

Distributed polymer optical fiber sensors using digital I-OFDR for geotechnical infrastructure health monitoring

Aleksander WOSNIOK¹, Korbinian KÖNIGSBAUER^{1*}, Nils NÖTHER², Jan FÄRBER³,
Maria-Barbara SCHALLER³, Katerina KREBBER¹

¹ Bundesanstalt für Materialforschung und –prüfung BAM, Berlin, Germany, info@bam.de
^{1*} at BAM till December 2023

² fibrisTerre Systems GmbH, Berlin, Germany, info@fibristerre.de

³ GGB Gesellschaft für Geomechanik und Baumesstechnik mbH, Rötha, Germany,
info@ggb.de

Abstract. We present a distributed polymer optical fiber sensor system for deformation monitoring of geotechnical infrastructure. The sensor system is based on the digital incoherent optical frequency domain reflectometry (I-OFDR) for the detection of local strain events along a perfluorinated polymer optical fiber (PF-POF) used as a sensing fiber. For the best possible load transfer, the PF-POFs were integrated onto geosynthetics which pose a sensor carrier for the sensing fiber. By using elastic PF-POF instead of a standard glass fiber as a sensing fiber the strain range of geosynthetics-integrated fiber optic sensors could be extended up to 10 % in accordance with the end-user requirements.

In order to reduce overall costs of the sensor system and achieve its robustness required for use on site, the standard vector network analyzer used by default was replaced by an integrated digital board for optical frequency domain reflectometry. This implementation showed a significant improvement in the dynamic range and sensitivity compared to the previous measurement system based on the conventional network analyzer.

The functionality of the entire sensor system was proven in the field test during the installation of two geogrids with integrated PF-POFs embedded into a road embankment in a section of the federal road B91 near Leipzig, Germany. To monitor the installation-related changes in the condition of both sensor-based geogrids several control measurements on the embedded PF-POFs and co-integrated reference glass fibers were carried as the construction works progressed. The measurements conducted in the field confirm the potential of the selected PF-POF. The sensor system is ready to be used for practical application.

Keywords: digital I-OFDR, distributed polymer optical fiber sensor, distributed strain sensing, smart geosynthetics, structural health monitoring

Introduction

The growing interests and demands in the realization of construction projects result in a significant upswing in development of new sensor technologies and methodologies for real-time structural health monitoring and early damage detection in large-scale structures. Efficient transport infrastructure as roads, bridges and tunnels providing economic and social benefits can be supported by several most electrical sensing technologies. Optimization of the monitoring solutions can lead to damage detection in an early stage eliminating the need of expensive repairs and even enables lifetime analysis resulting in the extended service life of the infrastructure. Compared to electrical sensors, various types of fiber optic sensors [1] offer unique advantages regarding their electromagnetic immunity, small size, light weight, corrosion resistance, multiplexing capability, and ability to distributed sensing [2-3].

In this paper we report about the development of a distributed fiber optic sensing system based on digital incoherent optical frequency domain reflectometry (I-OFDR) [4] using perfluorinated graded-index polymer optical fibers (PF-POFs) as sensing fibers. The high flexibility and large breakage strain of PF-POFs allows detection of large local deformations by measuring the Rayleigh backscatter profiles along the sensing fiber. The evaluation of the Rayleigh backscatter signature can furthermore provide information about the occurred local strain events. As required by the end users, local strain states up to 10 % can be detected in this way. With respect to the best possible transfer of deformations from the soil into the sensing fibers in the form of longitudinal strain, the geosynthetics were used as FOS substrate materials [5-6]. The use of such geosynthetics with integrated optical fibers enabled machine embedding in a road embankment of the B91 federal road near Leipzig, Germany. This installation on the B91 road section served to check the functionality of the entire sensor concept.

1. POF-based Digital I-OFDR

The goal of the research work was to develop a device suitable for use in the field. The fundamental principle of the I-OFDR has been known for several decades [7]. The implementation of I-OFDR principle for distributed fiber optic measurement of Rayleigh backscattering was done in [8] followed by an approach to quasi-distributed dynamic strain acquisition [9]. The frequency-domain reflectometry can provide an advantage of an increased dynamic range at shorter interrogation times [8] compared to conventional optical time-domain reflectometry (OTDR) [10]. The research presented here refers to the hardware development of a digital data acquisition unit (DDAU) replacing the previously used oversized vector network analyzer (VNA). This approach significantly reduces the costs and the size of the measuring system.

