

# Introductory Chapter: Fiber Optics

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## 1. Introduction

Whether covering a few meters or hundreds of kilometers, optical fibers allow to transmit information in a short time. Without communication over long distances, humankind would not have got far. It is the basis of every economic and political development. Up to the twentieth century, however, it was still the stagecoach that brought the information from A to B most quickly—at a speed of no more than 40 km an hour. Nowadays, optical fibers and light-wave technologies enable high-speed data communication.

In summary, this means that long-distance communication works in principle just like a Morse telegraph: a combination of pulsed signal travels in a medium bringing a coded information. The only difference is that we no longer send the signals with electricity, but with light. Indeed, optical fibers carry light in the visible and near-infrared region ( $\sim 100$  THz), and therefore, they are often called light-wave systems to distinguish them from microwave systems ( $\sim 1$  GHz) [1].

The principle is actually the same as in the Morse telegraph. Just as at the end of the 18th century, information is assigned to specific signals or light pulses. However, the copper cable was unsuitable for this purpose. In 1965, Manfred Börner, a German physicist, used a laser instead of a broadband light source to transmit information with optical fibers for the first time.

A typical fiber optic cable, as used by Manfred Börner and currently used all over the world, consists usually of a fiberglass core covered by a fiberglass cladding. To protect against external influences and to prevent scratches or dirt and moisture from penetrating, the entire fiber is covered with a protective layer. The material of the cladding must have a smaller refractive index than the material of the core [2]. This allows for total internal reflection, a phenomenon well known since the first half of the nineteenth century (Colladon and Babinet, Tyndall).

It is noteworthy that for more than a century the total internal reflection was mostly used for illumination systems and image transmission to short distances. The first person to try to transmit images by means of a bundle of optical fibers was Heinrich Lamm, the first to propose a fiber-optic endoscope in 1930 [3].

In 1954, van Heel [4], on one side, and Hopkins and Kapany [5], on the other, simultaneously reported a way of conveying optical images along a glass fiber; in particular, the former writes: “*Preliminary experiments, started in January 1950, have shown that coating the fibres with silver or any other metal yields an unsatisfactory transmission. A much better result was obtained when the fibres were coated with a layer of lower refractive index, which ensured total reflexion*”. The optical fiber was born.

However, for a breakthrough in optical communications, it has been necessary to wait for Börner to first use a fiber-optic cable in combination with a laser. So here he had built a true optical data transmission system. He also employed photodetectors at the end of the fiber optic cable. In 1966, Börner applied for a patent for the system for the targeted transmission of information via optical fibers for the company AEG-Telefunken. And then, it finally came out of the experimental phase

into the technical realization—until today. All optical long-distance transmission systems are also currently working according to this system principle proposed by Manfred Börner.

However, there was still a lot to improve. Because the data transfer did not really work well as the light intensity was simply too low, only short transmission distances were possible. One of the solutions to—at least this problem—was actually quite simple. The fiber material had minimal scratches, cracks, and bumps. Charles Kuen Kao has improved the fiber glass in 1966 and solved the problem. He received the Nobel Prize in 2009 for this and for further developments in fiber optic technology.

And yet, even the best and clearest glass fibers have natural limits. Therefore, it is necessary to amplify the light signal after a certain distance. Initially, intermediate stations were set up, in which the incoming light signal was first converted into an electrical signal—and then again into a light signal. As a result, it had the initial light intensity again and could be transmitted over a long distance. However, this solution was unsatisfactory because the intermediate stations drastically increased transmission time.

To solve this problem, purely optical amplifiers have been developed. With this, it was finally possible to guide the light without interruption over very long distances. The most important and widespread optical amplifier is the erbium-doped fiber amplifier [6]. In this case, a part of the cable is made of a special material that amplifies the light synchronously and seamlessly. The erbium-doped fiber amplifier works much like a laser where the active material (erbium), incorporated in the cable, is pumped to a population inversion state producing a regeneration of the signal intensity by stimulated emission [7]. The data transfer keeps hereby finally its fast pace without interruption of the propagation along the fiber cable. That is why it is on the longest transmission lines in the world, on the transatlantic route between Europe and the United States.

In a further step, several carrier wavelengths are transmitted through a single fiber to increase the information capacity. For this purpose, the wavelengths are all first brought together, which is known as multiplexing. At the receiver side, the wavelengths are separated again by demultiplexing. The further development of fiber transmission is not yet finished. Researchers see further potential, for example, with variable structures of the glass fiber.

A new generation of optical fiber has a fiber core, which is interspersed with holes. In this case, the light is confined not only in the core material but also in the holes or, in particular, in a larger hole in the middle of the fiber core. This works like a veritable turbo in the speed of data transmission. After all, light is extremely fast at around 300,000,000 km/s in vacuum. Unfortunately, the fiber material slows down considerably, by around 30% due to the larger refractive index.

A much better material, then, would simply be air, because it simply slows down less than glass or silicon. That is why researchers at the University of Southampton in 2013 developed a hollow core fiber in which the data could be transmitted at a rate of about 99.7% of the speed of light in vacuum [8]. Thus, data can be transmitted even faster or even more data can be transmitted at the same time.

Current research is also focusing on new modulation formats to increase the data rate and, therefore, to unleash the whole potential of optical communication. Such modulation formats employ different physical properties of light such as the amplitude, phase, and wavelength. During the last decades, several modulation formats like phase shift keying (PSK) and amplitude shift keying (ASK) but also advanced modulation formats such as  $m$ -th order quadrature amplitude modulation (QAM), binary phase shift keying (BPSK), and  $m$ -ASK were realized [9]. To generate such higher modulation formats, novel electrooptical modulators [10–12] are

combined with optical fibers, which is known as active optical fibers. These fibers are of special interest for rack-to-rack applications.

Optical fibers play a crucial role in telecommunication. Applications can be found in many areas such as optical fiber lasers [13], optical fiber interferometers [14, 15], optical fiber amplifier [16], and optical fiber sensors [17]. Especially the latter one has widespread applications in detecting magnetic fields [18], humidity [19], temperature [20], or biological molecules [21].

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