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Review Article

Optical Fiber Sensing Technology: Basics, Classifications and Applications

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Abstract: In this paper, the current state of art of optical fiber sensing technology is reviewed. The basics of operating principle are discussed in detailed and the various types of optical fiber sensors are classified. The performances, the limitations and a description of the technology used to fabricate the optical fiber sensors have presented. Also, the development of this technology and the expected application areas are briefly outlined.

Keywords: Optical Fiber Devices, Optical Fiber Sensors, Optical Interferometry, Modulation Techniques

1. Introduction

Since 1960, when the laser has been invented, a great interest in optical fibers as a data transmission system began. It has emerged to become the most important transmission medium, and has revolutionized modern communications and optical science. The ability of laser systems to send a very large amount of data compared than microwave and other electrical systems, encouraged researchers to study the possibility of fiber optics for data communications, sensing, and other applications [1].

In the beginning, large fiber optic losses of about 1000 dB / km make it impractical for communication uses. Scientists concluded that the reason for increasing the signal loss in optical fibers was due to the presence of impurities in the fiber material and after several studies, they succeeded to make a high silica-core multi-mode optical fiber with a 4 dB/km loss [1].

The huge and rapid development in optic fiber technology led to significantly changed in the telecommunications industry. The ability to carry several Gbits of information at the speed of light stimulated to increase the search in fiber optics [2-7]. The continuous improvements and low costs of optical components have led to similar emergence of new product areas. The inflamed revolution in optical communications has prompted designers to produce a new product by combining optical fiber telecommunications with optoelectronics devices to create optical fiber sensors [8-10].

With continuous improvements, fiber optic sensor technology has begun to be used effectively by technology related with optical and fiber optic communication industry. This led to the development of many components associated with these industries for fiber optic sensor applications [7-10].

Fundamentally, a fiber optic sensor has driven by two main factors: the continuous improvement and the large and increased production of components related to these industries. As components prices have decreased and quality improvements have made, the ability of fiber optic sensors to compete and replace traditional sensor devices have increased [7-10].

Optical fiber sensors are the optimal choice for monitoring environmental changes; they offer many advantages compared to traditional electronic sensors, such as increased sensitivity and design diversity, which allows configuration to arbitrary forms [7]. Due to their suitability to harsh environmental conditions, they have become an indispensable option in many technical applications include civil, mechanical, electrical, aerospace, automotive, nuclear, medical and chemical sensing [7-10]. Also, they are used to monitor a wide range of physical parameters such as position, vibration, strain, temperature, humidity, viscosity, current, electric field and several other environmental factors [11].

As a result of their high susceptibility to the sensor, the diversity of their application areas and their great competition to displace traditional methods encouraged researchers to study it [12-16]. The aim of this paper is to extend the previous studies to include the basic components, the major classifications, the most significant developments and applications of fiber optic sensors in recent years. The paper is organized into six sections to provide a clear and logical sequence of topic.

2. Basics of Fiber Optics

An optical fiber is an optical waveguide made of glass or plastic/polymer materials [7]. It composed of three parts: the core, the cladding, and the coating as shown in Figure 1.

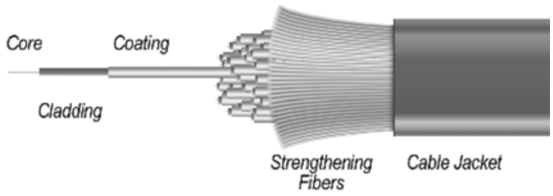

Figure 1. *Schematic of an optical fiber.*

Mainly, light propagates along the core of the fiber. The cladding is made of a dielectric material with an index of refraction less than that of the core material. The cladding works to minimize the loss of light from the core into the surrounding air, minimize scattering loss at the surface of the core, protects the fiber from absorbing surface contaminants, and provides mechanical strength. While, coating layers are used to protect fibers from physical damage [1]. The transmission of light along the fibers depends on the principle of "total internal reflection", which is related on the angle of the incident beam light between two materials with different refractive indices. When the beam light is propagate from a medium with a high refractive index, n_1 to one with a lower refractive index, n_2, the transmitted beam always appears at an angle, φ_2, that is greater than the incident angle, φ_1. By increasing φ_1, there will come a point where φ_2 is 90º; at this point, the value of the angle of incidence is known as the critical angle, φ_c; which the total internal reflection was occurs as given in Figure 2. In contrast, if the angle of incidence beam is greater than φ_c, there is no refraction occurs and all of the light becomes totally internally reflected (see Figure 2c).

