Optical Fibers

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Abstract

Integrating optical fibers into textiles opens up a wide range of new, fascinating applications – starting from data transmission to sensory abilities, new lightening concepts, and advanced medical therapies.

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This chapter gives first an overview on the working principle and light transmission mechanisms in optical fibers. It discusses different types of optical fiber materials, before it summarizes recent developments in processing these materials into textile structures. Finally different application fields are explored, which leads to highlighting future trends and potentials of optical fibers.

Keywords
Optical fibers • Polymer optical fibers • Glass fibers • Refractive index • Data transmission • Light therapy • Optical fiber sensors • Photonic textiles

Introduction

Developing the laser in 1960, optical communications engineering was suddenly spotlighted in the research and development world. While the propagation of laser light in the atmosphere has been studied, an attempt was made to guide light in cable ducts. However, the line required a frequent refocusing of light and therefore lenses were used. Over the time, optical fibers evolved and were broadly accepted as their installation and operating costs were lower and they could be more bended. Optical fibers can be categorized into two groups: glass fibers and polymer optical fibers. Due to their diverging properties, they are both applied in different application areas. The development and evolution of both optical fiber types is briefly described below [1].

Optical Glass Fibers

Glass fibers were already known in 1960. They were able to lead light through curves. However, the materials, at that time known, were not suitable for signal transmission, due to their high losses. A breakthrough was achieved by K. C. Kao and G. A. Hockham in the UK in 1966. They attributed the strong losses to chemical contaminants and proposed suitable fibers for communication purposes. Kao was awarded the Nobel Prize in physics for his pioneering achievements in the field of light transmission in 2009. Already in 1969, the first glass fibers were presented with losses of less than 100 dB/km. Thus, they were suitable for communication purposes. Losses are usually expressed in decibels per kilometer. The decibel is one-tenth of a bel. The name is attributed to A. G. Bell. A bel is referred to as the ratio of two quantities having the dimension of power. Table 1 shows typical values of losses.

In 1970, a fiber with losses below 20 dB/km was produced. Nowadays, a lower limit of 0.2 dB/km is obtained with quartz glass. The cost of glass fibers amounted to 5 US$ per meter in 1981. Today the price is below 10 cents per meter. The tremendous price reduction was achieved, because the cost of the raw material quartz is low, the costs of labor are reduced through a high degree of automation, and the market volume is high.

Table 1 Losses in the decibel range (source: ITA, RWTH Aachen University)

Decibel (dB)	Factor ≈
3	2
6	4
10	10
20	100

The development of glass fibers as optical fibers and the advances in laser sources made it possible that most of our telecommunications systems are based on optical technologies today. Minor losses within the fiber enable the bridging of long distances without intermediate stations. The benefits are also evident in comparison to copper-based coaxial cables when used for long transmission distances. One gram of glass fibers replaces around 10 kg of copper – a great weight and space reduction. This difference is partly caused by the limited power density of copper, which is in turn attributed to the skin effect. The skin effect means that the current density is inconstant over the entire cross section of a conductor. This leads to an increase in electrical resistance, especially with increasing frequency [1].

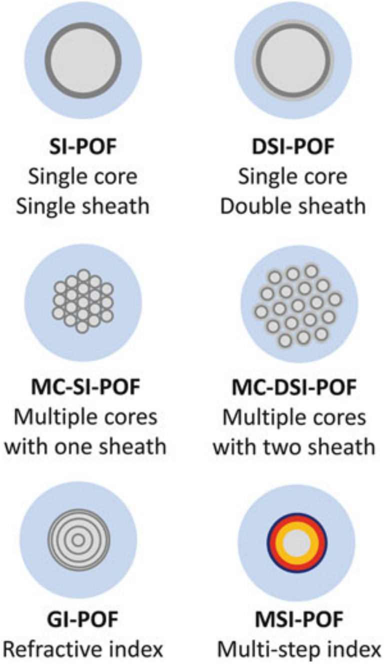
Polymer Optical Fibers

The company DuPont presented the first polymer optical fiber (POF) in 1963. The loss was in the range of 1000 dB/km due to material impurities. In the 1970s, the losses could be reduced to 125 dB/km. This value is close to the theoretical limit for this materials group. The theoretical limit is determined by the unavoidable light absorption of the pure material. However, during this time period, there was no market for these fibers: glass fibers were used for long-distance transmission and copper wires were suitable in the short-range transmission. The progress of digitization in the last two decades has led to a growing demand for powerful transmission systems at short range. Thus, polymer optical fibers are now again increasingly in the focus of research works.

The first polymer optical fibers had, like glass, a single step-index profile (SI-POF). This means that a homogeneous core is surrounded by a single optical cladding. Additionally, a protective layer is coated on top, as illustrated in Fig. 1. An important characteristic of an optical fiber is its numerical aperture (NA). This describes the range of angles within which light that is incident on the fiber will be transmitted along it (see section "Light Transmission by Total Reflection"). For SI-POF a numerical aperture (NA) of 0.5 is used as a standard [2].

Various research teams and companies are continuously looking for ways to improve data transmission rates and to decrease possible bending radii. Nowadays, polymer optical fibers with different core-sheath arrangements exist, which are highlighted in section "Polymer Optical Fibers (Properties and Production)." Figure 1 gives an overview on the different fiber structures existing today.

Fig. 1 Overview of different structures of optical fibers [2]



Light Transmission Mechanisms

The propagation of light in optical fibers can be described as geometrical optics. The basic principles, which are described in the following subsections, apply to both glass fibers and polymer fibers.

Light Transmission by Total Reflection

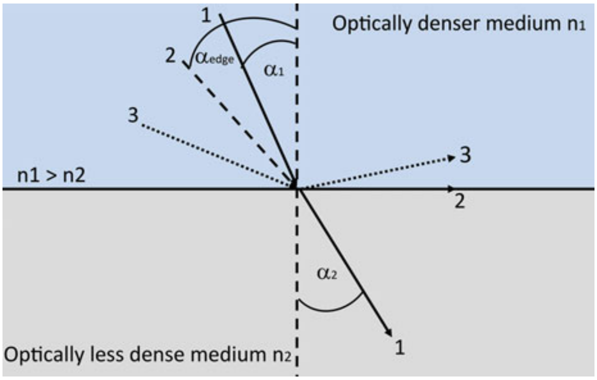
When a light beam passes from one medium to an optically different medium, the light is refracted and reflected at their interface. The refraction depends on the material or medium and a specific material property, which is referred to as refractive index n_{Medium}.

The refractive index is dimensionless and described as the ratio of the speed of light in vacuum c_0 to the speed of propagation of light in the medium c_{Medium}:

$$n_{\text{Medium}} = \frac{c_0}{c_{\text{Medium}}} \tag{1}$$

According to Albert Einstein, the refractive index is greater than one for normal materials.

Fig. 2 Refraction of light and total reflectance



The change of direction of a light beam on a surface can be described by the Snell's law:

$$\frac{\sin \alpha_1}{\sin \alpha_2} = \frac{n_2}{n_1} \tag{2}$$

Knowing the refraction indices of the media, the critical angle can be calculated. Above the critical angle, total reflection occurs at the transition of light from an optically denser material into an optically thinner material, i.e., a light beam is reflected into the denser medium without losses at angles greater than the critical angle [1]. Figure 2 illustrates this phenomenon.

Step-Index Fibers

When designing optical fibers, there are two fundamentally different types: step-index fibers and refractive profile. The step-index fiber is mostly used. It has a core-sheath structure with a circular cross section. Most likely the base material used is glass. The core consists of a glass type with a slightly higher refractive index than the cladding. Hence, the light is guided through the core. The surface of the sheath plays only a minor role, and flaw or damage of the sheath is therefore unproblematic. Nonetheless, the fibers are often additionally coated with a protective layer, as illustrated in Fig. 1.

