnitude while evaluating the relative position changes and power changes of the 4 scattering points.



Figure 5.19: Schematic of the setup with indications of the position of the scattering centres (z_1 to z_4) and the strained section (left) and I-OFDR backscatter plot (right); $\Delta f = 1$ MHz, $f_{m,max} = 2$ GHz; $t_{meas} = 50$ min, $\Delta f = 1$ MHz, $f_{m,max} = 2$ GHz, $f_{zp} = 20$, $\alpha_K = 3$.

The measurement repetition rate has been set to $f_{meas} \approx 21$ Hz. Figure 5.20 (left) shows the length changes Δl (position changes Δz relative to the previous scattering points) during straining and releasing the fibre. The position of point 1 (Δz_1) and the distance between point 3 and point 4 ($\Delta z_4 - \Delta z_3$) remain unchanged while point 2 and point 3 are displaced relative to the previous scattering point.



Figure 5.20: Dynamic measurement of relative position changes of the 4 fs laser-inscribed reflections in the fibre (left) and detected power changes ΔP (right), $f_{meas} \approx 21$ Hz; d = 13, averaged two times, $f_k = 1.924$ GHz...1.948 GHz, $\Delta f = 2$ MHz, BW = 1 kHz.

Figure 5.20 (right) shows the absolute optical power changes ΔP at the 4 scattering points calculated from the same measurement. The detected power changes ΔP are caused by the movement of the fibre during straining and releasing the fibre. The measured values in Figure 5.20 have been verified by analyzing position and reflected power changes of the whole backscatter response of the fibre. The measurement resolution and the measurement repetition rate could easily be increased by inducing increased scattering damage.

5.4.3 Seismic shaking test results

Within the European project POLYTECT¹ and the SERIES² project the possibility arose to test the dynamic measurement technique and I-OFDR setup under field test conditions at the facilities of the EUCENTRE³ in Pavia, Italy. A two-storey masonry building placed on a seismic shaking table has been retrofitted with technical textiles with integrated fibre optic sensors. Also the dynamic measurement technique has been tested on this site by installing sensor fibres on the outside of the building. Three sensor sections with different gauge lengths have been installed on selected locations of the building. Two different fibre types were installed: a standard 50 μ m core diameter MM silica fibre (OM2) and the in chapter 4 introduced PF POF are measured in parallel as part of the same sensor network. The silica fibre sections have been glued onto two metal plates that have been screwed to the wall. The POF sensor section has been clamped and screwed onto the wall. All sensors sections are installed in prestrained condition. Figure 5.21 shows the schematic of the sensor network and the building with indication of the locations of the single sensor section 2 and section 3 are the MM silica fibres with about 2 m gauge length each. The POF section (about 4 m gauge length) has been installed at the location where the highest damage and deformation was expected (section 1).



Figure 5.21: Schematic of the installed fibres and sensor sections with 4 reflection points in the fibre (left) and masonry building with indications of the locations of the installed sensor sections 1 (PF POF) and sensor sections 2 and 3 (MM silica fibres).

The reason for not bonding the whole sensor section onto the wall but only fixing the ends of the sensor section was to protect the fibres from damage due to the expected occurrence of cracks in the walls. In order to also measure possible out-of-plane oscillation of the walls and prevent low frequency resonances of the fibre itself, the sensor fibres have also been glued at few intermediate spots separated by about 50 cm. The sensor application approach for precise crack detection and crack propagation measurement using brittle silica fibres would have to be some sort of suspended fibre in pre-strained condition to prevent extreme local strain and fibre breakage. The ruggedness and high strainability of the PF POF, however, would allow direct bonding of the fibres onto the wall with little risk of sensor damage if the cracks do not exceed a certain width.

