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Optical Fibers in the Design and Fabrication of Smart Garments – a Review

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Abstract
Several publications and even commercial products showcasing the application of optical fibers for textile goods abound in literature. Optical fibers can be employed as sensors by making use of physical principles to sense strain, temperature, and other quantities by tailoring the fiber such that the quantity to be measured alters the intensity, phase, polarisation, and wavelength of light within the fiber. However, a paper directed at the development of textile based applications or smart garments using optical fibers is lacking. This review seeks to serve as apt reference material for the development of optical fiber based textile sensors or smart garments with a focus on the application of plastic optical fibers (POFs). Highlighted are the salient material properties of POFs and their importance in delivering satisfactory sensing results. Special treatment has also been given to their proposed feasibility for embedment within weft knitted structures.

Key words: *plastic optical fibers, knitting, smart garments, textiles and optical materials.*

Introduction

The majority of society now depends on technology, from performing basic tasks like vacuuming our living rooms to complex tasks such as carrying out life-saving surgical procedures and even cars without drivers [1]. The clothes we wear today are no exception. Textiles and clothing are no longer restricted to the conventional role of providing comfort and protection. Terminologies like *Smart, Intelligent and Electronic textiles* have emerged to describe clothing and textiles that in addition to their conventional role; now provide other functionalities and also have the capability to detect changes in their internal or external environment [2].

Different approaches for delivering these smart solutions in textile fabrics and garments have been intensively studied in recent years. Popular technological trends include optics, electrical conduction related [3], GPS [4, 5], thermal conduction [6], acoustics, bio-sensing [7, 8], ultrasonic [9], photochromism [10], and strain sensing [11]. The application domains include health and wellness, entertainment, sports, education and security. In the sphere of health and wellness, physiological signal monitoring such as respiration and heart rate and cadence are the main functionalities of these smart wearables. Optics accelerometry and conductivity related technologies have been the major ones used in accomplishing this end.

Comparatively, optics offers a number of advantages lacking in conventional electronic circuits and systems. Optics for smart apparels are generally applied in three main areas, namely sensors, fancy lighting and phototherapy. The optic technologies for sensors are matured and quantities and indices such as oxygen saturation levels, which hitherto have not been able to be used with techniques such as conductivity based sensors, can be measured. Other advantages of integrating flexible optical fibers into textiles for wearable sensor applications are their light-weight, insensitivity to electromagnetic fields, water and corrosion resistance, reduced motion artifacts and high sensitivity. [12].

Notwithstanding these rather appealing attributes of optic technologies in the fabrication of smart garments, there are equally very thorny issues that continue to linger on. Optical fiber sensors are based on the measurement of the transmitted optical intensity [13] or wavelength variation relative to deformation of the fibers. However, the light transmitted within the fibers is prone to leakage due to the curvature that results when interlaced or interlooped within fabric structures [13]. Also optical technology for smart wear has been widely and variedly characterised in literature but with terminologies which tend to be confusing.

Thus, this review attempts to comprehensively classify and explain the various theories underpinning the use of optics for smart apparels. The study also illuminates the current problems negating the use of optical technology in textiles or garments and proffers some measures worthy of researching into to enhance the feasibility of their embedment.

Optical fibers/fiber optic systems

Laser, an acronym for "light amplification by stimulated emission of radiation, invented in the 1960's, spurred on researchers to study the potential of fiber optics for data communications, sensing, and other applications [14]. A laser results when the electrons in atoms inside special glasses, crystals, or gases are activated through the absorption of energy from an electrical current or another laser. The activated electrons travel from a lower-energy orbit to a higher-energy orbit around the atom's nucleus.

Fiber-optic communication systems thus ensued as systems that transmitted signals more than a few kilometers

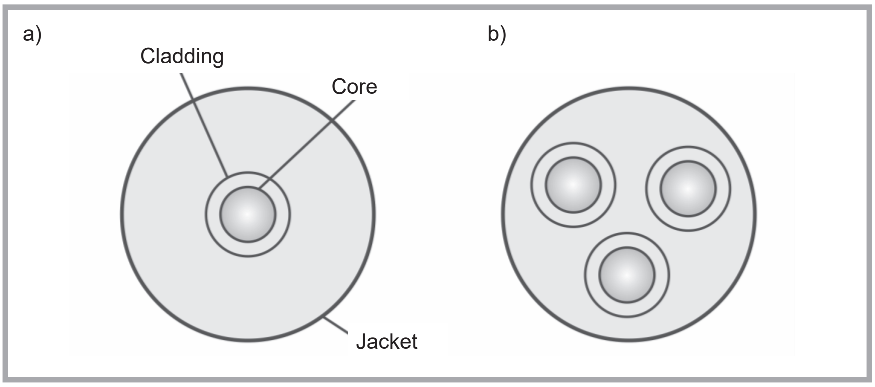

Figure 1. *General structure of an optical fiber: a) single core, b) multi-core (image by authors).*

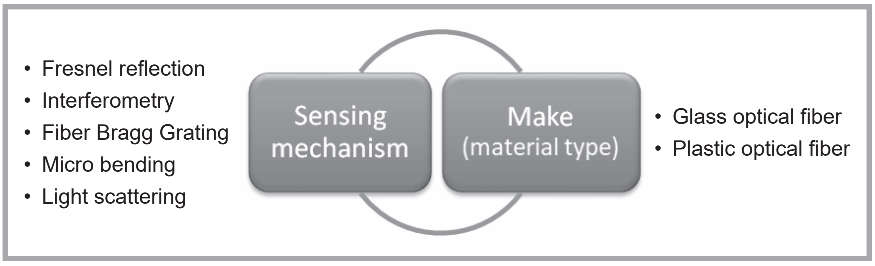

Figure 2. *Classifications of optical fibers (image by authors).*

using semiconductor laser beams [15]. Researchers conducted experiments by transmitting lasers from different external light sources through different types of waveguides. An optical fiber is thus described as a cylindrical dielectric waveguide (nonconducting waveguide) that transmits light along its axis, by the process of total internal reflection. Total internal reflection describes the situation where light traveling in an optically dense medium hits a boundary at a steep angle, and if the angle is larger than the critical angle for the boundary, the light will be completely reflected.

According to a method describing the fabrication of an optical fiber (glass based), to begin with, a preform containing quartz glass as the main component is heated and melted in a drawing furnace to produce a quartz glass-made optical fiber. Subsequently, a liquid ultraviolet curing resin to serve as the cladding is applied to the quartz glass-made optical fiber by using a coating die, and then it is irradiated with ultraviolet rays to cure the ultraviolet curing resin. In this way, the quartz glass-made optical fiber is coated with a primary layer (cladding) and secondary layer (jacket), and thus an optical fiber is manufactured [16]. The secondary layer can be made of an ultraviolet curing resin, a urethane acrylate-based resin or an epoxy acrylate-based resin.

The general structure of an optical fiber consists of the core, which is an inner cylinder with a high refractive index; covering the core is the cladding with a lower refractive index. It may also have an outer protective polymer layer called the jacket. The general structure is shown in ***Figure 1***.