As light guidance, as discussed earlier, occurs only in the core, the coupled light beam needs to stay inside the core. Light rays passing in the sheath are lost for the light conduit. Hence, the light must be totally reflected at the core-sheath interface. The maximum critical angle $\alpha_{\max}$ can be calculated when considering Snell's law and the trigonometry of the fiber. A typical value for single-mode fibers is $\alpha_{\max} = \pm 7°$:

$$\alpha_{\max} = \arcsin\sqrt{n_{\text{Core}}^2 - n_{\text{Sheath}}^2} \tag{3}$$

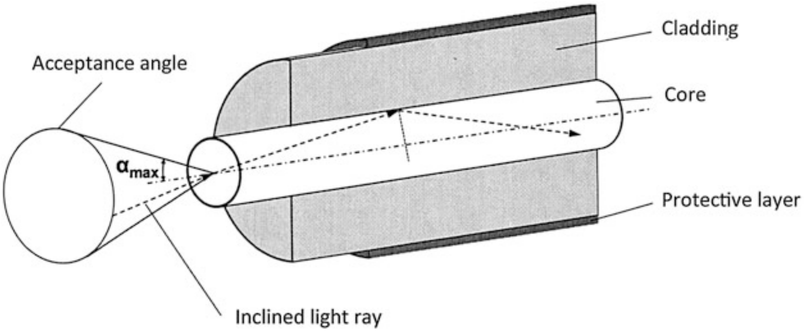


Fig. 3 Principle of aperture and propagation of light in an optical fiber possessing a core-sheath structure

This angle spans that a "cone of acceptance" as within this cone light transmission is possible. The cone is identical when entering the fiber and when exiting due to the irreversibility of the light passing in linear optics. The aperture of light is depicted in Fig. 3.

The argument of arcsin of Eq. 3 is simultaneously a measure of the refractive index difference between core and sheath and is referred to as numerical aperture (NA):

$$\mathrm{NA} = \sqrt{n_{\mathrm{Core}}^2 - n_{\mathrm{Sheath}}^2} \tag{4}$$

A typical value for single-mode fibers is NA = 0.11. Glass multimode optical fibers typically possess values in the range of 0.2. A change of the numerical aperture (NA) affects various fiber properties. An increase of the aperture causes a lower bending sensitivity but an increase in light transmission losses. On top of that, the refraction index difference between core and sheath increases [1, 2].

Modes and Multimode Distortions

For optical fibers, the term mode is often used. There are single- and multimode fibers. Because of its great importance when talking about light transmission, the terms modes and mode dispersion are briefly introduced.

Modes are designated as radiation entering at various angles in the fiber. From Snell's law, it follows that, due to different angles of incidence, other beam paths through the fiber are possible. These may possess different lengths. Figure 4 illustrates this phenomenon.

Since the core has a uniform refractive index, different light paths cause different traveling durations. This results in a transit time jitter for a fed signal. This is also referred to as mode dispersion. As the sub-beams are at an angle to each other, it only leads to an interference pattern over the cross section. If the rays are not inclined to each other, it will come to destructive interference within a few hundred wavelengths due to the path difference. The problem of mode dispersion remains.

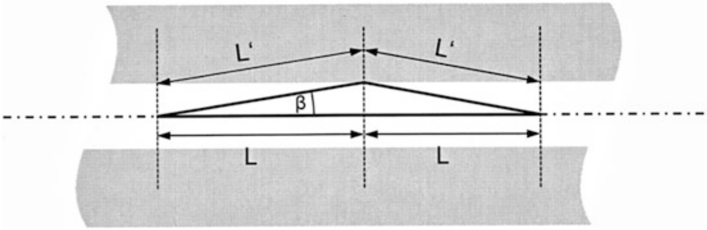


Fig. 4 Mode dispersion: differential mode delay [2]

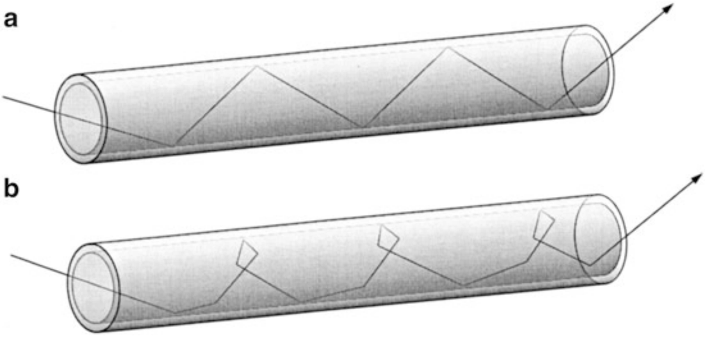


Fig. 5 Propagation of light in the form of a meridional beam (**a**) or helical beam (**b**)

It is even strengthened by a similar effect, which occurs when a coupled beam is inclined in two instead of only one spatial direction. The beam does not spread out as meridional, but propagates as a helical beam on a helix. Figure 5 illustrates these two propagation variations.

These two effects result in a scattering of times. This leads to a broadening of the pulses due to short light pulses and thus to a reduction of the transmission capacity. If the pulses succeed too fast, they cannot be distinguished.

Refractive Index Profile Fibers

Mode dispersion can be minimized or prevented by the use of refractive index profile fibers. This can be achieved by a special refractive index profile as a function of the radius. An optimum can be achieved with a parabolic profile, wherein the profile exponent α equals 2 in Eq. 5:

$$n(r) = \left\{ n_K \sqrt{1 - 2\Delta \left(\frac{r}{R_K} \right)^{\alpha}}; |r| \leq R_K \right. \tag{5}$$

Equation 5 takes into account the core radius r_{Core} as well as the monic refractive index difference Δ and the refractive indices of the core n_{Core} and the cladding n_{Sheath}.

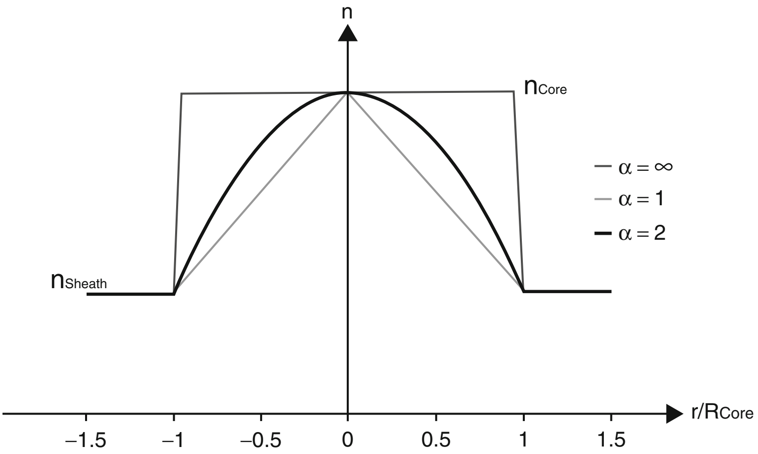


Fig. 6 Three typical index profiles according to [2]

Figure 6 shows three typical index profiles, which result from Equation 5. The y-axis indicates the radius-dependent refractive index. This axis is only partially displayed, since the refractive index difference between core and cladding is very small.

Types of Optical Fibers

Optical fiber types are basically distinguished by their raw materials. They are either based on glass or polymers. For most applications, silica (SiO_2)-based glass fibers are applied. However, polymer fibers have properties that make them attractive for special applications.

While the near-infrared range between 850 and 1,600 nm is particularly well suited for glass fibers, polymer optical fibers are preferred in the visible range from 380 to 780 nm.

Glass Fibers

Glass is the oldest synthetic material. It is used by humans for 7000 years. There are, among other things, evidences of the manufacture of glass from Egypt, Mesopotamia, and China. The modern glass technology has its origin in Germany with Otto Schott (1851–1935), Ernst Abbe (1840–1905), and Carl Zeiss (1816–1888).