After installation of the sensor fibres, the building was subjected to 5 independent seismic load patterns of increasing acceleration, each lasting about 45 seconds. The seismic acceleration has been applied to the building in direction of the orientation of sensor 1 and perpendicular to the wall with the sensors 2 and 3. During the first few seismic loads, damages have already been detected. Small cracks appeared perpendicular to sensor 1 and a small crack has been detected by sensor 3. As proposed above, the data acquisition for the dynamic evaluation has been conducted by sweeping a greater number of points than required for solving a single system of equations. The sweep results are divided

¹ The EU project "Polyfunctional Technical Textiles against Natural Hazards" (POLYTECT) within the Sixth Framework Program under Grant NMP2-CT-2006-026789.

² "Seismic Engineering Research Infrastructures for European Synergies" (SERIES)

³ European Centre for Training and Research in Earthquake Engineering (EUCENTRE)

into multiple systems of equations and solved individually. This has the advantage of increasing f_{meas} (reducing communication and data transfer times) and also yields the possibility to later analyse the measurement results for higher or lower measurement frequencies by adapting the size of the systems of equations (changing d). The length change results of the 3 sensor sections during the last seismic shaking test of the already pre-damaged building are shown in Figure 5.22. The measurement has been evaluated for $f_{meas} \approx 160$ Hz.



Figure 5.22: Length change results of all sensor fibres during the seismic load at $f_{meas} = 160$ Hz, d = 16, $f_k = 2.75$ GHz...2.9895 GHz, $\Delta f = 500$ kHz, BW = 2 kHz.

The figure shows that the greatest deformation occurred along sensor 1 with a maximum elongation of about 8 mm. It can also be seen that already existing or new cracks caused a permanent deformation of about 1 mm. After the test, a small crack line perpendicular to sensor 3 has also been observed in the wall where sensor 2 and sensor 3 are installed. The acceleration perpendicular to sensor 2 and sensor 3 excites an oscillation of the wall and results in a concentrated deformation at the location of the existing crack bridging sensor 3. The oscillation of the wall and the resulting opening and closing of the crack at sensor 3 can clearly be seen and a remaining deformation of about 500 µm can be observed.

The calculation of the measurement results not only delivers length change results but also reflected optical power change results for each sensor section. The additional information of optical loss between the reference points can be used to detect and analyze the deformation behaviour of the structure during the test. The measured optical power changes are calculated for a measurement repetition rate of $f_{meas} \approx 27$ Hz in Figure 5.23.



Figure 5.23: Optical power changes for all sensor sections, $f_{meas} \approx 27$ Hz, d = 96, $f_k = 2.75$ GHz...2.9895 GHz, $\Delta f = 500$ kHz, BW = 2 kHz.

It can be assumed that the optical power changes during the seismic load are induced by macrobends at the locations where the fibre is fixed at the wall. Therefore, also small displacements or vibrations perpendicular to the fibre that do not result in significant length changes could be detected. The relatively strong one-sided attenuation changes of sensor 3 between 50 s and 60 s for example might be attributed to appearing and disappearing macrobends in the fibre at the crack during the out-ofplane oscillation of the damaged wall. Only the outward deflection of the wall leads to loss (Figure 5.23) whereas the length change occurs for deflections of the wall in both directions (Figure 5.22). Permanent power changes, positive and negative, may have been caused by loosening or appearing fibre bends at the fixation points. The measurement showed good agreement with results obtained with other sensor techniques at similar locations and proved that the proposed technique can be transferred from the laboratory stage towards application-like conditions.

Like any other fibre optic sensor technique, also the presented system is subjected to temperatureinduced measurement deviations. Length change deviations are caused by the temperaturedependency of the refractive index of the fibre and thermal expansion coefficients of the sensor fibre and the surrounding structure (section 4.3.1). As proposed for other fibre strain measurement systems, the temperature influence can for example be compensated for by measuring an additional strain-free fibre installed in parallel to the strain measurement fibre and subtracting the temperature-dependent influence.