There also exist optical fibers with multicores (***Figure 1.b***). Multicore fibers are composed of a solid cylinder forming the sheath, with several parallel cylindrical recesses and a variety of cylindrical cores, each rod being located in one of the recesses made in the cylinder [17]. These constitute multichannel fibers. To confine the optical signal in the core(s), the refractive index of the core must be greater than that of the cladding. The refractive index describes the means of measuring the speed of light in the fiber. The boundary between the core and cladding may either be abrupt, as in step-index fiber, or gradual, as in graded-index fiber.

Types of optical fibers and sensing mechanisms

The commonest type of optical fiber classification available in literature is that of communication system optical fibers, which is based on the differences in the structure of the core – single mode and multimode optical fiber with stepped or graded refractive indices. Graded-refractive-index means that the refractive index of the light transmission medium varies continuously in a specific direction. Graded-index fibers mainly find applications in medium-range communications, such as local area networks. They are also suitable for refractive index sensors where light attenuation varies when the fiber is immersed in fluids of different refractive indices [18].

Step refractive index fibers have a uniform refractive index of the core throughout and undergo an abrupt change at the core cladding boundary. They are suitable for applications requiring high power densities, such as medical and industrial laser power delivery.

Therefore, for the subject under review, we have classified fiber optics for sensors and smart apparels into two main groups based on the make (material type) and sensing mechanism. ***Figure 2*** shows our classification of optical fibers.

Classification based on make (material type)

Glass optical fiber

They are transparent fibers made by drawing glass (silica) to a diameter of about 125 microns. Examples include SiO_2 core with SiO_2 cladding and GeO_2-SiO_2 core with SiO_2 cladding. A good deal of progress has been made in the manufacture of glass based optical fibers since the 1970s. Most studies in this direction have been directed at reducing optical losses using improved chemical purification techniques [19] and a multitude of materials.

Conventional glass based optical fibers exhibit excellent light transmission properties and therefore find predominant application in long distance communication systems. However, these types of optical fibers exhibit poor flexibility and, thus, easily break, making them unsuitable for textile applications. More emphasis will therefore be on plastic optical fibers.

Plastic optical fiber

Plastic/Polymer optical fiber (POF) is an optical fiber which is made out of plastic or polymer as opposed to conventional glass. A variety of optical polymers are used in the manufacture of POFs, including polymethyl-methacrylate (PMMA), amorphous fluorinated polymer (CYTOP), polystyrene (PS), and polycarbonate (PC) [20]. POFs transmit light through the core of the fiber. The core of

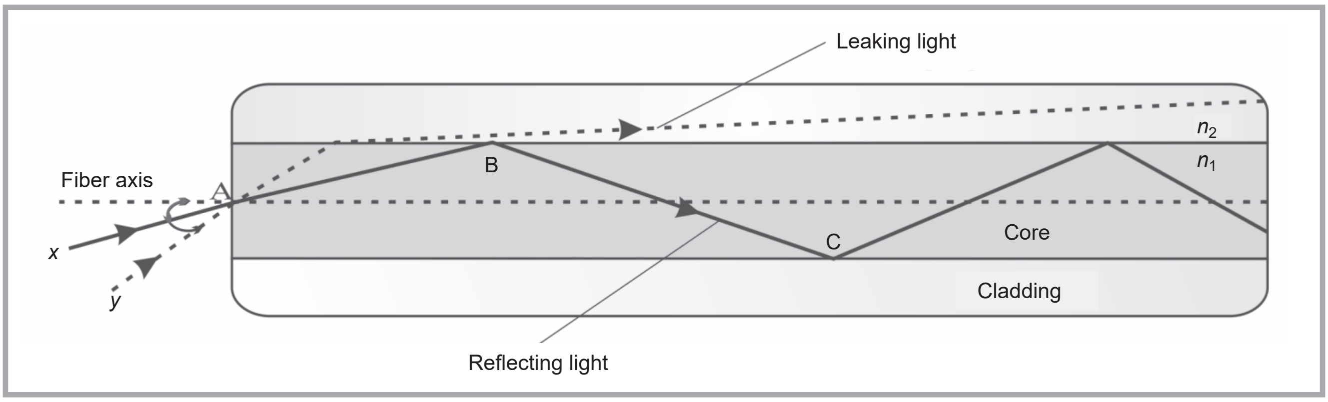

Figure 3. *Total internal reflection of light within an optical fiber (image by authors).*

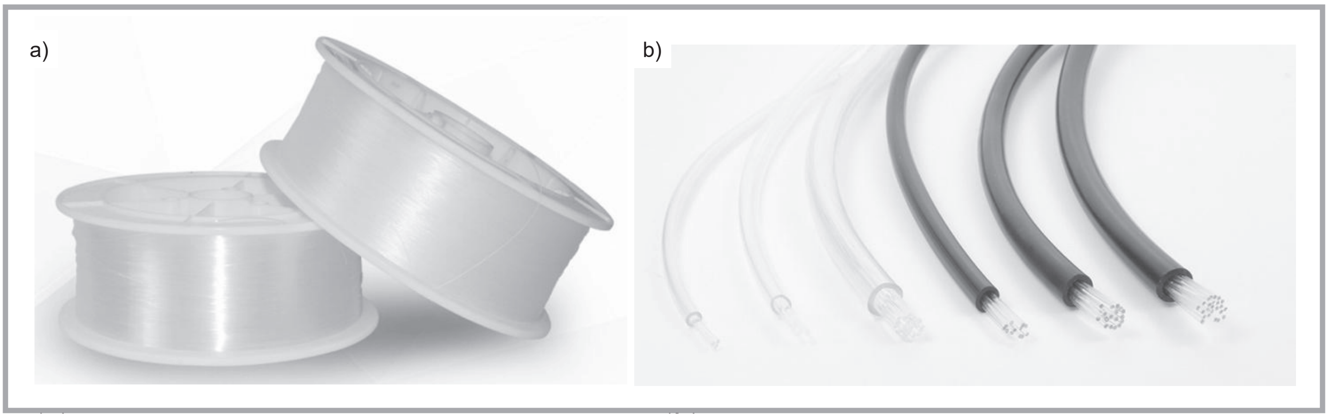

Figure 4. *Some plastic optical fiber specimens (image by authors).*

a POF may consist of one or more acrylic-resin fibers with a diameter within the ranges of 0.25 to 1 mm and 0.01" to 0.04", encased in a polyethylene sheath. Plastic fibers are found to be lightweight, relatively cheap, and flexible.

Examples of POFs include those with a PMMA core with co-polymer plastic cladding and a polystyrene core with methyl methacrylate cladding. Plastic optical fibers are characterised by a reflection angle of 35 degrees, and those made of a PMMA core possess an operating temperature between -40 to 82.2 °C [21]. However, there exists other makes with higher operating temperatures beyond 120 °C [22].

During fabrication, care is taken to minimise optical losses (attenuation) due to absorption and scattering along the length of the core, so that light applied to one end of the optical fiber material is efficiently transmitted to the opposite end of the material [23]. It is therefore important that the refractive index of the core polymer (1) and the refractive index of the cladding copolymer (2) satisfy the relationship (I) [24]:

$$n_1 - n_2 \geq 0.01 \qquad (1)$$

If the difference between the refractive indices and is less than 0.01, the resultant optical fiber exhibits an unsatisfactory reflectance of light at the interface between the core and cladding.

