Optical Fiber Sensors: Classification & Applications

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***Abstract*— Beside advantages; recent advances and cost reductions has aroused interest in optical fiber sensing. So, the outgrowths of optical fiber telecommunications are combined with optoelectronic devices to develop optical fiber sensors. In past decades several researches have been conducted using optical fiber sensors with different techniques. Intensity, phase, and wavelength based optical fiber sensors are the most widely used sensor types. In this paper the overview, types and applications of optical fiber sensors is discussed.**

***Key Words*— Optical fiber, optical fiber sensing.**

I. INTRODUCTION

The field of fiber optics has undergone a tremendous growth and advancement over the last 25 years. Initially conceived as a medium to carry light and images for medical endoscopic applications, optical fibers were later proposed in the mid 1960's as an adequate information-carrying medium for telecommunication applications. Ever since, optical fiber technology has been the subject of considerable research and development to the point that today light wave communication systems have become the preferred method to transmit vast amounts of data and information from one point to another. Among the reasons why optical fibers are such an attractive are their low loss, high bandwidth, EMI immunity, small size, lightweight, safety, relatively low cost, low maintenance, etc.

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II. OPTICAL FIBER BASICS

An optical fiber is composed of core, cladding, and coating or buffer. The basic structure is shown in Figure 1.

The core is a cylindrical rod of dielectric material and is generally made of glass. Light propagates mainly along the core of the fiber [1]. The cladding layer is made of a dielectric material with an index of refraction. The index of refraction of the cladding material is less than that of the core material. The cladding is generally made of glass or plastic. The cladding executes such functions as decreasing loss of light from core into the surrounding air, decreasing scattering loss at the surface of the core, protecting the fiber from absorbing the surface contaminants and adding mechanical strength [1].

The coating or buffer is a layer of material used to protect an optical fiber from physical damage. The material used for a buffer is a type of plastic. The buffer is elastic in nature and prevents abrasions [1].

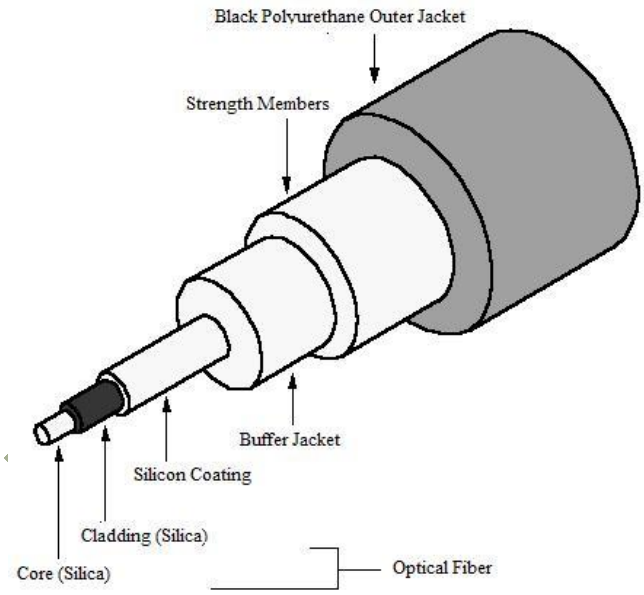

Figure 1 Basic structure of an optical fiber.

The light-guiding principle along the fiber is based on the "total internal reflection". The angle at which tot al internal reflection occurs is called the critical angle of incidence. At any angle of incidence, greater than the critical angle, light is totally reflected back into the glass medium as shown in Figure 2.

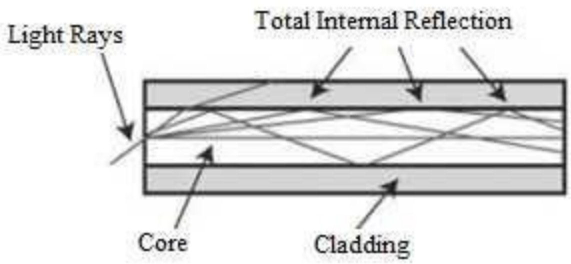

Figure 2 Total internal reflections in an optical fiber.

The critical angle of incidence is determined by using Snell's Law. Optical fiber is an example of electromagnetic surface waveguide [1].

III. SENSORS BASICS

As shown in Figure 3, a optical fiber sensor system consists of an optical source (laser, LED, laser diode, *etc.*), optical fiber, sensing or modulator element transducing the measurand to an optical signal, an optical detector and processing electronics (oscilloscope, optical spectrum analyzer, *etc.*) [2].

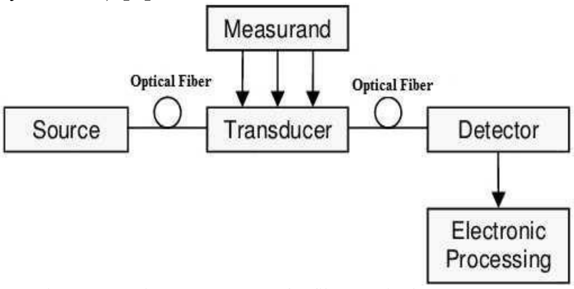

Figure 3 Basic components of a fiber-optical sensor system

Light sources used to support optical fiber sensors produce light that is often dominated by either spontaneous or stimulated emission. A combination of both types of emission is also used for certain classes of optical fiber sensors.