Conclusion

The proposed technique allows for dynamic and simultaneous measurement of length changes of arbitrary gauge length and optical power changes at multiple reflection points in an optical fibre network. Due to the incoherent detection, measurements can be performed in SMF as well as in MM fibres and MM POF. Depending on the measurement settings, dynamic measurements up to $f_{meas} = 2 \text{ kHz}$ or high-resolution measurements with length change resolutions in the µm-range at lower measurement repetition rates can be conducted. Possible sources of system-inherent dependencies, measurement errors and sensitivities to external disturbances have been discussed. A measurement fault recognition algorithm and a phase step compensation technique for the case of extreme length changes have been implemented. Laboratory tests demonstrated that length changes and power changes (in this case refractive index change) can be measured simultaneously and independently. The sensor system has successfully been tested in a field-like application measuring the deformation of a masonry building during a seismic shaking test.

This quasi-distributed sensing approach is very versatile and can also be used to multiplex other existing fibre optic sensor systems. The multiplexing of extrinsic Fabry-Pérot interferometer (EFPI) sensors has exemplarily been conducted using the dynamic I-OFDR approach [126]: strain measurement using the power evaluation on multiple EFPIs and simultaneous length change measurement of the EFPI peak shifts is demonstrated with the proposed setup.

6 Summary and outlook

The aim of this thesis was to thoroughly consider the incoherent optical frequency domain reflectometry approach (I-OFDR) and its potential for general optical backscatter measurement and precise optical fibre sensing applications.

Prior to this work, the I-OFDR technique has only been demonstrated conceptually for distributed backscatter measurement [2] and had little impact on the further development of optical backscatter measurement techniques. The time domain equivalent using optical pulses (OTDR) has meanwhile matured and found widespread application and commercial success for fibre characterization as well as for fibre sensing applications. Concluding the results of this work, it can be stated that disregarding the potential of the I-OFDR technique for precise backscatter measurement has been premature. The I-OFDR approach was thoroughly analyzed in theory and experimentally. A laboratory setup was designed and optimized and demonstrates astonishing measurement performance in both, SMF and MM fibres. Potentially critical issues such as system linearity, systematic limitations and interference influences were analyzed in detail.

The spectral properties of the optical source were identified as crucial for precise backscatter measurement and were investigated theoretically and experimentally. A Fabry-Pérot laser diode was found to exhibit the best measurement performance. Its multimode characteristic has advantages in terms of coherence properties and SNR compared to singlemode lasers. Active spectral averaging was optimized and implemented for effective interference reduction.

Importantly, the general performance parameters and system-specific limitations of an I-OFDR setup were defined and characterized. The system performance for general backscatter measurement is generally best described using absolute backscatter sensitivity and dynamic range. As opposed to pulse domain techniques, the dynamic range of an I-OFDR system is the fundamentally limiting system parameter which may prevent using the system for low-power backscatter measurement at the presence of strong reflections. This only practical limitation compared to the OTDR approach may be reduced by implementing the proposed active reflection suppression technique. Necessary signal processing techniques such as windowing and zero-padding and its impact on the measurement performance, meaning spatial resolution and power levels, was simulated and applied. Accurate power and distance measurement can therefore be conducted at reflections in the FUT as well as on distributed backscattering. Performance measurements proved very high linearity, signal stability and measurement reproducibility of the I-OFDR setup. This owes to the precise generation and filtering of the optical 'pulse' components in the frequency domain. High-resolution position measurement in the µm-range as well as precise power measurement can be conducted, exceeding the performance of the OTDR technique. The I-OFDR approach shows competitive performance for both intended uses and appliance classes: general long-distance backscatter measurement as well as precise and highresolution sensing applications. Spatial resolutions up to 3.1 cm can be achieved in SMF with the laboratory setup.