The principle of the digital I-OFDR already presented in [4] and shown in Fig. 1 is based on the measurement of the complex transfer function of the sensing fiber by a stepwise amplitude modulation of the broadband laser light from the Fabry-Pérot laser diode. This type of light modulation using an electro-optic modulator (EOM) before coupling into the POF under test enables high optical power distributed over several laser modes with the possibility of fixed setting of a less coherent operating point of the laser diode. The occurrence of several laser modes and the associated spectral distribution of the optical power reduce the negative interference effects at different locations along the sensing fiber. The key tasks of signal synthesis for the amplitude modulation of the laser source and signal analysis of the backscatter signal as well as the control of the operating point of the EOM are completely controlled by the DDAU.

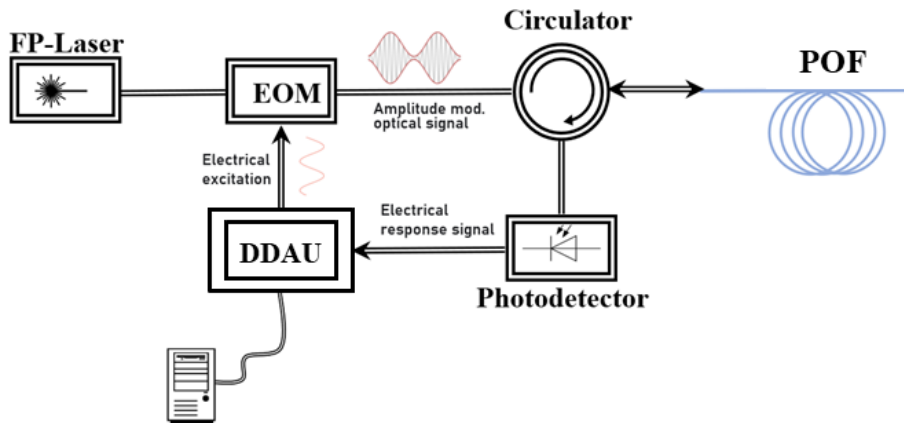


Fig. 1. Measurement principle of the POF-based digital I-OFDR.

As a result of the development work, a fully functional measuring system was assembled in a robust and compact housing (Fig. 2).



Fig. 2. Demonstrator - Digital I-OFDR device suitable for outdoor use in a robust and compact housing.

The proof-of-concept laboratory test [11] shown in Fig. 3 demonstrates the feasibility of the sensor concept for detection of local strain events with a strain resolution of less than 0.5 % based on a measurable strain-related local increase in backscatter.

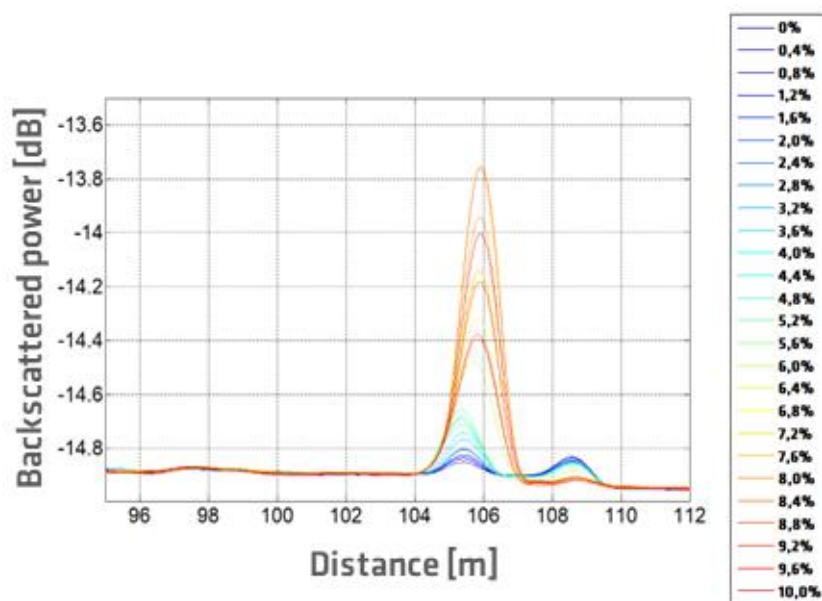


Fig. 3. Backscatter profile of the sensing fiber – local increase in backscatter between 105 m and 107 m by applied strain up to 10 %.