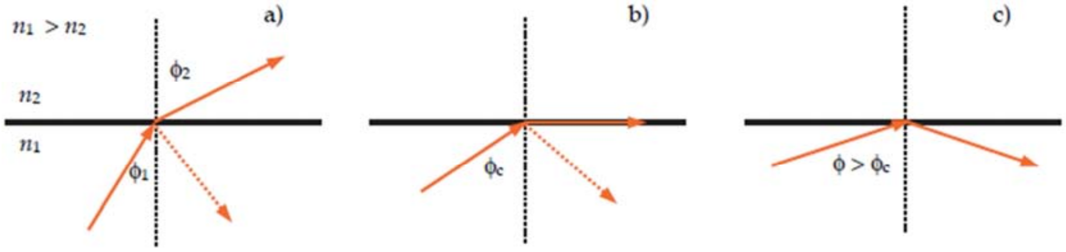

Figure 2. *Critical angle and total internal reflection.*

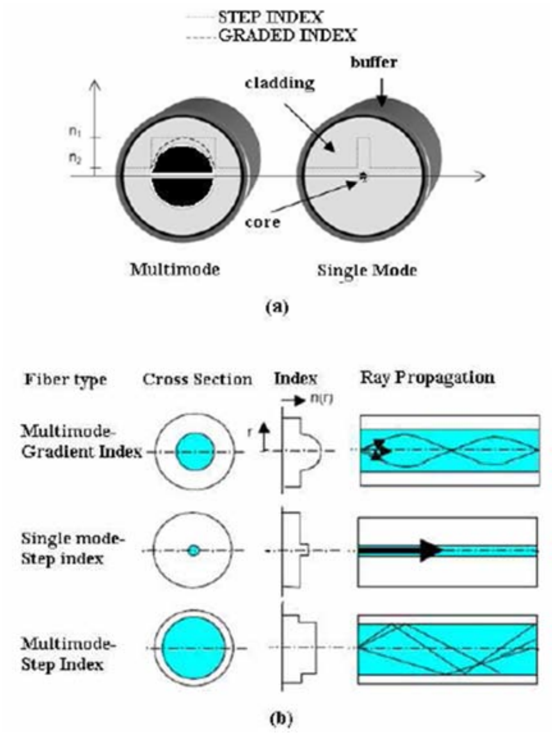

Figure 3. *Optical fibers types.*

Optical fibers can be classified based on the number of signals that can be transmitting into two groups: single mode and multi-mode. Also, it can be classified based on the refractive index shape in to step-index and graded-index fibers. In step index fibers, the refractive index profile is uniform along the fiber core. While, in the second one; the refractive index is made to vary as a function of the radial distance from the center of the fiber [1]. Figure 3 shows the different types of fibers.

3. Fiber Optic Sensors: Basic Components and Structure

The basic structure of an optical fiber sensor system is illustrated in Figure 4. It consists of an optical source, a transducer and a receiver. The optical source often it is laser, diodes or LEDs. An optical fiber and bulk materials are used as a modulator element. At the receiver, a photodetector is used to detect the change in the optical signal that is caused by the physical perturbation of the system.

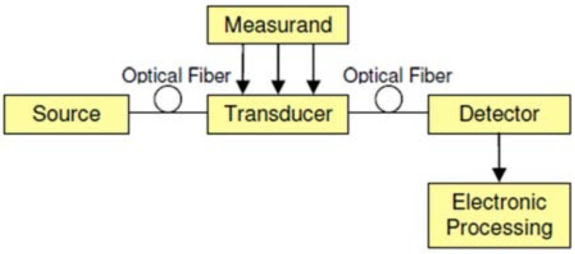

Figure 4. *Basic components of an optical fiber sensor.*

Fiber optic sensors are classified based on location, operation principle and applications to three categories. In the first category, fiber optic sensors are classified as an extrinsic or intrinsic. In an extrinsic one, the fiber is used to carry light to and from an external optical device where the sensing takes place. In this case, fiber is work as a guide to deliver light to the sensing location. While in an intrinsic case, the physical properties of the fibers are subject to change. These changes are works on the fiber to change some of the light characteristic (see Figure 5).