In terms of *optical fibre sensing*, several techniques were proposed and demonstrated: A *new low-loss MM POF* type was investigated *for distributed strain sensing*. The occurring backscatter level change with strain in these fibres can be used to locate strained sections along the sensor fibre with cm-spatial resolution. The high signal stability and spatial resolution of the I-OFDR technique allow for measuring distributed length changes along the POF: position shifts of the relatively strong backscatter variations along that fibre type can be measured by applying a correlation algorithm to the backscatter measurement results. Length change resolutions better than 1 mm can be achieved using the proposed correlation technique. This is a considerable improvement compared to results obtained using high-resolution OTDR. The sensor fibre type is extensively investigated for cross-sensitivities to temperature, humidity as well as modal excitation and mode propagation. The combination of the investigated POF sensor fibre and the I-OFDR allows for distributed detection of strained fibre sections with high spatial

resolution as well as precise distributed length change measurement up to several hundreds of meters. The extraordinary strain range of this fibre type exceeding 100% strain promises great potential for structural health monitoring applications where strong deformations are expected and the use of established silica fibre-based sensing techniques is prevented.

Also a dynamic measurement approach based on I-OFDR was proposed for simultaneous and quasidistributed measurement of length changes and optical power changes on multiple reflective events in the FUT. The evaluation of partial results of the frequency response allows for calculating precise power and position changes at high measurement repetition rates up to 2 kHz. Systematic limitations, system linearity and external influences were discussed. Compensation techniques and a measurement fault recognition technique are implemented. Laboratory tests demonstrated that length changes and for example refractive index changes can be correctly and simultaneously measured. The field applicability was successfully demonstrated by measuring the deformation of a masonry building during a seismic shaking test. The proposed sensor system has a great potential in the structural health monitoring sector, especially when dynamic and long-gauge measurement up to kilometre-lengths is intended. Application examples are the monitoring of buildings, bridges, vessels or structural components such as wind turbine components. The possibility to additionally evaluate optical power changes provides a great range of sensing applications to simultaneously measure for example mechanical or chemical quantities in a distributed sensor network. Various existing fibre optic sensing principles can be easily implemented and multiplexed. The concept of using focused femtosecond laser pulses for inscription of strong scattering points into the core of SMF and PF POF as reference points is proposed and demonstrated for static and dynamic measurement. This may be an effective and flexible method to insert sensing points into optical fibres without introducing mechanical discontinuities and maintaining the small form factor of the sensor fibre.

Outlook

As a result of the promising performance of the I-OFDR approach as a general backscatter reflectometer and the versatility and performance of the proposed sensing techniques, a research project with the fibrisTerre GmbH was initiated. The aim of this project is the realization of a digital implementation of the I-OFDR by replacing the costly analogue VNA. First comparison measurements up to $f_{m,max} = 100$ MHz with the digital measurement device in the I-OFDR laboratory setup show superior performance and signal stability compared to the VNA-based implementation [66]. The sensitivity could be increased by about 10 dB (to 100 dB after 3 min of averaging) and the dynamic range improvement is about 12 dB (52 dB absolute) compared to the VNA I-OFDR. The planned extension of the digital approach up to $f_{m,max} = 500$ MHz will provide high-resolution backscatter measurement with the flexibility to incorporate the proposed dynamic sensing principles and the distributed strain and length change measurement in PF POF.

The I-OFDR system in combination with the proposed sensing principles may have prospects in the market for structural health monitoring and remote sensing. Especially the possibility of precise and dynamic long-gauge strain sensing provides a solution for certain applications that could not be satisfyingly solved with existing techniques. The I-OFDR approach may also be competitive in market niches aiming at high-resolution backscatter measurement and precise fibre characterization.