Due to the negligible cross-sensitivity on temperature and humidity, the change in backscatter profile in the defined strain range up to 10 % can be regarded as a function of the longitudinal strain.

The test was conducted on a PF-POF manufactured by the Japanese company Asahi Glass Co., Ltd. The optical attenuation of the fiber measured at the operating wavelength of 1310 nm is about 30 dB/km, which enables a measurement range far over one hundred meters. The backscatter profile of the selected PF-POF is not uniform showing randomly distributed scattering centers along the fiber. These scattering centers cause intermode coupling and are thus the reason for the high optical bandwidth and the relative independence of the sensing fiber from the type of coupling.

Fig. 4 demonstrates the robustness of the PF-POF investigated using a tensile testing machine in a series of stress-strain tests.

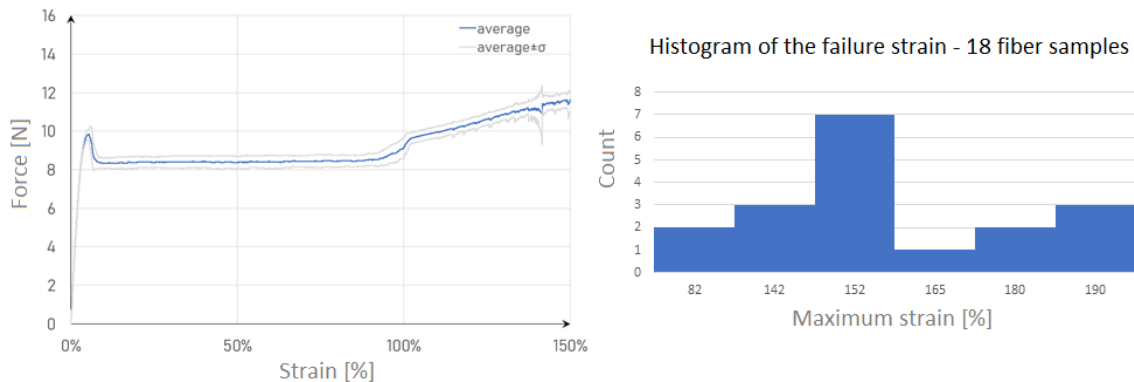


Fig. 4. Mean stress-strain curve with the standard deviation σ (left); Distribution of the failure strain of the sensing fiber (right).

The sensing fiber can normally be strained over 80 % without damage. Some fiber samples even withstood an elongation of 190 %. In a further long-term test of cross-sensitivity to moisture, several fiber samples were stored in distilled water for recording the stress-strain curves at specified time intervals. A slight reduction in breakage strain of around 5% was observed after 271 days. However, this in turn has no negative impact on the use in the strain range of up to 10% as required by end users.

2. Test of the POF-based Digital I-OFDR in the Field

The functionality of the developed measuring system based on digital I-OFDR and the applicability of the PF-POF selected as a distributed fiber optic sensor were tested at the construction site in the section of the federal road B91 near Leipzig, Germany. The renovation work on this section included upgrading the route to a motor road and laying new asphalt layers.

For the purpose of simplifying mechanical embedding of the fiber optic sensors on the construction site, sensing fibers were applied to geosynthetic carrier materials manufactured by HUESKER Synthetic GmbH. Fig. 5 illustrates a geogrid with integrated POFs and pre-incorporated glass optical fibers (GOFs) earmarked for reference strain measurements ready for installation under real construction site conditions. A total of four integrated PF-POF loops were prepared in this way, which means 2 loops in each of the two geogrids prepared for the field test.