The term glass does not describe a special element but a particular spatial arrangement of molecules. Many materials can adopt glassy states. In the optical glass industry, mainly glass made of silica is used.

The irregularity of the glass as compared to the crystal structure causes a local minimum of free energy. The result is a crystallization of the glass. This is known as devitrification [1].

Structure of Glass Fibers

For optical fibers, glassy materials can be used. Crystals are not used because they always contain voids or cross-links, which scatter and reflect the light. This results in larger optical losses. Glass is known as fragile. High flexibility and thus good usability of glass optical fiber result from different effects, e.g., its dimensions. Diameters of optical fibers are in the range of 70–500 μm. Few internal defects may already lead to failure of the fiber in production. The fibers have such a high minimum strength, which has a positive effect on the failure probability.

The main reason for failure of glass is microcracks, which appear when reaching a critical crack length and finally result in total failure of the material. A crack increases as the mechanical energy (caused by residual stress and external stress at the crack tip) is greater than the additional surface energy. Through a minimization of the resistance-reducing microcracks, especially at the glass surface, the flexibility can be increased. In addition, a protective layer can prevent water from entering into the cracks [1].

Production of Glass Fibers

The manufacture of optical fibers can be divided into two steps. In a first step, preform is manufactured typically with a length of about one meter and a diameter of 10–25 mm. The applied methods to manufacture the preform vary among manufacturers and can be outside vapor deposition (OVD), modified chemical vapor deposition (MCVD), Plasma-activated chemical vapour deposition (PACVD), and vapor-phase axial deposition (VAD). When applying the OVD method, glass particles are deposited on a rotating support tube. The glass particles originate from a burner flame, to which gaseous chemicals are added. Subsequently, the resultant glass tube is sintered, the support tube is removed, and the glass tube heats up and collapses. Hence, a massive rod can be produced. The MCVD process is similar to the OVD method: a rotating glass tube is externally heated with a burner flame and gaseous materials are passed through the tube interior. During the PCVD procedure, the tube is electrically heated. The gaseous materials are heated by means of microwave radiation. In this method, the sintering and the rotation of the tube are omitted. The fourth method, the VAD, is different compared to the previously described methods. Here, the glass is formed in a burner flame. The preform is formed in axial direction. A sintering process is required, but the collapsing to a massive rod is eliminated.

During the second step, the preform is molten and stretched to the desired fiber diameter, which is typically 125 or 250 μm. Depending on the drawing ratio, the production speed of the fibers is around 8 m/s. The drawing unit is a major bottleneck during the production. Directly after the cooling down of the pure glass fibers, the fibers are coated with two layers of a protective polymer. The first layer is soft and elastic while the top layer is characterized by rigidness and abrasion resistance. These layers protect the fibers from mechanical and chemical forces [1].

Mechanical Properties

The mechanical strength of glass fibers having a small diameter cannot be compared to glass due to their structure. Glass fibers can be regarded as elastic; the strain is proportional to tension. Elongation can be described by Hooke's law:

$$\frac{\Delta l}{l} = \frac{1}{E} * \frac{F}{A} = \frac{\sigma_{\text{Tensile Strength}}}{E} \tag{6}$$

For optical glass fibers with very small microcracks and a polymer protective layer, the mechanical parameters are in the range of $\Delta l/l_{\text{crit}} = 3\text{–}7\ \%$ for the elongation at break and $\sigma_{\text{Tensile Strength}} = 2{,}000\text{–}5{,}000\ \text{N/mm}^2$ for the tensile strength. During the product life cycle, the strength is decreased by fatigue caused by aging, environmental conditions, and the load history.

The properties of glass fibers lead to very high data rates over long distances. In this area, optical transmission method has displaced the electrical transmission method. Due to their mechanical properties, very small diameters are needed and the minimal possible bending radius is limited. This, in turn, leads to a complex and cost-intensive installation. In particular, the coupling and decoupling of light is complicated due to small diameter sizes. Glass fibers are most likely applied in the area of long-distance communication, as additional costs per unit length are not so high. However, in the area of short-range communication with mostly lower required transmission rates, the fibers have not been successfully applied [1].

Polymer Optical Fibers (Properties and Production)

Polymer optical fibers (POF) have been developed at about the same time as glass fibers. The reason was also the research on optical fibers for optical transmission method according to the development of the laser. First, however, a market for polymeric optical waveguides lacked. Progress in the production of very pure polymer fibers with specific refractive index profiles and the progression of digital development now lead to new market potential for this fiber type. The coupling and decoupling of light in polymer optical fibers having large diameters has become inexpensive and easy. However, the production of the fibers themselves, similar to glass fibers, is associated with high costs. In particular, the generation of a refractive index profile is subjected to an increased difficulty.

Structure of Polymer Optical Fibers

Polymers with linear or branched chains are called thermoplastics. The cohesion of single-molecule chains with each other is solely based on secondary bonding forces. If there are only a few and short branches, the molecular chains will be close to each other. This is called crystallization. Long molecular chains prevent complete crystallization, and such polymers are referred to as semicrystalline thermoplastics. At the boundaries of the crystallites, the light is scattered, which

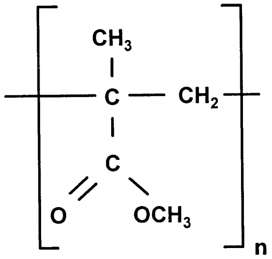


Fig. 7 Chemical formula of PMMA

leads to cloudy or milky optical properties. Plastics with many branches and long side chains are irregular and cannot hold a tight packing. Therefore they have no crystalline areas. The chain molecules are intertwined with each other. They freeze amorphously and are called amorphous thermoplastics. They are optically transparent and crystal clear. Therefore they are also termed synthetic or organic glasses. Typical representatives of amorphous thermoplastics are polymethyl methacrylate (PMMA), polycarbonate (PC), and polyvinyl chloride (PVC) [3].

The thermoplastic PMMA, also known as Plexiglas®, is most commonly used for the production of POF. It is resistant to alkalis, mild acids, gasoline, and mineral and oil of turpentine. The optical transparency is due to the amorphous structure of the macromolecules. The refractive index of PMMA amounts to 1.492. The density is 1.18 g/cm^3 and the region of the glass transition temperature ranges from 95 °C to 125 °C. Each repeat unit of PMMA contains eight CH bonds (Fig. 7).

Many applications require higher operating temperatures. This can be increased when cross-linking PMMA. By means of chemical agents or UV irradiation, the polymer chains are cross-linked to one another. Consequently, the glass transition temperature and thus the operating temperature are increased to 130 °C. Other side effects are deteriorated mechanical properties and an increased scattering. However, the latter offers the possibility to influence the lateral scattering of the fiber.

Another way to increase the operating temperature is the use of polycarbonate. The first PC optical fiber was introduced by Fujitsu in 1986. The operating temperatures are in the range of 130 °C to 147 °C. The disadvantage of this fiber is the high sensitivity to moisture, which leads to a greatly accelerated aging.

Recently, elastomers appear to be suitable as a new family of materials for temperature-resistant POFs. They are also known as elastomeric optical fibers (EOF). The first prototypes have already been realized by some institutions. However, the development of a marketable product is still pending.

Theoretically, cyclic polyolefins can be used as POF material. They can be prepared with a transparent amorphous structure. Their transparency is theoretically better than PMMA, and its glass transition temperature is greater than 150 °C. Currently, however, they are not the subject of research and development projects.

Polystyrene (PS) is also suitable for polymer optical fibers. The first PS-POF was manufactured by Toray in 1972. They can be used in up to 70 °C for use. However, currently they have no significant advantage over PMMA-POF, so they are practically not used at the moment [2].

Production of Polymer Optical Fibers (POF)

Polymer optical fibers can be subdivided into step-index fibers (SI-POF) and index profile fibers (GI-POF). Initially, only step-index fibers were produced. The demand for an increase in the possible data transmission rates has led to the development of index profiles. In the following, different manufacturing processes of two extreme cases are presented: the simplest version of the step-index profile and the most elaborate of the refractive index profile [4].