Another important property of POFs is the numerical aperture (NA), referring to the maximum angle at which the light incidence on the fiber is totally internally reflected and properly transmitted along the fiber core axis [25]. For example, as shown in ***Figure 3***, a ray entering the fiber core at that steep angle intersects the core-cladding boundary, resulting in light leaking into the cladding. This therefore means that only light that enters the fiber within a certain range of angles can travel down the fiber axis without leaking out. For typical plastic optical fiber cables, NA ranges between 0.5-0.6. ***Figure 4.a*** shows a single core optical fiber and ***4.b*** multi-core optical fiber specimens made of PMMA as the fiber core material and fluorinated polymer as the fiber cladding material. Its numerical aperture is 0.5 and the core refractive index 1.492 [26].

In ***Figure 4.b*** the jacketing material is made of PVC. Plastic optical fibers with both core and cladding made from flexible polymers are less subject to fracturing but have the deficiency of strongly attenuating the light passing through [27]. Light attenuation describes the exponential decay of light within the length of the fiber axis due to absorption and scattering losses. Attenuation is caused by conditions such as irregularities in the core diameter and geometry or changes in the fiber axis direction. Any occurrence that imposes dimensional irregularities, such as micro-bending, aggravates scattering and, hence, attenuation.

POFs have found application within the field of smart garments and are currently being widely applied for generating lighting effects in garments and some sensor applications.

Sensing mechanism based classification

Fiber optic Fresnel reflection

In optics, Fresnel reflection describes the reflection of a portion of incident light at a discrete interface between two me-

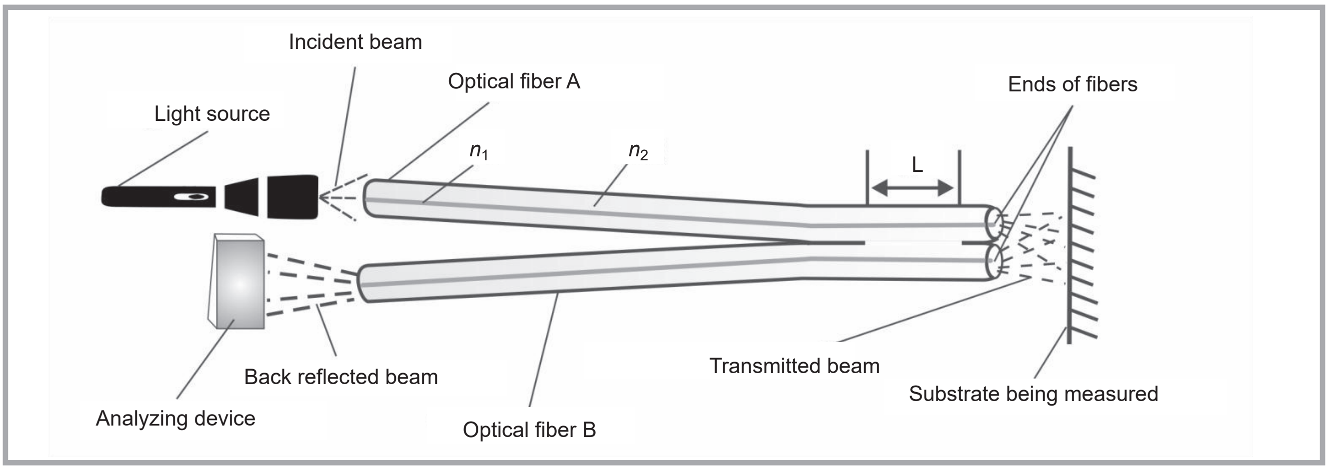

Figure 5. *Scheme of a fiber optic interferometric sensor (image by authors).*

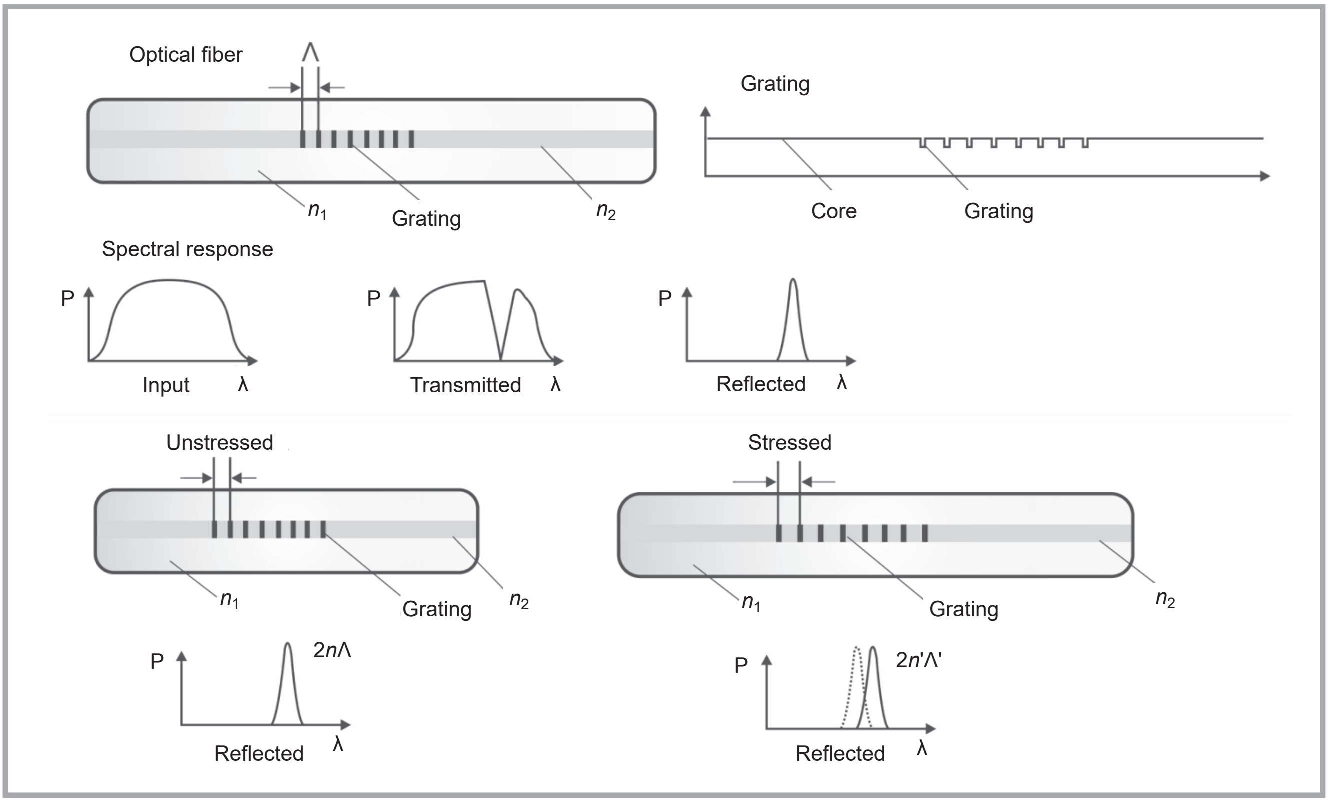

Figure 6. *Fiber Bragg gratings and their sensing scheme (image by authors).*

dia having different refractive indices. Fresnel reflection occurs at the air-glass interfaces at the entrance and exit ends of an optical fiber. An example is an optical fiber Fresnel reflection sensor for detecting the solid-liquid phase change in n-octadecane [28]. The sensor probe consists of a single-mode fiber with a cleaved end immersed in the material sample under test. As the n-octadecane changes from solid to liquid or from liquid to solid, its refractive index (RI) varies, resulting in changes in the light power ratio reflected by the probe [28]. There have been several applications in the area of solution and temperature concentration measurement by measuring the Fresnel-reflection signals from sensing heads inserted into the solutions [29, 30]. Their application in smart textile has not yet been cited.