Symbols and Abbreviations

Abbreviation	Meaning
	Asahi Glass Company
APC	angle-polished connector
BW	bandwidth
CRN	coherent Ravleigh noise
CW	
DFB	distributed feedback
DFT	discrete Fourier transform
DMA	differential mode attenuation
DMD	differential mode delay
DOP	degree of polarization
FFPI	extrinsic Fabry-Pérot interferometer
FOM	electro ontical modulator
FSA	electrical spectrum analyzer
FBG	fibre Bragg grating
FFT	fast Fourier transform
FMCW	frequency-modulated continuous wave
FP	Fabry-Pérot
FUT	fibre under test
FWHM	full width at half maximum
GI	gradient-index
GPIB	general purpose interface bus
IFFT	inverse fast Fourier transform
I-OFDR	Incoherent optical frequency domain reflectometry
LO	local oscillator
LTI	linear time invariant
MC	mode converter
MM	multimode
NA	numerical aperture
NPSD	noise power spectral density
OBR	optical backscatter reflectometer
OFDR	optical frequency domain reflectometry / reflectometer
OLCR	optical low coherence reflectometry
OSA	optical spectrum analyzer
OTDR	optical time domain reflectometry / reflectometer
PC	physical contact (connector)
PD	photodetector
PF	perfluorinated
PMD	polarization mode dispersion
PMMA	poly(methyl methacrylate)
POF	polymer optical fibre
PRS	pseudorandom signal
PTFE	polytetrafluoroethylene
RH	relative humidity

Abbreviation	Meaning
rms	root mean square
SFM	step frequency method
SHM	structural health monitoring
SI	step-index
SLD	superluminescent diode
SM	Singlemode
SMF	singlemode fibre
SNR	signal to noise ratio
SOP	state of polarization
SWI	swept wavelength interferometry
TF	transfer function
VNA	vector network analyser
VOA	variable optical attenuator

Symbol	Description	Introduced in chapter
α	fibre attenuation coefficient	1
α_K	Kaiser Bessel window parameter	2
α_L	linear expansion coefficient	4
α_s	Rayleigh scattering loss	1
α _a	fibre absorption loss	1
а	complex correction term	2
Α	amplitude of harmonic signal	2
A_s	amplitude of harmonic suppression signal	2
b	3dB bandwidth / spatial resolution (in FFT bins)	2
β	exponent of relation for pulse broadening-length dependency	3
B_{val}	energy constant of laser diode	2
BW	filter bandwidth (VNA and ESA)	2
<i>c</i> ₀	vacuum speed of light	1
C_{ε}	strain transfer coefficient	4
δt_{bin}	time separation of FFT bins (no zero padding)	2
δz	nominal spatial resolution (no zero padding applied)	2
δz_{bin}	spatial separation of FFT bins in reflection (no zero padding)	2
δz_{res}	spatial separation of FFT bins with zero padding applied	2
δz_{eff}	effective two point resolution (zero padded result)	2
Δf	modulation frequency step size	2
Δf_k	frequency difference for dynamic evaluation	5
$\Delta \varphi_{cal}$	phase deviation of I-OFDR transfer function	2
	phase difference at phase step; phase step compensation	
$\Delta \varphi_{max}$	solution	5
$\Delta \varphi_r$	relative phase changes for dynamic evaluation	5
Δl	length change of the fibre or fibre section	2
ΔL	optical path length difference	2
Δλ	wavelength tuning range for spectral averaging	2
$\Delta \nu$	laser linewidth	2
Δt_s	system response time	2
Δau_{π}	time difference for phase difference equivalent to π	2
Δz	position change	2
Δz_{max}	distance change for phase step, dynamic evaluation	5
Δp	pulse length in the fibre	1
ΔP	optical power changes in a backscatter trace	5
ΔP_{g}	optical power difference between reflection and ghost reflection	5
ΔSNR	signal to noise ration improvement factor	2
ΔU	tuning voltage for wavelength averaging	2
d	number of measured frequency points	5
dz	periodicity of the interference maxima of the interferogram	2
D	dynamic range of backscatter measurement (2D)	1
ε	Strain	2
Ε	electric field	2
E_{pulse}	pulse energy	2
E_Y	Young's modulus	4
f	Frequency	2