Production of Step-Index Polymer Optical Fibers (SI-POF)

SI-POFs are produced by continuous processes, such as spinning, extrusion, or drawing from preforms. For the preform methods, first a cylinder is made with a much larger diameter as of the later fiber. The cylinder has a core-sheath structure. The fiber is then drawn out of the cylinder, and the index profile is maintained. Drawing speeds of about 0.2–0.5 m/s can be achieved.

During spinning and extrusion, the core polymer is extruded through a die. The sheath or cladding can be applied directly in a co-extrusion process or thereafter. Some methods make use of an addition cross-linking by UV light, after the polymer has passed through the spinneret. In summary, the spinning and extrusion processes for SI-POF are very similar to conventional melt spinning processes for chemical fibers [2].

Production of Refractive Index Profile Fibers (GI-POF)

The first GI-POFs were presented by Ohtsuka and Hatanaka in 1976. They used a heating drawing method to prepare a fiber composed of a polymer rod. The rod, also called preform, already possessed a gradient profile.

Today, there are five basic manufacturing processes for GI-POF:

- Surface-gel polymerization
- Centrifugation
- Diffusion
- Photochemical reactions
- Extrusion of multilayers (polymerization or coating)

For most methods, a preform is manufactured, which is subsequently thinned to the desired fiber diameter. The preform has a diameter of up to 50 mm.

The surface-gel polymerization technique was developed by Yasuhiro Koike, Keio University, in Japan in the 1990s. In this method, a PMMA tube is filled with two monomers. One monomer has a higher refractive index and large molecules, while the other one is characterized by a small refractive index and small molecules. Subsequently, the tube is rotated at 95 °C for about 24 h. First, the inner wall of the tube is slightly etched. It forms a gel layer which accelerates the polymerization. The smaller monomer can better diffuse into the gel layer. In this way, a concentration gradient forms in the tube. This is fixed with the progressing polymerization of the gel layer. Thus, the desired gradient index can be generated.

The first considerations for the production of GI-POF by centrifugation originate also from the 1990s. The differences in density of different monomers are used as different centrifugal forces lead to a concentration gradient during centrifugation. When the concentration gradient is fixed, a graded index profile can be produced. Fixing is usually caused by an increase in temperature after the desired profile has been formed. One has to take into account process times of 24 h for the formation of the index profile and 12 h for polymerization. So far, this production technology could not be transferred to an industrialized process.

In 2001, a method based on diffusion and rotation was presented. In this method, a cylindrical glass reactor is equipped with two materials: a monomer which surrounds a rod of a material having a higher refractive index. The rod material diffuses slowly in the surrounding monomer at room temperature. The rod and the reactor rotate at different speeds, ranging from 6 to 60 min^{-1}. In this way, process variations can be compensated and a rotationally symmetrical profile is formed. This process takes several hours. Subsequently, the polymerization is initiated by an increase in temperature and the profile is fixed.

Some older methods use photo-copolymerization to shape the index profile. In these cases, a rotating glass tube is filled with a monomer mixture and irradiated with UV light. Due to the higher radiation intensity in the outer regions, the polymerization proceeds rapidly. Thus, a gel forms. If the lower-breaking monomer component has a higher reaction rate, it will accumulate in the outer regions. At higher temperatures, the index profile can be adjusted and finally fixed.

Extrusion of multiple layers is explored for the production of multi-step-index fibers [2, 4].

A more recent development is the polymerization in the centrifuge developed by C. W. Park. The rotation is not used for separation, but to form a rotationally symmetrical index profile. The profile itself is obtained by copolymerizing a polymer blend; its composition is changed stepwise or continuously. The polymerization is initiated by heat or UV radiation. This method results in fibers with a fine layer structure, which leads to an almost ideal parabolic index profile. The process was patented in 1996 [5].

Most of the manufacturing methods of GI-POF use an intermediate step of a preform which is subsequently drawn to the desired fiber diameter. A continuous production for PF-GI-POF has been developed by the company Chromis Fiberoptics (formerly Lucent, OFS). In this method, a SI-POF is first prepared by a co-extrusion. While the core consists of doped CYTOP®, undoped CYTOP® is used for the cladding. Thereafter, a protective layer is applied. The index profile is adjusted by the diffusion of the doping material, which is activated through temperature [2, 4].

Properties of Polymer Optical Fibers

The mechanical properties of polymer optical fibers are characterized by the same effects as for other synthetic fibers. Their properties are optimized, however, particularly in respect to their optical properties. Amorphous thermoplastics are fragile glasses. This means that their viscosity strongly increases with decreasing temperature. The temperature-dependent change in viscosity can be described by the Vogel-Fulcher law. At higher temperatures, the Arrhenius law applies. Despite the high viscosity, relaxation processes occur in a nonfrozen state of equilibrium in the polymer. These are mainly local rearrangement processes by movement of chain segments and rotations of side groups or parts of them. The relaxation processes are strongly temperature dependent. Long-term storage, for example, leads to embrittling of the polymers just below the glass transition temperature. By a UV irradiation, a similar effect is caused in many polymers. The mechanical strength can be described by Hooke's law in the elastic range. The stretchability during the manufacturing process is temperature dependent. With decreasing temperature, the polymers become more brittle. While drawing, the chain molecules are oriented in fiber direction by the high tensile stresses. If the orientation by local rearrangements cannot take place, crazes are formed. These are elliptical areas in which highly stretched polymer fibrils and microcavities alternate. In the deformation of amorphous polymers, they are visible by white lines in the otherwise transparent material. They can be recognized as white lines in transparent materials during deformation of the polymer fiber. Hence, material defects can strongly affect the optical properties of such a fiber. The transparency of polymer fibers is negatively influenced by microcracks. These are usually caused by inhomogeneities in the material, such as surface defects, foreign bodies, or residual stresses caused by inhomogeneous cooling. In addition, microcracks are often the cause of material failure (break) at too high loads. In this case, the cracks propagate in excess of the critical crack stress. In principle, the fracture properties can be varied by the addition of plasticizers such as methanol. However, plasticizers are often undesirable, because they degrade the optical properties [6].

The mechanical performance properties of polymer optical fibers are better than those of glass fibers. Especially fibers with larger diameter and smaller minimum bending radii can be produced. Depending on the polymer material, the fibers can withstand fatigue bending without loss of optical properties or mechanical failure. However, the absorption properties of the materials lead to a much higher attenuation compared to glass fibers. As a result, polymer optical fibers are often better suited when looking at the performance properties and costs but eliminated due to their high attenuation. Therefore, they play no role in the long-distance communication. The number of required repeaters would be too high. Instead they can be used as sensors, sensor cables, or lighting elements [2].

Processing Optical Fibers into Textile Structures

Optical fibers are challenging when it comes to integrating them into a textile structure. They are sensitive to bending and mechanical stress. The minimum bending radius of a fiber is the smallest possible value of the radius of the arc formed by the fiber as it is bent. If the fiber is bent over this radius, it will break immediately. Usually the bending radius is at least several millimeters. For instance, a typical polymer optical fiber with a diameter of 250 μm has a minimum bending radius of 1.5 mm [7]. Processing optical fibers into textile products leads to thin and lightweight structure, offering manifold 2D design possibilities. Advantages of optical fiber solutions are multifaceted. Optical fiber textiles enrich the range of illuminating products with their enhanced appearance, flexibility, and even drapability.

The most explored textile technology to process optical fibers into textile structures is weaving. The individual characteristics of different weaving patterns and weft insertion principles offer a variety of optical fiber textile structures. In most applications optical fibers are used as weft yarns to allow a certain flexibility during production since weft yarns can be exchanged easily. When applying them in warp direction, optical fibers are exposed to more process steps and are guided over and through more machine elements, hence, causing friction and tension. Warp yarns are spooled onto a warp beam, guided through weaving frames and bent up and down during shed action. This exposes the warp to more stress than weft yarns, possibly damaging the surface or breaking the fibers [8].