Fiber optic interferometry

Interferometry is a measurement method that makes use of the phenomenon of wave interference, be it light, radio or sound waves. An interferometer can be used to determine refractive indices, as well as measure the deformation of surfaces and small ultrasonic vibrations in a surface [31]. Demonstrations of using light interference principles as a measurement tool were achieved by Armand Hippolyte Fizeau and Edouard Stephan in the 1880's; however, it was Albert A. Michelson who invented the first interferometer. A clear explanation of interferometry using optical fibers, however, can be credited to David W. Stowe in his 1983 US Patent (US4380394A). ***Figure 5*** shows an adaptation of one of the various embodiments of his invention [31].

The sensing system has two fiber optic fibers, *A* and *B,* connected over a fi-

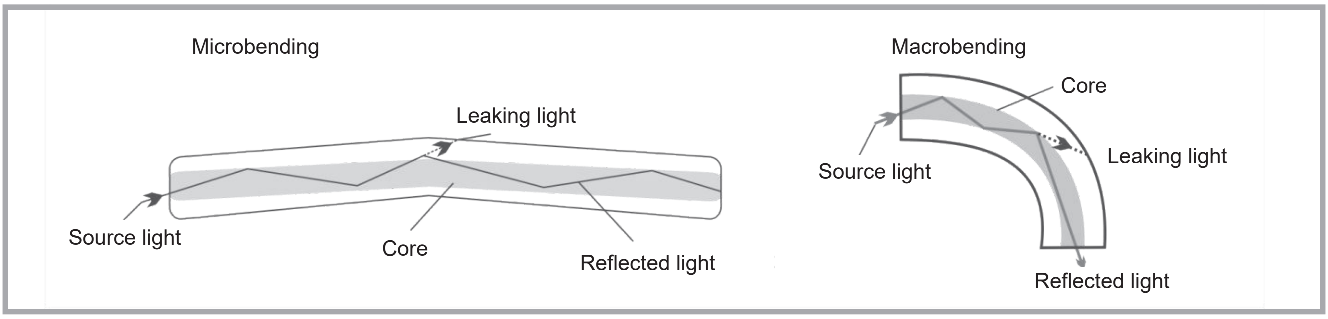

Figure 7. *Micro and macro bending in optical fibers (image by authors).*

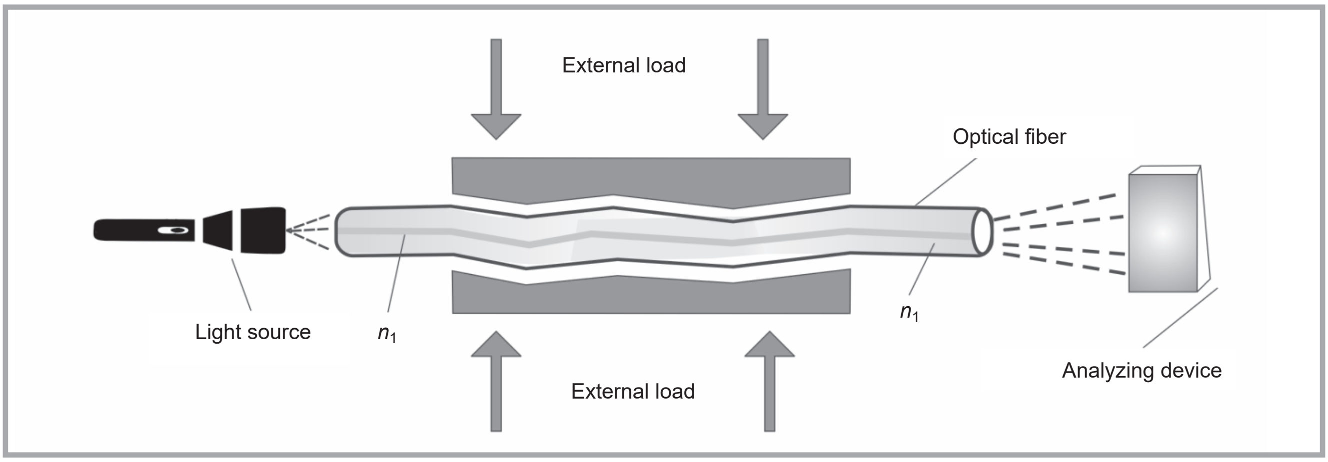

Figure 8. *Scheme of a micro bend sensor (image by authors).*

nite length L such that evanescent wave coupling occurs between both cores of the fibers. A light source directs a beam of light toward fiber optic and carried toward the end of the fiber. A reference beam is formed within fiber optic waveguide *A* as a result of back reflection at the end of the fiber. Such reflection occurs naturally due to the difference in the refractive index between the core of the fiber (n_1) and the air. A finite amount of optical energy will pass through both ends of the fibers and project onto the substrate to be measured.

A quantifiable amount of light reflected off the surface of the substrate being measured will again enter the fiber optic through the ends, respectively. This reflected light will combine with the initial reference back reflection beam and will be received by the analysing device. The optical energy received by the analysing device will vary in intensity as a function of vibrations of the surface of the substrate being measured, a phenomenon described as interferometry. Interferometry has been applied in various measurement instruments and systems; examples of which include the Michelson interferometer, Fabry-Pérot interferometer or etalon, Fizeau interferometer, Mach-Zehnder interferometer etc.

Fiber Bragg grating

Fiber Bragg gratings are made by laterally exposing the core of a single-mode fiber to a periodic pattern of intense laser light. The exposure produces a permanent increase in the refractive index of the fiber's core, creating a fixed index modulation according to the exposure pattern.

The FBG fibers are classified as either long period grating (LPG) or fiber Bragg grating (FBG) depending on the length of gratings. The period of the LPG is of the order of micrometers, while for the FBG it is given in nanometers [32]. The working principle of the FBG is such that when light is injected into the optical fiber, only light within a very narrow spectral width centered at the Bragg wavelength will be reflected back by the grating. The remaining light will continue through the optical fiber to the next Bragg grating without experiencing any loss, as shown in ***Figure 6***. The characteristics of FBGs have made them suitable for strain, pressure and temperature sensor applications. This happens because the deformation of the optical fiber leads to a change in the period of the microstructure, Bragg wavelength, and reflected light, as shown in ***Figure 6***.

Fiber optic macro/microbending

Microbends are microscopic bends of an optical fiber, causing light to escape the inner core through the cladding, even when the fiber is macroscopically kept straight. ***Figure 7*** shows the micro and macro bending phenomenon in optical fibers.

The difference between micro and macro lies in the magnitude of bending. Macrobends are bends that are large enough to be seen by the human eye, whilst microbends are microscopic deviations along the fiber axis.