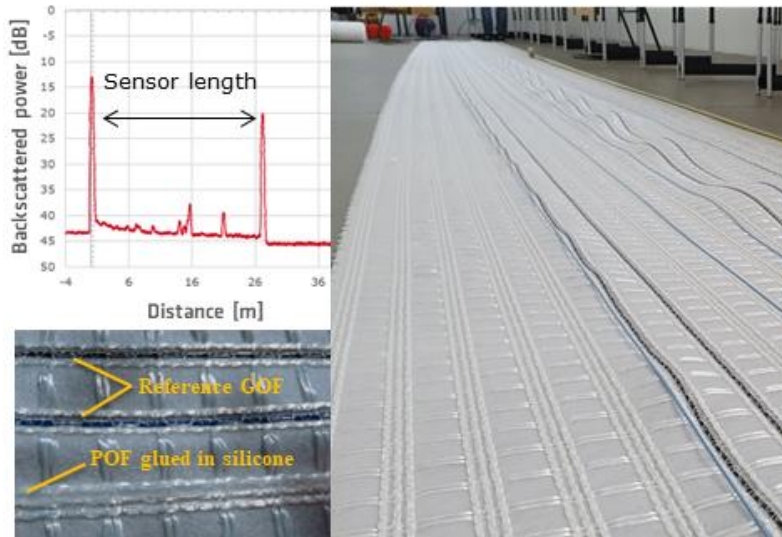


Fig. 5. Instrumentation of a sensor-based geogrid covered with an additional non-woven membrane and a control measurement on a one of the two integrated PF-POF loops (top left).

As shown in Fig. 6, the two geogrids with integrated sensing fibers were installed into the road embankment perpendicular to the driving direction together with further geosynthetics conventionally used for reinforcement [12].



Fig. 6. Installation of sensor-based geogrids under construction site conditions into a road embankment along B91 near Leipzig.

Since the construction work on the road section took several months, the changes in the condition of the sensor-based geogrids caused by the construction progress could be monitored by measurements conducted at different times. The recorded backscatter profiles shown in Fig. 7 confirm the potential of the digital I-OFDR and the usability of PF-POF as a distributed fiber optic strain sensor. In addition to the significant reduction in measurement times, the digital I-OFDR method has the further advantage of improving the signal-to-noise ratio compared to commercial measurements recorded with a ν -OTDR from Luciol Instruments.

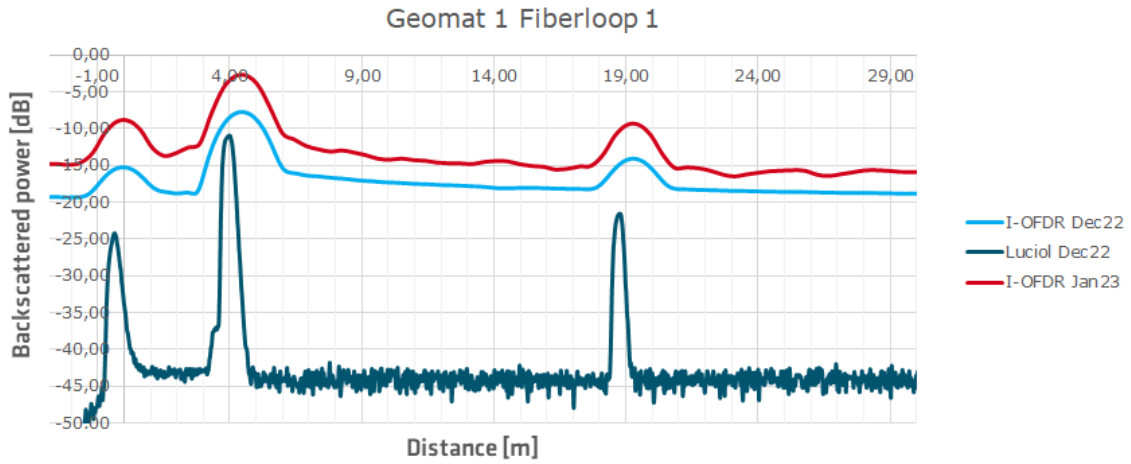


Fig. 7. Backscatter measurements recorded in the field using the digital I-OFDR demonstrator and a commercial measurement device.

The wider local peaks in case of the I-OFDR backscatter profiles compared to the v-OTDR measurements are to be explained by the lower spatial resolution in the range of 1 m by measurements using the digital I-OFDR prototype.

The progress of the construction work was accompanied by slight movements in the soil body of the road embankment. As shown in Figure 8, these changes could be detected using the digital I-OFDR device in the form of the strain-related local increase in backscatter.