Flexibility and drape, typical characteristics of a textile, are influenced by the arrangement and type of optical fibers used to create a woven optical fiber fabric. Generally, the fiber diameter, the weaving pattern, and the fabric density (number of yarns per cm) influence the flexibility [9]. The selection of the right fiber diameter is crucial, as a thick fiber causes inflexibility and fibers with small diameters result in low shear resistance and loss of light intensity. Furthermore, choosing an open weaving pattern increases the flexibility and bendability of an optical fiber fabric.

Knitting optical fibers is mostly explored by the creative industry to create illuminating interior textiles and installations as knitted structures are able to conform to sophisticated forms. As the bending and friction forces during the loop-forming process tend to be very high, optical fibers may break. A way to integrate optical fibers in a knitted structure is achieved by weft insertion or inlays.

Embroidery is another technology that is explored to apply optical fibers onto a textile substrate. Most likely, tailored fiber placement (TFP), where the optical fiber is attached to the substrate material, fixing it with a sewing yarn in a zigzag manner, is applied. This technique allows freedom in pattern shapes and designs.

Application Fields

Being originally developed for data communication, optical fibers are increasingly explored for illumination and sensing applications nowadays. This section provides an overview on a variety of application fields of optical fibers.

Data Transmission

Modern technologies often address optical fibers as an efficient scope for fast and reliable data transfer. There is a lot of literature available on optics applications

Fig. 8 Wearable Motherboard^{TM} for vital signs monitoring based on optical fiber technology [11]

for these purposes, and optics technology for data transmission is already presented on the market in a great variety of products. Since the first attempts to develop smart clothes and textiles appeared, optical fibers were used for data transmission. Already as a classic example of optical fiber application in smart textiles, the Wearable Motherboard^{TM} (Fig. 8) developed by Georgia Tech can be mentioned [10]. In this study, optical fibers carry multiple functions and ensure both biomonitoring and data transmission. A vast field of research is technical textiles which enable sensorial functions ensured by optics technology. Also herein optical fibers provide continuous data flow to the processing unit, making them advantageous and multifunctional material for smart textile developers.

Light Therapy

Optical fibers have a significant role in biomedical engineering, especially based on laser technologies. Those are crucial compounds in many medical devices for imaging and diagnostics for all medicine spheres. Within new social, technological, and economic trends, optical fibers found applications in wearable technologies and particularly in smart textiles for medicine and healthcare. Optical fiber technology for medicine can be used not only as a sensorial compound but also a mean of healing, i.e., in light or phototherapy. In phototherapy, exposed light of specific wavelengths is applied for therapeutic purposes. For therapeutic applications, a polychromatic polarized light can be used or light generated by LEDs, fluorescent, dichroic lamps, or very bright full-spectrum light. Light therapy finds applications in dermatology, wound healing and treatment of neonatal jaundice, neuropathy, and blood circulation damages and is effective in circadian sleep rhythm disorders. Some have reported that light therapy can be an asset in the treatment of such serious disorders as Parkinson's and Alzheimer diseases. For some applications though, light is not enough as the only instrument treatment. Then treatment results

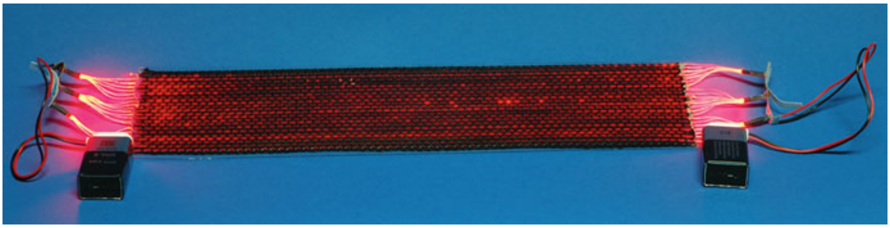


Fig. 9 Woven textile light diffusers

depend on a combination of several parameters that include also drug dose or photosensitizer (PS), drug-light interval, and oxygen and light influence rate [12]. Such light therapy is referred as photodynamic therapy and is important in antitumor immunity. In this case, the PS increases light therapy efficiency by targeting the tumor cells, and light affects exactly the cancer cells.

Initially, research that focuses on textile-based technology for light therapy has addressed light-emitting diodes (LEDs). Some of these solutions are already available on the market, such as the BlueTouch Technology by Philips. In this approach textiles serve as a carrier material and the primary function is brought by LEDs. This approach is a fine solution for applications in which flexibility and drapability are secondary requirements. However, for applications, in which textile properties are crucial, optical fibers may be used. Above that, optical fibers are not influenced by thermoelectrical effects that might cause inconveniences in ready-made clinically tested product manufacturing. Moreover, the integration technology of optical fibers is a continuous processing that can be carried out by such conventional textile manufacturing methods as weaving, knitting, embroidery, and braiding.

Although this sphere of optical fiber use for smart textile development can be regarded as relatively new and challenging in comparison with other applications, there are already a number of studies reported that have started investigations and manufacturing of textile diffusers [13, 14]. To create a textile light diffuser, POFs are appropriate candidates due to their physical properties, while weaving technology encourages design and production of a homogenous flexible light diffuser (Fig. 9). Moreover, this approach has a number of advantages when a large-area light-emitting probe is necessary to be manufactured. On the other side, a single optical fiber can be an asset for miniature concepts and find itself in such applications as wound healing.

Nevertheless, it should be mentioned that single optical fiber phototherapy units are already available for customers online [15].

Sensors

Sensorial functions based on optics are demanded in many technical and medical spheres. Physical and biochemical measurements are required almost in every field of human activity. Smart textile sensors first of all can be referred to as wearable

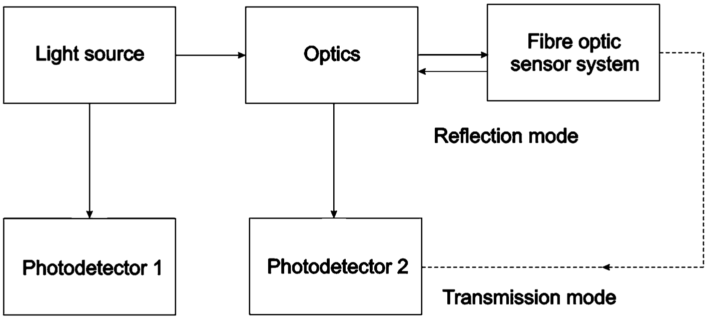


Fig. 10 Block diagram of a generic optical fiber sensor (Adapted from Gupta [16])

and wireless technology. Although the idea of wearables goes down to the 2nd part of the twentieth century, a significant breakthrough was achieved only in the 1990s, and one of the first materials considered for flexible textile-based sensor implementation was optical fibers.

Optical fiber sensors can be defined as fiber-based devices for assessment of physical measurands and concentration of chemical species. The most simple and common scenario to describe the working principle of optical fiber sensors is measuring the changes in the input and output light, i.e., the measurand is characterized by the light loss. Another common approach is time measurements of light distribution over the fiber. In both cases, the light is generated by a light source and then is coupled into the fiber by the appropriate optics in a single fiber or in one or several fiber Bragg gratings. The instrumentation of such sensors varies in their complexity according to specific technical requirements and applications. The working principle of a generic optical fiber sensor is visually introduced in a block diagram pictured in Fig. 10 [16].

Modern fiber-optic sensor technology originally goes down to the breakthrough achieved over five decades ago in the 1960s, when laser technology and low-loss optical fibers were investigated. It aroused the interest was followed by pioneering experimental works focusing on the use of low-loss optical fibers for sensorial applications. It aroused the interest for the sensing and measurement potentials of optical fiber technology in R&D sphere. At present, there are a variety of manufacturing methods to produce optical fibers for sensorial applications that ensure an efficient measuring process [17]. The main advantageous characteristics of optical fiber sensors are their lightweight, compact size, flexibility, immunity to electromagnetic interference (EMI), high sensitivity, large bandwidth, efficient signal transmission, potential of distributed sensing, and relatively low cost.