The sensing mechanism shown in ***Figure 8*** is such that light traversing an optical fiber from a source of known intensity can be altered through microbending by applying an external load such as stress, pressure and temperature. Therefore, the resulting intensity variation analysed by the device can be used to measure the magnitude of disturbance or pressure encountered.

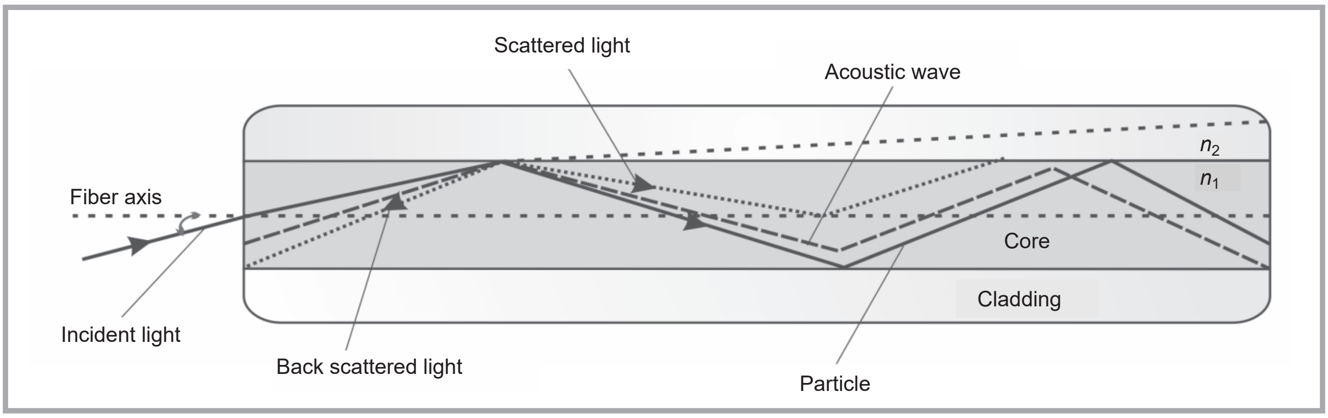

***Figure 9.** Schematic spectrum of scattered light resulting from acoustic Brillouin scattering (image by authors).*

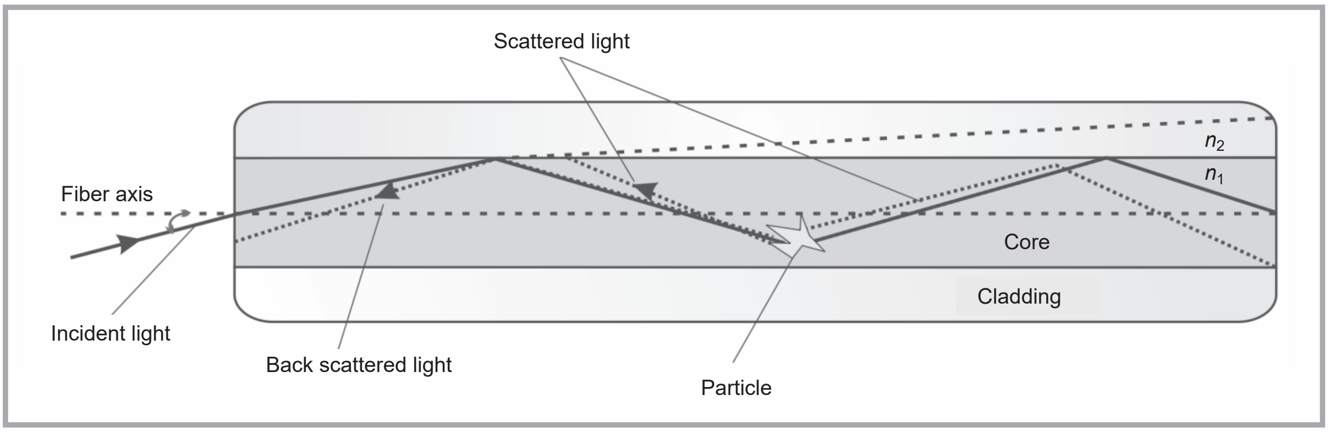

***Figure 10.** Schematic spectrum of scattered light resulting from Rayleigh scattering in optical fibers (image by authors).*

Fiber optic light scattering

In fiber optic transmissions, scattering defines the loss of a signal caused by the diffusion of a light beam, where the diffusion itself is as a result of microscopic fluctuations in the transmission medium [33]. The major light scattering phenomena used for fiber optic sensors are Brillouin, Raman and Rayleigh scattering. Brillouin scattering can be described as the reflection of the incident light from a three-dimensional diffraction grating as a result of refraction index changes in a material due to propagating sound waves. The light reaching the point directly along the incident light path will be modulated by the presence of the acoustic wave, as shown in ***Figure 9***.

Raman scattering also typically involves vibrational energy being gained by a molecule as incident photons from a visible laser are shifted to lower energy. Both Brillouin and Raman techniques analyse the inelastic scattering interaction of light with vibrations of matter resulting in a frequency change [34]. However, while Brillouin scattering involves the scattering of photons from low-frequency phonons, in Raman scattering photons are scattered by interaction with vibrational and rotational transitions in molecules, with the frequency shift and material information being very different [35].

Rayleigh scattering describes the dispersion of electromagnetic radiation by particles that have a radius less than approximately 1/10 of the wavelength of the radiation [36]. Matter responsible for Rayleigh scattering neither loses nor gains energy, and hence the scattered light has the same frequency as the radiation from which it is produced [37]. For sensor applications Rayleigh scattering in an optical fiber is captured by the guiding structure of the fiber itself and back propagates to the fiber input. This "backscattered light" is the signal detected by Rayleigh-based distributed optical fiber sensors (DOFSs) [38] (***Figure 10***). Brillouin spectroscopy is the technique most frequently used for measurements of strain, [39] while Raman's scattered magnitude is usually applied for temperature sensing. Rayleigh is usually applied for the detection of fast intensity variations in acoustic signals.

Experimental setup of a fiber optic sensing system for smart apparel

Generally, fiber optic systems for smart garments have been based on light intensity variation (micro/macro bending) using ordinary plastic optical fibers or FBG fibers. To a lesser degree, however, phototherapy application also exists in literature. Sensor applications are, however, based on mechanisms such as interferometry and Fresnel reflection and others that have not been tried yet. Usually, in a lab setting, the experimental setup and instruments required are determined by the sensing mechanism and or choice of experimenter. However, a typical experimental fiber optic sensing system requires an illuminator as the light source, a harness with holder and coupler, an optical fiber, and optical detectors or processing electronics, similar to the setup of a macrobend sensor, shown in ***Figure 8***.

Illuminator/light source

It is necessary to supply a light source to the fiber optics for illumination. The external broadband light source provides a wide light spectrum which is focused into the core of the fiber. The light source could be from light-emitting diodes (LED)[13], laser diodes [40], and halogen lamps [41]. LEDs and photo-detectors are interesting solutions for low-cost and miniaturised intensity-based schemes [42].