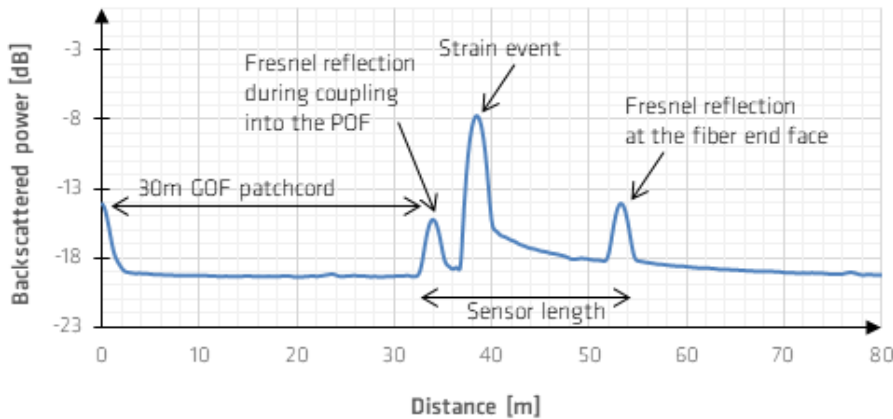


Fig. 8. Backscatter-based detection of a strain event using the digital I-OFDR demonstrator.

4. Conclusions

The presented results prove the functionality of the digital I-OFDR prototype in the field. The sensing system can be used for strain detection up to 10 % as required by end users. Replacing the oversized VNA with the DDAU reduced costs of the measurement device allowing its easy use on construction site. The high elasticity and break-down strain of the PF-POF indicates robustness of the fiber optic sensor needed for distributed sensing of large mechanical deformation.

5. Acknowledgements

This research was supported by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) on the basis of a decision by the German Bundestag (ZIM Central Innovation Programme for small and medium-sized enterprises).

The authors would like to thank Léon Neff (HUESKER Synthetic GmbH) for conducting tests to identify suitable procedures for the preparation of POF sensors integrated into geosynthetics. Special thanks go to Naumburger Bauunion GmbH & Co. for installing the sensor-based geosynthetics and technical support on the site.

References

- [1] Leung, C. K., Wan, K. T., Inaudi, D., Bao, X., Habel, W., Zhou, Z., Ou, J., Ghandehari M., Wu, H.C. and Imai, M., 2015, Review: Optical fiber sensors for civil engineering applications, *Materials and Structures* 48, 871-906
- [2] Monsberger, C. M., Lienhart, W., and Hayden, M., 2020, Distributed fiber optic sensing along driven ductile piles: Design, sensor installation and monitoring benefits, *Journal of Civil Structural Health Monitoring* 10(4), 627-637
- [3] Mizuno, Y., Theodosiou, A., Kalli, K., Liehr, S., Lee, H., and Nakamura, K., 2021, Distributed polymer optical fiber sensors: A review and outlook, *Photonics Research* 9(9), 1719-1733
- [4] Königsbauer, K., Wosniok, A., Nöther, N., and Schaller, M. B., 2023, POF-based digital I-OFDR for strain detection in road construction, *Proc. of SPIE* 12643
- [5] Zangani, D., 2009, Multifunctional textiles for protection against natural hazards, *Advances in Science and Technology* 56, 601-608
- [6] Fuggini, C., Zangani, D., Wosniok, A., Krebber, K., Franitza, P., Gabino, L., and Weigand, F., 2016, Innovative approach in the use of geotextiles for failures prevention in railway embankments, *Transportation Research Procedia* 14, 1875-1883
- [7] Ghafoori-Shiraz, H., and Okoshi, T., 1986, Fault location in optical fibers using optical frequency domain reflectometry, *Journal of lightwave technology* 4(3), 316-322
- [8] Liehr, S., Nöther, N., and Krebber, K., 2009, Incoherent optical frequency domain reflectometry and distributed strain detection in polymer optical fibers, *Measurement Science and Technology* 21(1)
- [9] Liehr, S., and Krebber, K. (2010), A novel quasi-distributed fibre optic displacement sensor for dynamic measurement, *Measurement science and technology* 21(7)
- [10] Dengler, S. A., Lubert, M., Neff, L., Hangen, H., Schmauss, B., Ziemann, O., and Engelbrecht, R., 2023, OTDR Strain and Force Sensing by POF on Geotextiles in a Geotechnical Application Test, *Optical Fiber Sensors*, Optica Publishing Group
- [11] Königsbauer, K., Nöther, N., Schaller, M. B., Wosniok, A., Krebber, K., 2022, Distributed POF sensors for structural health monitoring in civil construction applications, *Proc. Of POF 2022*
- [12] Müller, W. W., and Saathoff, F., 2015, Geosynthetics in geoenvironmental engineering, *Science and technology of advanced materials*