Optical fiber sensors generally can be divided into physical and chemical or biochemical sensors and have many technical and medical applications competing on the market with electronic measurement devices.

Optical fiber technology can provide appealing solutions to assess such measurands as strain, temperature, pressure, current and voltage, rotation, vibration and acceleration, bending and torsion, positioning, or displacement [18].

This technology is based on physical parameter investigations. It is widely used in structural health monitoring to evaluate stress and strain in buildings and vehicle constructions. Moreover, such lightweight sensor arrays enable remote data transmission.

Above that, optical fibers find applications in the development of biosensors. Those are capable of ensuring qualitative and quantitative assessment of bimolecular interactions and detecting toxic substances and some chemical constituents [19]. Biosensing and biochemical optical sensing is crucial in biotechnology, water and air quality monitoring, and medicine and is used for sensing such parameters as pH, partial pressure of carbon dioxide, glucose, and oxygen.

Optical fiber sensor technology is also an appealing know-how in the sphere of smart and intelligent textiles. The integration process of optical fibers can be fully automated and implemented with such conventional technologies as knitting and weaving. Moreover, these processing techniques ensure dimensional variations and manufacturing of large-scale sensorial areas [20]. Attempts to explore the potentials of optical fiber technology for intelligent textiles started within the first steps toward smart textile development. One of the first successful multifunctional smart clothing prototypes was developed more than 10 years ago. It was mostly based on optics technology using fibers as sensors and data transfer modules. At present, optical fiber is used in manufacturing of biosensing textiles and textile-integrated physical sensors for biomedical and technical applications.

Optical fiber sensor technology is a vast topic involving different manufacturing, processing, and measurement approaches. Hereby, in order to provide summarized information on optical fiber sensors for smart textile applications, those will be grouped and described according to the assessed measurands.

Temperature Sensors

Temperature is a significant factor in manufacturing, physiological, and biological processes. Optical fiber-based temperature sensors have a wide range of measured temperature and can operate at different environmental conditions [21]. Specifically designed and processed optical fiber sensors for temperature estimation have indeed many applications in technical and medical sphere. Temperature sensors based on optical fiber technology are in a great variety available on the market. Nevertheless, in the R&D sphere, those still arouse interest and encourage attempts to improve their performance and properties.

Smart textiles that are in the focus of many applied research projects definitely encourage further investigations and the development of textile-integrated sensors for temperature control. Such textile-integrated sensor or sensor arrays are used for microclimate evaluation and acquisition of body temperature. Especially for medicine and healthcare applications, optical fibers are promising materials to ensure continuous manufacturing and efficient processing of textile sensors based on optic technology.

The fiber Bragg grating (FBG) is the most widespread approach to produce a textile-integrated single sensor or sensor array for temperature assessment that is based on optic technology. FBGs can be defined as intrinsic fiber compounds/elements

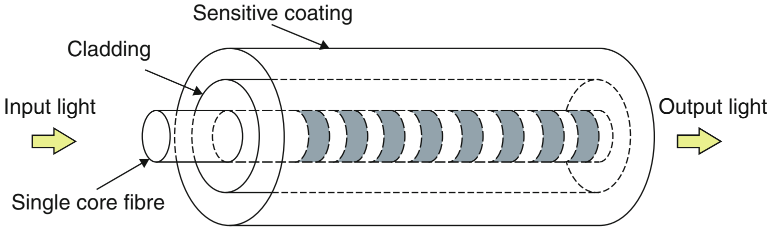


Fig. 11 General scheme of an optical fiber sensor based on FBG

in photosensitive fibers where the index of refraction in the fiber core is periodically modulated by illuminating UV light [22]. According to its processing, the FBG is used to develop a sensor for estimation of a great number of sensors with different applications. Figure 11 displays a generalized scheme of a FBG sensor, which can be applied to describe optical fiber sensors for the assessment of various parameters. Those can be used for evaluation of metal corrosion, bone declaration, humidity, gas, pressure mapping, deformation, and many other phenomena.

There are a number of characteristics that make the FBG an appropriate technologic solution for temperature sensor development in smart textile applications. Namely, FBGs have such advantageous characteristics as versatility for wavelength-encoding applications and simple manufacturing process that ensures regulation of such parameters as period, length, amplitude, apodization, and chirp of the fiber grating. Moreover, such sensors are highly sensible, continuously stable during use, and flexible and have immunity for electromagnetic interference [23]. At present, this topic attracts much interest, and many research projects have explored and continue their scientific work on the topic looking for solutions suitable for smart textile applications. According to specific requirements, the FBG sensor can be manufactured by joining different technologies; particularly such processing is made to increase such properties of the sensor as sensitivity and resolution. A bare FBG usually does not have enough temperature sensitivity (10 pm/°C at 1 550 nm) for physiological applications [24]. Thus, in order to create a durable FBG sensor with efficient performance, such approaches as cladding-etching, polymer packaging, coating, and many others can be applied. Processing that involves temperature-sensitive materials accordingly has a significant effect on the sensor thermal sensitivity [25].

Temperature values are estimated from the dependence of the wavelength and temperature changes. This relationship results in changes of the effective index based on the thermo-optic effect and thermal expansion of the glass material [26].

An example of an optical temperature sensor embedded into textiles is presented by [25]. The research team enhanced the sensing properties of the optical fiber by polymer packaging and achieved both stable structure of the optical sensor and relevant linear relationship between the FBG wavelength and measured temperature. The polymer used for the fiber processing is a copolymerization of unsaturated polyester resin mixtures. The first compound (5.0 wt% methyl ethyl ketone peroxide (MEKP)) was produced by the polycondensation of saturated and unsaturated dicarboxylic acids with glycols, which ensures highly durable structures and coating. Another polymer compound was 2.0 wt% cobalt naphthenate. Such a processing of the FBG has increased the efficiency of temperature measurements almost 15 times in comparison to the bare FBG. Subsequently, the developed FBG sensor was integrated into a woven fabric. It is crucial to mention that in this case, the sensor is not applied directly to the body, but is separated by an air gap between the skin and clothing. Hereby, the authors offer a mathematical model taking into consideration these particularities of the wearable system. Such a data processing allows acquiring more accurate values to estimate the real body temperature [25].

Besides wearable applications for physiological assessment, this approach has outlooks in structural health monitoring. Braiding technology ensures efficient integration of FBG-based sensors into various composite reinforcement structures. Above that, FBGs can be successfully used to evaluate other crucial parameters for construction quality evaluation, making this optical fiber technology multifunctional and interesting for investigations.

Strain Sensor

One of the most reported application of optical fiber sensors in smart technical and medical textiles is strain or stress measurement. Such sensors assist in monitoring of construction, geotechnics, medicine, and wellness. They give information on mechanical deformations and displacements. Thus, besides structural health monitoring, those have potentials in kinematic analysis. Moreover, optical fiber strain sensors find practical applications as pressure sensors in such fields as industrial process control, dental medicine, ulcer prevention, structural health monitoring in oil wells, and power plants [27, 28].

There are various scenarios for such sensor development resulting in the use of different materials or types of optical fiber sensors and accordingly sensing and data processing techniques. Finally, there are different offered solutions for sensor embedment into a textile structure. Of course, those are chosen accordingly to specific technical requirements and application specifics. Such textiles with integrated optical fiber sensors are already manufactured industriously and are available on the market. Still, in order to improve the technology and expand its applications, this topic is also in the focus of applied research [29]. Due to a great number of sensing techniques and a variety of used materials and approaches to data acquisition, only several most spectacular examples of strain sensors are briefly described further.