Connector or a Harness with Holder and Coupler

The main function of an optical connector is to maintain both ends of the optical fiber bunch such that the core of the fibers are axially aligned with that of the other fibers [43]. A fiber optic coupler is an optical device capable of connecting one or more fiber ends in order to allow the transmission of light waves in multiple paths. The device is capable of combining two or more inputs into a single output and also of dividing a single input into two or more outputs.

Optical Detectors and Processing Electronics

Optical interrogator – Specifically designed to measure the values generated by Fiber Bragg grating (FBG) sensors. It can measure a large sensing network composed of various types of sensors (such as strain, temperature, displacement, acceleration, tilt etc.) connected along multiple fibers, by acquiring data simultaneously and at different sampling rates. An example is the FS22 Industrial BraggMETER [44] by HBM (Hottinger Baldwin Messtechnik GmbH, Germany).

Optical spectrum analyser – An optical spectrum analyser (or OSA) is a precision instrument designed to measure and display the distribution of power of an optical source over a specified wavelength span [45].

Optic fiber power meter – An optical power meter (OPFM) is a device used measure the power in an optical signal. The OFPM is perhaps the most common type of test equipment used to support the development and implementation of optical fiber systems [46].

Optical loss test sets (OLTSs) – consisting of two separate devices – an optical light source and optical-power meter – in the same unit. An example is the Max-Tester 940/945 – telco OLTS

Optical time domain reflectometer (OTDR) – A precision instrument used to locate events or faults along a fiber link, typically within an optical communications network. Examples are the OptiFiber Pro OTDR [47, 48] and AQ7280 Modular Optical Time Domain Reflectometer, Yokogawa, UK [49].

Fiber optics sensing i-line series controller – An example is the i-Line BOX8B [13].

Embedment of optical fibers into textile structures

The difficulty in embedding optical fibers within textile structures is not in doubt. One research report even declared that it is impossible [21]. The size which can be chosen to fabricate wearable textiles and clothing, however, is also limited. A suitable optical fiber for embedment in fabrics must be as fine as a typical yarn. Currently, the finest optical fiber on the market is 0.25 mm, close to a conventional nylon-like yarn [21].

A strong case for embedding optical fibers into garments, however, is partly furthered by challenges posed by conventional, wrist-mounted wearables, which often suffer from large motion defects, many of which arise from the motion of the light sources/sensors relative to the surface of the skin.

Also there is the concern that the electronic components usually applied are rigid, incompatible with garments, and sometimes expensive. Ideal textile based sensing structures need to be flexible, fit closely to the human body, be lightweight, and provide wearer comfort during long-term use [50]. Textile and garment engineers are therefore hard-pressed to provide solutions to these problems.

So far fabric construction methods that have been used to attempt to embed optical fibers include weaving [13] and compositing or felting [51]. Fabric ornamentation method such as embroidery [52] and physical insertion [53, 54] into woven structures and garment construction methods like sewing [55] have also been reported. The latest research by Chen *et al.* [56], however. hints at the feasibility of knitting. In their study, optical fibers were embedded as float stitches. Their work is, however, focused on illumination effects, therefore as it stands now, there has not been any successful application of knitting to fabricate an optical fiber based sensor. Hence, the following discussions proffer some weft knitting techniques worthy of consideration to embed POFs into textile structures.

Weft knitted structures for optical fiber based knitted strain sensors

Laying-in and inlaid structures

An inlaid weft knitted fabric structure is composed of a base structure of knitted yarns holding in position other non-looping yarns which are embedded within the structure during certain knitting cycles [57]. An inlaid yarn usually does not need to be interlooped within warp knitted structures; however, when it comes to weft knitting, it is important that it is tucked-in to secure it within the fabric structure.

During weft knitting using two sets of needles, it is possible to insert the inlaid yarn into the structure merely by supplying the yarn across the back of the needles in order to trap it inside the fabric. Inlaid yarns are trapped inside the double needle bed fabrics by the loops of the two beds and towards the back of single bed fabric by the sinker loops. Laying-in can be employed to modify the stability, handle, surface interest, weight, visual appearance, elastic stretch and recovery of the resultant fabric. Also laying-in provides the opportunity to introduce fancy yarn or unusual yarn (in this case optical fiber), which are difficult to knit in the normal manner. The inlaid yarn generally assumes a relatively straight configuration and therefore will require less length of per course, as opposed to the loop forming ones.

Single jersey hopsack structure

Hopsack is a typical example of a single jersey inlaid structure. In this case, after every normal course, an inlaid yarn is introduced which is tucked in alternative needles, as shown in ***Figure 11.a***.

Tunnel inlay knit structure

On double-jersey machines, laying-in may be achieved using the tunnel inlay technique. The inlay is fed in advance of the knitting yarn at a feed and is trapped as an almost straight horizontal yarn inside the fabric, behind the cylinder and dial face loops. This could possibly be