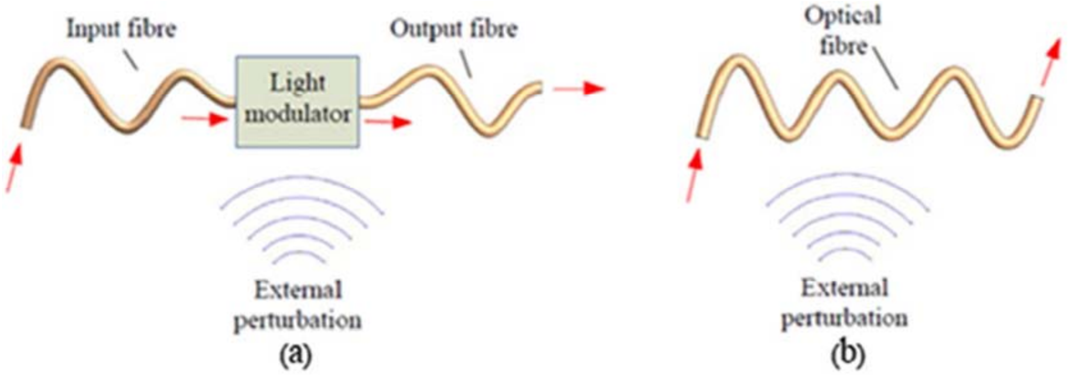

Figure 5. *Extrinsic and intrinsic fiber optic sensors.*

In the second category, fiber optic sensors can be classified as intensity, a phase, a frequency, or a polarization sensor. In this case, all parameters are subject to change due to external interference. Thus, by detecting these parameters and their changes, the external disturbances can be sensed. For the last category, a fiber optic sensor can be classified as physical, chemical and bio-medical sensors used to sense of temperature, stress, pH measurement, gas analysis, measurement of blood flow, glucose content etc [1].

4. Classification Based on Modulation Techniques

The propagation of light along the optical fiber can be described by four factors: density (amplitude), phase, wavelength (frequency) and polarization. When the surrounding environment experiences a change; at least one of the four parameters changes accordingly. By observing this change, useful information can be obtained. Thus, the fiber optic sensor's efficiency depends on its ability to convert these changes on the parameters reliably and accurately.

4.1. Intensity Modulation Fiber Optic Sensors

The sensing in this type relies on the loss in the transmitted light through the fiber measured using a suitable detector. Depending on the mechanism that changes the intensity of the signal, a wide range of configurations are possible for these sensors. Due to their simple structures, low manufacturing cost, versatility, durability and flexibility due to the lack of specialized components or fiber except for stable optical source, reasonable detection and signal processing unit, these sensors are widely spread [17]. However, its disadvantages are misread readings that may occur as a result of relative measurements and variations in the intensity of the light source, unless a reference system is used [18].

4.2. Phase Modulation Fiber Optic Sensors

In this type of sensors the principle is based on comparing the phase of the light in a sensing fiber to a reference. In general, these sensors use a coherent light source and two single mode fibers. The light is split and then injected into the reference and sensing fibers. The optical phase is high sensitive to the environment perturbations, so when the light in the sensing fibers is exposed to the changes, a phase shift occurs between them and then is detected interferometrically. Optical sensor based phase modulation technique is much more accurate than intensity modulated [11].

4.3. Polarization Modulation Fiber Optic Sensors

The refractive index of the optical fiber changes when exposed to stress or strain and this affect is known as a photo elastic effect. In many cases, stress or strain is different in different directions. Thus, the change in the refractive index is also different in different directions. This meaning that the different polarization directions results an induced phase difference. In other words, the external disturbances such as strain or stress make fiber acts like a linear inhibitor. Thus, by detecting the change, the external perturbation can be a sensed [11].

On the other hand, polarization plays an influential role in single mode optical fiber systems. Where, many physical phenomena affect the state of polarization of light [11]. This type of modulation can be introduced by a number of different means as applying stress to optical fibers or by mechanical twisting what we can sensing many physical and chemical phenomena based on this effect.

4.4. Frequency Modulation Fiber Optic Sensors

Frequency modulated optical sensors depend on changes in frequency (i.e. wavelength) of light for detection. Different configurations are exists for these sensors such as fluorescence sensors, Bragg grating sensors, etc. Fluorescent sensors are widely used for medical applications, chemical and physical sensing [18]. In Bragg optical sensor, a grating causes light to behave in a certain way dependent on the periodicity of the grating [2, 3, 4, 6].

5. Fiber Optic Sensors Applications

In comparison with the conventional types, fiber optic sensors are used in wide range areas such as physical, chemical, bio-medical, oil and gas applications. Different measurements can be made with high accuracy and optimal reliability such as strain, rotation, displacement, temperature, pressure, velocity, acceleration, electrical and magnetic fields, pH measurement, gas analysis, blood flow and glucose content etc (see Figures 6-8) [13, 15].

Figure 6. *Fiber optical sensors for temperature sensing.*

Figure 7. *Fiber optical sensors for power line monitoring.*

Figure 8. *Oil and gas well monitoring.*

In addition, its applications in civil engineering have proven to be more effective than traditional systems especially for buildings, bridges, tunnels, dams and heritage structures. Their ability for monitoring makes it very suitable and effective for concrete during setting, pre-stressing and spatial displacement measurements, convergence, damage detection; joint expansion monitoring, spatial displacement measurement and etc (see Figures 9-12) [13, 15, 17, 18].

Figure 9. *Dam Monitoring.*

Figure 10. *Structural Health Monitoring.*

Figure 11. *Highway monitoring.*

Figure 12. *Geological hazard safety monitoring.*

6. Conclusions

In this paper, an overview of fiber optic sensors, its principle, classifications and their applications has been presented. The basic components and the major types of sensors are discussed included optical fiber interferometers, phase, polarization and frequency modulated fiber optic sensors. Also, the advantages that they offer over conventional sensor types in wide application areas have been presented.

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