Initially, the concept of an optical fiber strain sensor is based on mechanical deformations of the optical fiber polymer coating. Deformation of the polymer structure, in which the optical fiber is embedded, results in modulation of the light passing through the optical fiber core. These changes can be described by physical parameters, and, thus, stress provided by the environment can be calculated.

One of the strain measurement approaches is based on silica fiber distributed sensors. Some years ago, one of the interesting and often used approaches in the variety of strain sensing techniques applied in geotechnical textiles was Brillouin optical fiber time-domain analysis (BOTDA). This approach is based on the

Fig. 12 Optical fiber pressure sensor: plastic optical fiber and two samples of a sensor-woven structure [30]

relationships of the transmitted light, which is sent as a short pulse along the optical fiber, and the backscattered light over the time function. The processed results of this process provide information on the strain applied to the sensor. Such sensor system can operate with a probe distance of 20–30 km but results in low resolution. At present, it is substituted with a more advanced data transmission and processing approach called Brillouin optical fiber frequency-domain analysis (BOFDA). It is based on measurements of a baseband transfer function in frequency domain by a network analyzer. It has a range of advantages such as data processing efficiency and obtained signal quality. Such distributed Brillouin sensor arrays that can be applied for monitoring of long-distance areas are of great interest and potentials for industry. Thus, there are several examples of research projects carried out to encourage further developments of such smart geotextiles [30].

Geotechnical textiles with strain sensor arrays can be developed in various structures, for example, nonwoven, woven, and braided. Especially for geotechnical textiles and those for other technical applications, textile technology offers efficient and low-cost solution in smart monitoring structure development. Figure 12 displays an industriously manufactured geotechnical textile sample [31].

Pressure Sensors

Optical fiber technology finds also applications in pressure sensing and mapping that can be implemented by different approaches. There are many examples of studies based on optics technology using different types of optical fibers. Weaving technology offers vast opportunities in pressure sensor implementation with pattern and structure variation. Some examples of woven pressure sensor design are presented by Swiss company EMPA professionals. They used a flexible silicone fiber to manufacture pressure samples with different patterns (Fig. 13) [30].

Other studies offer pressure sensor implementation addressing interferometry. Moreover, optical fiber sensors based on Fabry-Perot interferometric technology are reported to be able to capture the dynamic pressure transient changes during a blast. Such sensors can assist in the evaluation of a ballistic wave dynamics in military applications [32]. Some studies use also a combined approach of using interferometry technology and FBGs for multiparameter sensor system development [33, 34].

Such sensors find potential applications both in medicine and healthcare and monitoring of structural defects [35].

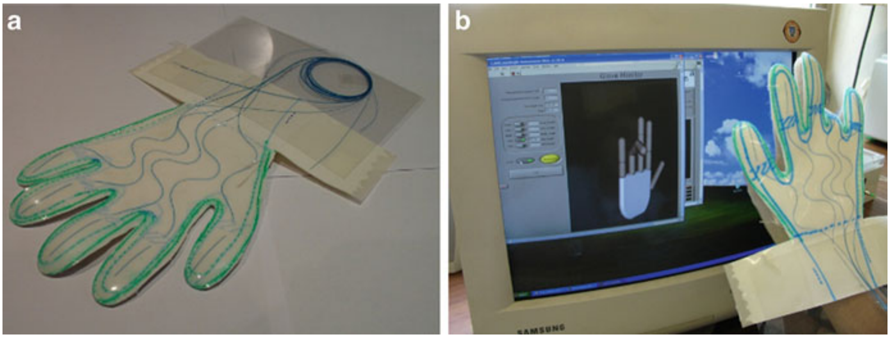


Fig. 13 Smart glove with integrated FBGs for motion visualization (© 2013 Carmo et al., licensee InTech. This is an open access chapter distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited) [38]

Humidity Sensor

Another crucial parameter describing the environment is humidity level. Usually it is associated with relative humidity (%) that traditionally indicates saturation of water vapor in the air. As absolute humidity, the amount of water in a substance is indicted.

Humidity level control is crucial in many technical and medical applications. Optical fiber technology for humidity assessment finds applications in geotechnical and technical textiles for structural monitoring. Moreover, an irrelevant humidity level can injure the construction or encourage bacteria and fungi growth. Above that, it has a great influence on such physiological processes as respiration and cardiac activity.

Since recent years along with the progress in technology, the number of competing techniques and optical fiber solutions for humidity measurements has significantly increased. Optical fiber solutions for humidity estimation include a variety of sensing techniques and involve application of in-fiber grating, evanescent wave techniques, hybrid approaches, and interferometric and absorption methods [36].

Previously described FBG sensors find vast applications also in humidity assessment. Moreover, such sensors are already available on the market, indicating the approach efficiency. Humidity sensing properties of FBG sensors are related to their strain sensitivity. The polymer coats the optical fiber, absorbs the moisture, swells, and expands in volume, thus applying stress on the grating. Such an effect causes the changes in the resonance wavelength, and humidity can be calculated from the strain function.

Kinematic Analysis and Motion Sensor

Kinematic analysis is of a great importance in physiotherapy, rehabilitation, sports medicine, and other spheres of healthcare. It regards gait and posture monitoring, as well as the assessment of dynamics and movements of a particular body part.

One of the urgent problems that encourage the development of such smart textiles is deviations of spinal curvatures and related diseases. Those might be concerned with both physical and social problems of patients of different ages, e.g., discomfort due to pains caused by spinal deformities and contorted posture. Assessments of the spinal cord are commonly realized by radiography, ultrasonography, and other methods that require to be realized by professionals in clinical or laboratory environments. Reduction of spinal deformities and improvement of posture require generally long-lasting therapeutic and physiotherapeutic treatments, e.g., orthotic intervention and therapeutic physical training. Still some extra arrangements might be appropriate during or after therapeutic and physiotherapeutic treatments to control and improve patient's posture in everyday life. One of the options to control patient body position for a long-lasting period is the application of wearable sensor arrays integrated into textiles.

There are a great number of research projects devoted to investigations and exploring possible wearable solutions. Many of them focus on application of inertial sensor systems involving accelerometers and gyroscopes. Nevertheless, textile-integrated systems based on optical fiber technology for these purposes have a range of advantages in comparison with the former due to continuous technological process ensured by such technologies as weaving and tailored fiber placement embroidery.

Initially, optical fiber sensors for motion control and kinematic analysis, as well as some optical fiber sensors for other physiological parameter assessments, are based on the working principle of the strain sensor, which is described in the previous part of the chapter.

Physical and mechanical properties of polymer optical fibers (POFs), as well as simplicity in signal processing, make them attractive both for technical and biomedical applications. Several research projects have introduced textile-integrated POF sensors for health monitoring. For example, an Irish research team has developed a vest with an integrated POF sensor for posture monitoring and control. The POF is integrated to ensure real-time evaluation of the trunk position in the sagittal plain. Strain measurements are caused by mechanical deformations in the fiber sensor that correspond to the wearer's posture [37].

There are also examples of FBG sensor applications for motion monitoring and visualization. One of the described approaches that ensures relatively simple and effective gait monitoring in real time can be implemented by measuring knee movements. This research project suggested the development of a sensing elastic bandage placed around the knee. One of the crucial objectives in such system is accurate measurements during flexion and extension dynamics that characterize movements of a knee joint. FBGs were integrated on a flexible stretchable foil and placed on a hosting polyvinyl chloride (PVC) material [38]. The same approach was applied in the manufacturing of a smart glove with integrated FBGs on a polymeric foil. The obtained data were used to visually reproduce movements of the wearer's hand.

Respiration Rate Monitoring Sensor

Respiration rate is one of the vital parameters that is crucial to be monitored both in preventive and therapeutic purposes. There is already a variety of attempts describing scenarios for smart textile development in order to ensure breath monitoring.

Optics technology offers a technologically simple and efficient solution based on mechanical deformation of the sensors.