fn maximum modulation frequency2fn,max maximum modulation frequency2fn,max minimum modulation frequency2fn,max measurement repetition rate5free free zero padding factor2g(t_0)coherence function2g(t_m)transfer function coefficient3h(z)time domain response2h(z)suppression path time domain response2h(j(u)(calibrated) frequency response of the FUT2H(j(u)measured frequency response of the FUT2H(j(u)measured frequency response of the FUT2Ioptical power1Ioptical power1Iappression path transfer function2Ioptical power1Ia2Ioptical power1Ia2Ir(x)interferometric power variation (interferogram)2Immodulation optical power signal2Immodulation optical power1Issingle lasing mode power2Itransmitted optical power1Jimaginary unit2knumber of full wavelengths for averaging calculation2Jinitial fibre length1Lccorrelation length4Lfibre length3Lcmode coupling length for strain measurement)2Lcmode coupling length for strain measurement)2Lc<	Symbol	Description	Introduced in chapter
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M measurement result (complex frequency domain value)5 n number of reflections in the fibre2 n_e effective refractive index of the fibre1 n_{ar} group refractive index1 n_{zero} number of additional zeros (for zero padding)2 N length of window function2 v optical frequency2	m	modulation depth	2
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n_e effective refractive index of the fibre1 n_{ar} group refractive index1 n_{zero} number of additional zeros (for zero padding)2Nlength of window function2voptical frequency2	п	number of reflections in the fibre	2
n_{ar} group refractive index1 n_{zero} number of additional zeros (for zero padding)2Nlength of window function2voptical frequency2	ne	effective refractive index of the fibre	1
noonnumber of additional zeros (for zero padding)2Nlength of window function2voptical frequency2	n _{ar}	group refractive index	1
Nlength of window function2voptical frequency2	nzero	number of additional zeros (for zero padding)	2
v optical frequency 2	N	length of window function	2
	ν	optical frequency	2
ω angular frequency 2	ω	angular frequency	2
ω_0 centre angular frequency of the optical field 2	ω	centre angular frequency of the optical field	2
p number of FP lasing modes 2	p	number of FP lasing modes	2
P backscatter peak power 2	P	backscatter peak power	2
P _{cal} detected calibration signal power 2	P_{cal}	detected calibration signal power	2
P_d detected reflection signal power 2	P_d	detected reflection signal power	2
P _{mod} detected modulation signal power 2	P_{mod}	detected modulation signal power	2

Symbol	Description	Introduced in chapter
ϕ	laser phase noise	2
φ_r	phase of reflection frequency response	5
q	number of measurements (averaging)	2
R	reflectivity (optical power)	2
${\mathcal R}$	detector responsitivity	2
R_0	diode thermistor nominal resistance	2
R_{th}	resistance of laser diode thermistor	2
RH	relative humidity	4
S	backscatter capture coefficient	1
$S_{FP}(\lambda_i)$	optical power spectrum of FP laser	2
$S_{I_{CW}}$	phase-to-intensity NPSD (optical power) of CW component	2
$S_{P_{CW}}$	phase-to-intensity NPSD of CW component	2
$S_{P_{mod}}$	phase-to-intensity NPSD of modulation component	2
$S_{P_{tot}}$	phase-to-intensity NPSD of CW and modulation component	2
σ	backscatter factor	1
σ_P	standard deviation of backscatter peak power	2
σ_{RBS}	standard deviation of Rayleigh backscattering	2
σ_z	standard deviation of reflection position	2
$ au_0$	time delay	2
$ au_{coh}$	coherence time of optical source	2
$ au_d$	signal delay (optical and electrical)	2
$ au_{diff}$	time difference for compensation	2
$ au_p$	optical pulse duration	1
$ au_r$	receiver response time	1
$ au_s$	suppression path signal delay	2
t	time	2
t _{meas}	measurement time	2
Т	temperature	4
T_P	periodicity of the Fourier transform	2
T_0	temperature of laser diode	2
u _d	disturbing signal from reflection	2
u_m	modulation signal	2
u_r	backscatter signal	2
u _{s cal}	suppression path calibration measurement signal	2
v_{gr}	group velocity	1
W	window function	2
x_m	amplitude modulated optical power signal	2
X_r	complex solution for dynamic measurement	5
Ζ	distance in the fibre	2
<i>z</i> ₀	distance for length change evaluation (covariance distance)	4
Z_{max}	maximum distance range of the I-OFDR	2

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