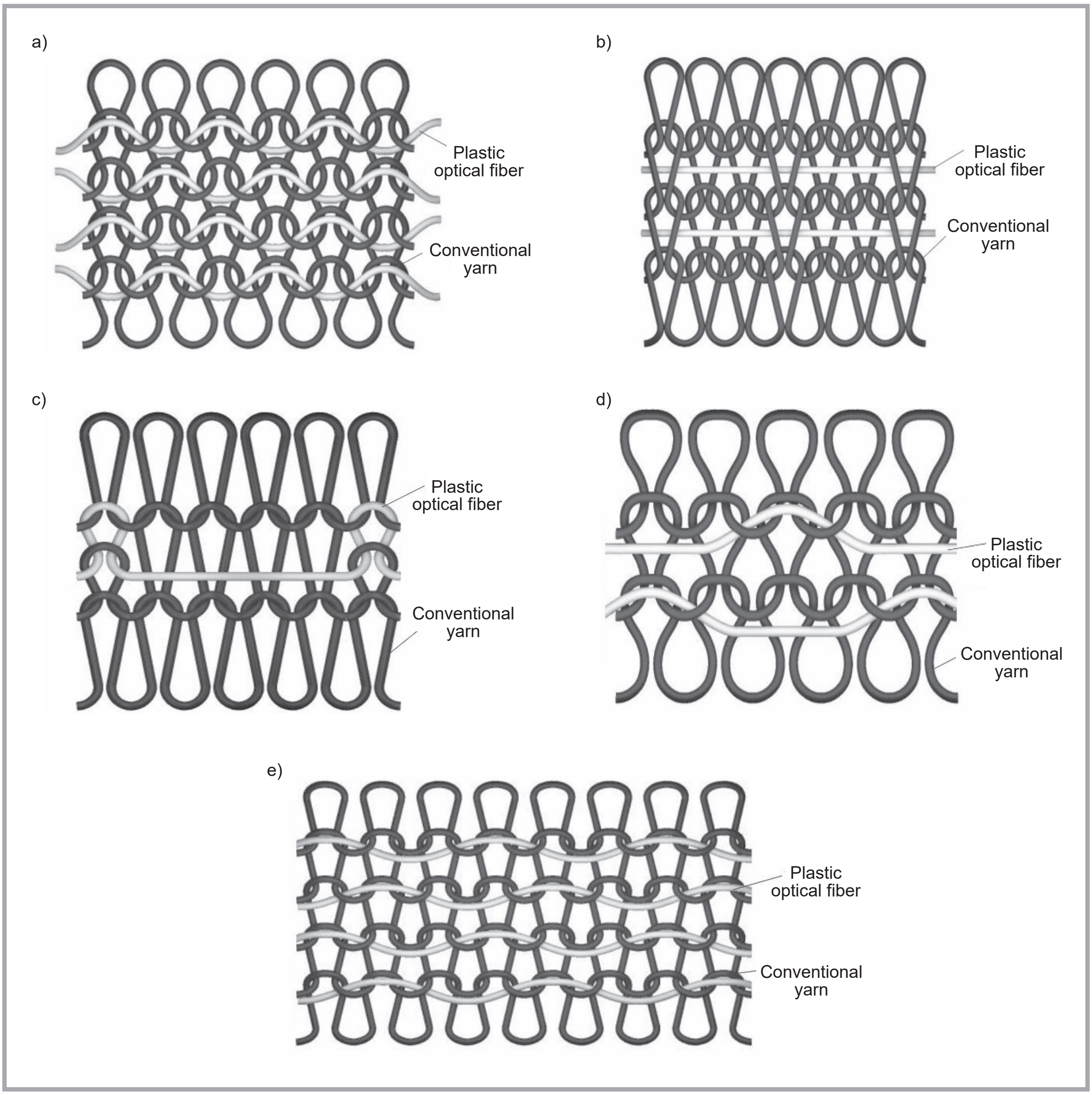

Figure 11. *Some weft knitted structures proposed for optical fiber based knitted strain sensors (image by authors): a) single jersey hopsack structure, b) tunnel inlay knit structure, c) 1×4 float knit structure, d) 3:1 fleece fabric structure, e) 2:1 fleece fabric structure (image by authors).*

the best knit structure for embedding optical fibers as there is virtually no bending of the inlay yarn within the structure. ***Figure 11.b*** shows an inlay structure.

Float stitches/miss stitches

Float or miss stitches are produced when a needle holding its old loop fails to receive the new yarn that passes, rendering the new loop to float on the back of the needle. The number of floats can be varied from 1 to (1×n) number of floats [58]. ***Figure 11.c*** shows a 1×4 float knit structure where the missed yarn is shown floating freely on the reverse sides of the held loops. Even though float knit structures also afford minimal bending of POFs as compared to fleece and hopsack structures, which have single jersey as the base structures, the structure is very loose and therefore not suited to specific applications requiring compact structures, such as socks and other under garments.

Fleecy fabric knit structures

There are generally two types of fleecy fabrics, namely simple fleece (two threads) and invisible fleece (three threads). Fleecy fabrics are produced on single jersey circular knitting machines. The fleecy or backing yarns are tucked into the base fabric at regular intervals on the reverse (inner) side of the fabric. Common points for inlay tucking are at each second needle (1:1 fleece) or at each fourth needle (3:1 fleece). If the interlacing points are staggered in successive rows, the structures are called 1:1 and 3:1 staggered fleece. ***Figure 11.e*** also shows a 2:1 fleece fabric structure.

As fleecy yarns do not assume a stitch configuration, relatively thick and soft yarns, and for that matter optical fibers can be used for the purpose. A simple fleecy structure consists of a base yarn and fleecy yarn which are guided by normal holding down sinkers on successive feeders of a circular knitting machine. Since the base yarn is relatively finer, the fleecy yarn may become visible on the technical right or face side of the fabric at the inlaid points. The three thread fleecy structure shown in ***Figure 11.d*** is composed of fleecy yarn, binding yarn and face yarn and is produced with the help of some special attachment fitted on a plain circular structure. A fleece knit structure is suitable for illumination applications as fleece yarns (POF yarns) become visible on the right or face side of the fabric at the inlaid points. Also three-thread fleece fabrics have a relatively high mass and thickness and are widely used in outdoor active and sportswear garments [59].

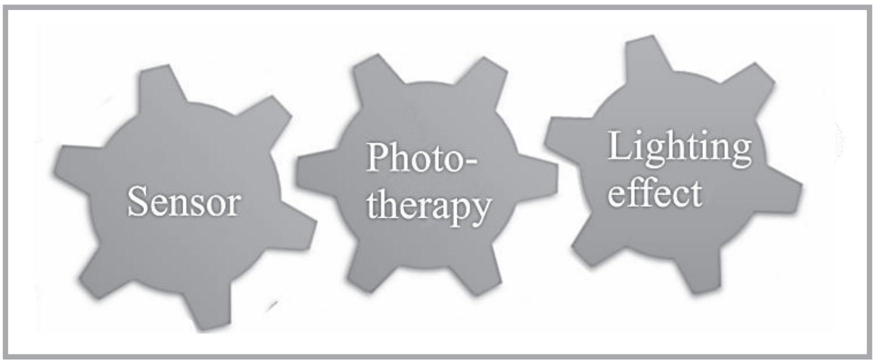

Figure 12. *Current areas of optical fiber application (image by authors).*

Current areas of application

Currently, three areas of optical fiber application in smart textiles exist, including sensor, lighting effect and phototherapy applications, shown in ***Figure 12***.

Terms such as luminous textile [55], luminescent fabric, illuminative fabrics [51], photonic textiles [60], and fiber optic textiles [61] have been used to describe optical fiber applications for smart wear. Photonic fibers can be defined as fibers that generate, transmit, modulate and detect photons [62]. Luminous textiles describe textiles that emit or reflect usually steady, suffused, or glowing light. The luminous and photonic types have generally lighting effect and therapy applications, while fiber optic textiles are more linked with sensor applications.

Lighting effect applications

A rather interesting characteristic of POFs used for lighting effect applications is that the fibers require purposive mutilation of the cladding along the lateral side of the fibers to enable light emission along the length of the fiber, as light in unmutilated POF is only visible from the ends of the fibers [56].

Several surface treatment methods directed at making POFs that emit light exist in literature. They include but are not limited to mechanical side-notching [63], which creates simple figures of light dots. Others include surface mechanical abrasion [64], surface chemical etching [65] or sandblasting, leading to a more coherent light distribution.

Alternatively, writing Bragg gratings or embedding scattering particles within the core of the fiber can also cause fibers to emit light [66]. Fashion designers and artists have used POF within woven textiles to incorporate harmonising illumination effects. ***Figure 13*** [26] shows some textile products adorned with POFs.

Phototherapy applications

Phototherapy is one of the oldest therapeutic modes of treating various health conditions [67]. Fabrics embedded with side-emitting polymer optical fiber (POF) have been found to offer great potential for phototherapy application. A well-defined wavelength is essential for phototherapy since cellular reactions occur within certain irradiation wavelengths. Several past study reports indicate that low level light irradiation at about 630 nm delivers low energy stimulation to tissues, resulting in enhanced cellular activity, the inducement of the proliferation rate of fibroblasts and keratinocytes, as well as enhanced collagen production [34].

Phototherapy has proven to be an efficient means for the treatment of hyperbilirubinemia (neonatal jaundice) by emitting blue light over the patient's skin. This blue beam converts toxic bilirubin molecules in the blood into less toxic isomeric forms due to photo-oxidation and photoisomerisation. Smart textile products include the proprietary *Royal Blue Biliblanket* [68], shown in ***Figure 14***, and the *O-blanket,* developed by researchers at Hong Kong Polytechnic University.