One of the most spectacular examples of optical fiber solutions for physiological monitoring is found in the research project OFSETH, which has achieved breakthrough results by developing a respiration rate sensor based on a bare optical fiber fully integrated into textiles. Although other alternatives have already existed before, this development was created particularly for a magnetic resonance imaging (MRI) environment, where conventional medical devices are not compatible or may complicate the examining process. The assessment of respiration rate by optical fiber sensor was ensured by measuring abdominal and thoracic respiratory movements. In the frames of the research project, several scenarios for the wearable sensor were accomplished. Those have addressed different types of optical fibers and implementation technology solutions. Nevertheless, a special focus in the research was made on POF sensor applications as an alternative solution to silica-based fiber due to its biocompatibility [39].

Besides wearable textile sensors, there are possible alternative solutions for respiration monitoring via optical fiber technology. A research team from Japan has reported about the application of an optical fiber pressure sensor as a system for continuous real-time respiration monitoring in a radiation therapy environment. The system was developed on a commercially available pressure sheet that consisted of optical fibers and “Kinotex” tactile sensors embedded in urethane cellular foam. The working principle of the sheet is based on evaluation of changes in light scatter intensity caused by applied pressure. Synchronization and calibration of the acquired data according to a reference medical spirometer ensured the opportunity to display the respiratory wave profile [40].

Another research project carried out in Slovenia has proposed the estimation of respiration rate and heartbeat by a technique based on optical interferometer and wavelet transform. The working principle of interferometry sensors is based on measurements of optical fiber elongation. According to the reviewed literature, such sensors are reported to be of high sensitivity and capable of reacting to micrometric changes in optical fiber length. These characteristics of the described approach bring new potentials for biomonitoring smart textile developers. In this case, the interferometer of the experimental setup was a twisted optical fiber placed under persons’ body. Physiological information about respiration and heartbeat was estimated by processing the distorted interferometric signals caused by the mechanical motions during breathing and cardiac activity [41].

Sensor for Cardiac Activity Assessment

Cardiac activity can be characterized by heartbeat and electrocardiography (ECG). Monitoring of cardiac activity was initially a challenging task for smart textile developers, and at present, there are a variety of solutions using different approaches. Optical fibers for cardiac assessment primarily have potentials in clinical applications during MRI.

Heart frequency can be estimated from cardiopulmonary components registered by optical fiber sensors, and this parameter can be obtained by processing physiological data acquired by respiratory optical fiber sensor. This approach is suitable for compact and wearable solutions.

More complicated objectives appear in a sensorial system development for electrocardiographic signal estimation. There are already several studies that have investigated and reported about the applications of optical fiber-based sensors in biopotential activity estimation [42]. One of the scenarios to implement an optical fiber-based bioelectric acquisition system is the application of an interferometer module as the sensing compound. For example, Fernandes at el. proposed a wearable solution based on the electro-optic technology. It uses a photonic setup, which consists of a photodiode, dual-drive lithium niobate ($LiNbO_3$) and Mach-Zehnder interferometer (MZI) modulator, and electronic circuitry for signal processing [43].

Biochemical Sensors

Besides physical measurements, optical fiber-based technology is often chosen for manufacturing biochemical sensors. This is a challenging and promising research field that finds applications for different purposes and environments. Those can be gas sensors where a significant compound of the optical sensor is its coating. In this case, this coating acts as a “smart skin” reacting with specific chemicals in the environment [44].

Hereby, the studies that are looking for new solutions for gas sensing primarily focus on fiber coating technologies, their chemical sensing properties, and durability of the coating. Optical fiber sensors are used as indicators for such chemical compounds as ethanol, methanol and formaldehyde vapor, ammonia gas, etc. [45, 46]. Sensitivity and durability of a gas sensor can be increased by using a multilayer coating approach [47].

Textile-integrated optical sensors for biochemical analysis find application first of all in medicine and healthcare. For example, the BIOTEX research project presents a study that demonstrated a pH sensor for sweat analysis. The sensor was implemented by joining technology and was based on colorimetry [48]. Researchers from Switzerland offered a smart solution for pulse oximetry. They have used weaving and embroidery for sensor manufacturing with polymethyl methacrylate polymer optical fiber (PMMA-POF). The patterns were designed to reproduce light-emitting and light detectors using optical fibers in order to assess human tissue probe [32].

Lightening Effects for Ambient Assisted Living

Social and demographical changes have caused a necessity for new solutions to ensure a safe and comfortable environment of such part of the population as the elderly and those who need professional, social, and medical assistance. Accompanied by technology progress, this situation has triggered the growth of interest and rapid development of the research sphere associated with Ambient Assisted Living (AAL) [49].

The main goals of AAL systems are to enable a networking of the environmental system compounds, provide specific situation-oriented solutions, and be an asset in individual activities. Moreover, the idea of AAL proposes an autonomic recognition of the necessities and flexible adjustment of the system.

The AAL environment incorporates tools for purposes, such as safety insurance of the user, communication, monitoring of his vital signs and behavioral patterns, and navigational assistance. The provided solutions require a multidisciplinary approach and are supported by communication and information technology, engineering, and design. Smart textiles are often a convenient scope to bring additional functionality to the surrounding environment and keep it friendly and aesthetic. Those find applications almost in every AAL tool development and can carry sensor and actuator functions in interactive interface, communication or data transfer, and behavioral and physiological monitoring.

Optical fibers can be an alternative option in some applications of conductive textiles and traditionally are used for data transfer. Moreover, optical fiber technology brings vast opportunities in lightening effect creation. Lightening effects for AAL can be characterized by a fusion of functionality and design. Topographical disorientation can be a serious problem that needs solutions in navigational assistance [50]. Single fibers and textile diffusers are a perfect tool to ensure lightening track and assist the user in coordination and movement in the home environment. Moreover, those can carry the function of a light indicator in a textile interface or give a user a stimulus for specific actions or decisions, for example, assist as a reminder or coordinator. Finally, textile diffusers or compounds based on optical fiber technology can be an asset in light therapy incorporated with interior design.

Summary

Optical fibers are lightweight, flexible, and compatible with textile yarns. One distinguishes mainly two sorts of optical fibers: glass fibers and polymer optical fibers. Having diameters varying between 125 and 1000 μm, they carry signals in the form of pulses of light over distances of up to 50 km without the need for repeaters. These signals may code voice communications or computer data.

Generally, optical fibers have a cylindrical cross-sectional shape. They possess a central core, in which the light is guided, embedded in an outer cladding of slightly lower refractive index. Light rays incident on the core-cladding boundary at angles greater than the critical angle undergo total internal reflection and are guided through the core without refraction. Rays of greater inclination to the fiber axis lose part of their power into the cladding at each reflection and are not guided.

There are three main kinds of fiber optics, the most simple being the “step index” where the light is bounced along the length of the fiber from one side to the other. Two materials with different densities are needed, the less dense being used as coating. In this method, the light travels in zigzag motion and thus transmission of information can take some time. Another way of producing fiber optics involves the “graded index” fiber which also relies on materials with different densities.

The variation occurs in the center of the fiber causing the light to bounce but in a smoother and more gradual curve. The sharpest and most direct transmission of light traveling in a straight line is achieved by applying a synthetic fiber possessing a very narrow inner core, almost the width of the actual path of light.

Interest in the use of light as a carrier for information grew in the 1960s with the advent of laser as a source of coherent light. Initially, the transmission distances were very short, but as manufacturing techniques for very pure glass arrived in 1970, it became feasible to use optical fibers as a practical transmission medium. At the same time, developments in semiconductor light sources and detectors meant that by 1980, worldwide installation of fiber-optic communication systems had been achieved. The Japanese company Mitsubishi Rayon was one of the first companies that were active in developing plastic fiber optics for illumination in the 1990s. Nowadays, optical fibers are applied in versatile areas, ranging from pressure and chemical sensors, illuminating textiles, to light therapy.

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