The *O-blanket* is made up of a light-emitting fabric covered by a wrapper made of reflective top and back fabrics. The light-emitting fabric is woven from side-emitting polymer optical fibres and textile yarns. Others include an experimental flexible luminous fabric device

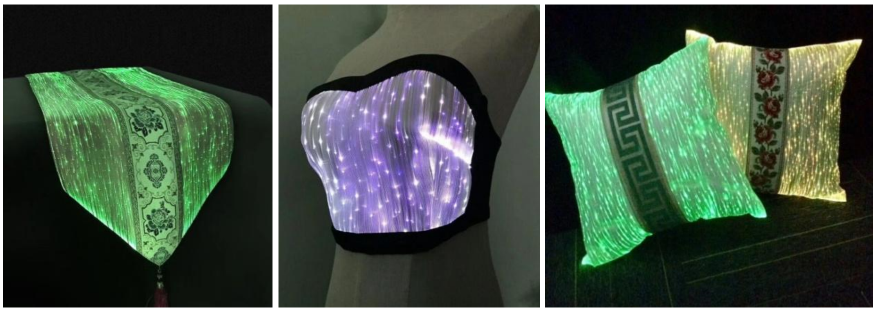

Figure 13. *Some lighting effect applications of POFs [26].*

Figure 14. *POF embedded blankets for phototherapy applications [68].*

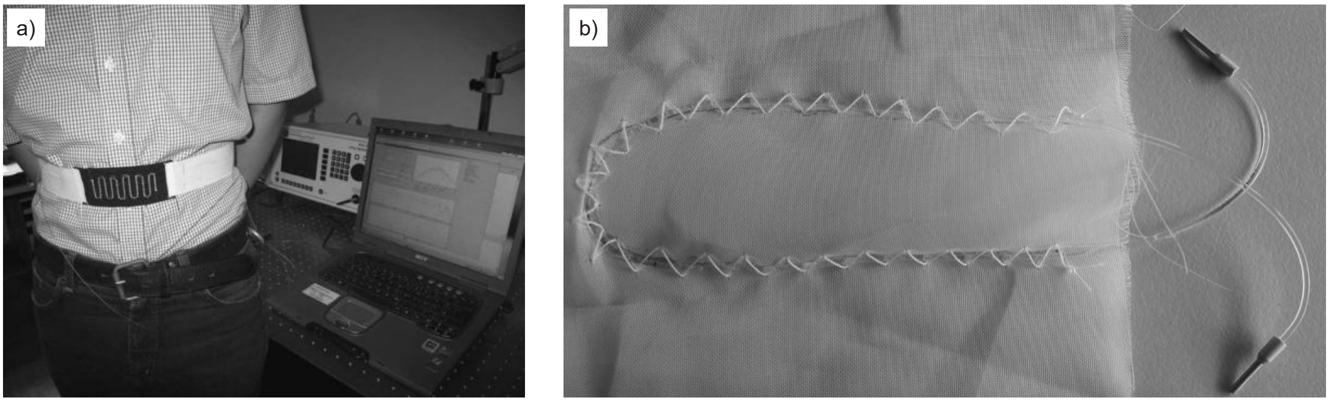

Figure 15. a) Monitoring the abdominal movement of an adult with a POF OTDR respiratory sensor [53], b) integration of optical fiber into textile to form a sensing unit [55].

[67] and a fiber optic phototherapy pad [69]. Diseases that are currently being treated using these devices include psoriasis vulgaris (Pv), eczema, atopic dermatitis etc.

Sensor applications

Bragg grating and micro-bending are the main types of fiber optic sensors that have been applied in smart garments. The areas include physiological signal monitoring and posture or physical activity tracking.

Physiological measurement applications

Insensitivity to electrical fields is the great advantage of fiber optic sensors applied for physiological monitoring in tests that may take place in a hospital environment because a lot of electromagnetic fields are present there [55]. The most widely applied method of physiological monitoring in smart apparel is the use of strain sensors, where abdominal circumference elongation relative to sensor deformation during breathing is measured.

Fiber optic sensors are embedded in belly belts, chest straps 70], beds [71], fitted shirts [13], or vests [72], and they measure the oscillation of the cross-sectional area of the rib cage and abdomen relative to altering of the intensity or wavelength variation of the optical fibers. ***Figure 15.a*** shows monitoring of the respiratory abdominal movement of an adult by POF OTDR [73], and ***Figure 15.b*** illustrates the integration of optical fiber into textile to form a sensing unit.

One other method which is less popular in textile applications, probably due to its comparative difficulty of implementation, is the use of the light absorptive characteristics of hemoglobin and the pulsating nature of blood flow in the arteries to measure the level of oxygen in the body. However, some remarkable attempts have been cited [74], where optical fibers embroidered into textiles measured the heart rate and oxygen saturation in the reflection mode. These sensors have an advantage over ECG electrodes, as they do not require wetting of the skin to acquire a signal, which would otherwise change dermal conditions [75].

Posture or physical activity tracking

This type of analysis embraces the measurement, description and assessment of quantities that characterize human movement [3]. During knee flexion, the upper knee perimeter increases with the shrinkage of the knee joint flexor, and this can be monitored for various applications such as the progress of recovery from accidents or injury, the recognition of shortcomings in athletic performance etc. Examples include the application of an FBG smart wearable belt for knee joint [76, 77] and trunk motion [78] monitoring. These applications are set to enable athletes, coaches, ergonomists and physicians to track functional movements, workload, biomechanical and bio-vital markers to maximise performance and reduce the potential for injury [79, 80].

Future trends

The main drawback of embedding POFs into textile structures is in their susceptibility to breakage. Future trends in dealing with this problem is the use of new technologies such as 3D printing to produce more pliable filaments and yarns for fabric construction. Also, due to the limited choice of semiconductors available for producing yarns or filaments conventionally, as compared to the more amorphous silicon used in electronic devices, these comparatively inferior electronic performing semiconductors end up in devices which have the limited bandwidth and sensitivity of such sensors as compared to a standard silicon photodiode [81]. An adaptable hybrid-fiber fabrication method that assembles in-fiber material architectures similar to integrated microelectronic devices and systems using silica, silicon, and high-temperature metals have been proposed to deliver a new class of durable, low-cost, widespread fiber devices and sensors enabling the integration of fabrics [81].

Conclusions

This review details fiber optic materials and their various sensing mechanisms. Even though quite a number of optical fiber sensing mechanisms exist and are being applied in other fields, such as medical instrument design, temperature sensing and phototherapy, adoption into smart textile applications rather seems to be limited. This study thus seeks to provoke discussion and research into the adoption of the various sensing mechanisms into the design of smart textiles.

The current application and probable suitability of optical fibers for application in the design and production of smart apparels with a focus on the material properties of optical fibers and their suitability for in-situ embedment in apparels have thus been discussed in this study.

Salient issues regarding the development of optical fiber based textile sensors or smart garments with a focus on relevant applications have also been discussed. We also stated that the use of knitting technology to embed optical fibers into apparels, which hitherto has not seen significant attention, is possible. Subsequent work will thus be directed at actualising some of the proposals put forward.

Conflicts of interest

The authors declare no conflict of interest.

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