IV. OPTICAL FIBER SENSOR CLASSIFICATION

Optical fiber sensors are classified under three categories [2]: the sensing location, the operating principle and the application, as seen in Table 1.

Table 1 Sensor classifications under three categories

Category	Types
Sensing Location	Point Sensors
	Distributed Sensors
	Quasi-distributed Sensors
Operating Principle	Intensity Sensors
	Phase Sensors
	Frequency Sensors
	Polarization Sensors
Application	Physical Sensors
	Chemical Sensors
	Bio-medical Sensors

Based on the sensing location, a optical fiber sensor can be classified as extrinsic or intrinsic. The intrinsic optical fiber sensor has a sensing region within the fiber and light never goes out of the fiber. Perturbations act on the fiber and the fiber in turn changes some characteristic of the light inside the fiber. In extrinsic sensors, light has to leave the fiber and reach the sensing region outside, and then comes back to the fiber. In this case, the fiber just acts as a means of getting the light to the sensing location.

Based on the operating principle or modulation and demodulation process, a optical fiber sensor can be classified as intensity, a phase, a frequency, or a polarization sensor. All these parameters may be subject to change due to external perturbations. Thus, by detecting these parameters and their changes, the external perturbations can be sensed.

Based on the application, a optical fiber sensor can be classified as follows:

• Physical sensors: Used to measure physical proper ties like temperature, stress, etc.
• Chemical sensors: Used for pH measurement, gas analysis, spectroscopic studies, etc.
• Bio-medical sensors: Used in bio-medical applicat ions like measurement of blood flow, glucose content etc.

V. INTENSITY BASED SENSORS

In these types of sensors, the measurand modulates the intensity of the transmitted light through the fiber and these variations in intensity are measured using a detector situated at the output end of the fiber. These optical fiber sensors are compatible with the multimode fiber technology.

One of the intensity based optical fiber sensor is the evanescent wave sensor that utilizes evanescent field created whenever light undergoes total internal reflection at the boundary between two dielectric media. The evanescent field penetrating into the cladding decays exponentially as shown in Figure 4.

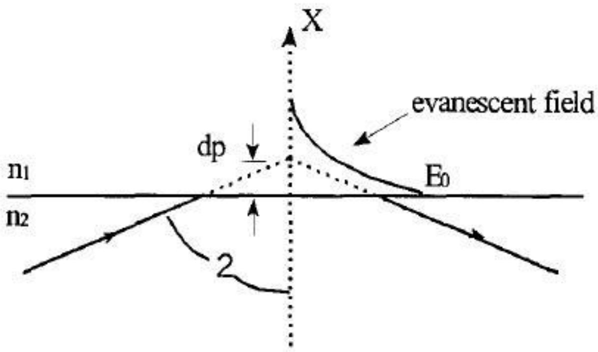

Figure 4 Evanescent waves in the lower index region

These sensors are widely used as chemical sensors. The sensing is achieved by stripping the cladding from a section of the fiber and using a light source having a wavelength that can be absorbed by the chemical that is to be detected. The resulting change in light intensity is a measure of the chemical concentration. But the disadvantage of this type of sensor is that the sensitivity is dependent on the mode distribution and hence on launching conditions and external disturbances.

Another type of intensity based optical fiber sensor is the microbend sensor. They work on the basis of transmission loss occurring due to microbending of the optical fibre. Bending of a multimode fiber waveguide causes a redistribution of light power among the many modes in the fiber. The more severe the bending, the more light is coupled to radiation modes causing the light propagating in the fiber to decrease.

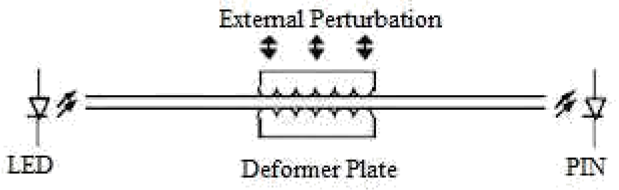

Figure 5 Microbend optical fiber sensor

When a fiber is subjected to small deformations (microbends), light rays in the core of the fiber exceed the critical angle. This causes redistribution of energy between core and cladding modes. The guided higher order core modes couple to the cladding modes causing the light propagating in the fiber to decrease. This mode coupling can be achieved by squeezing the fiber between a set of corrugated plates called deformer plates. Hence, microbending causes the light intensity to decrease due to light leakage into the cladding. By monitoring and correlating the loss of light intensity, different types of microbend sensors can be designed [3]. In addition to the general advantages of fiber optic sensors, microbend sensors are easier to implement and have lower cost than other types of fiber optic sensor [4].

VI. WAVELENGTH BASED SENSORS

Wavelength modulated sensors use changes in the wavelength of light for detection. Fluorescence sensors, black body sensors, and the Bragg grating sensor are examples of this type of sensor. For measuring temperature, viscosity and humidity fluorescent based fiber sensors are being widely used.

Blackbody sensor is one of the simplest sensors of this type. A blackbody cavity is placed at the end of an optical fiber. When the cavity rises in temperature, it starts to glow and act as a light source. Detectors in combination with narrow band filters as shown in Figure 6 are then used to determine the profile of the blackbody curve and, in turn, the temperature.

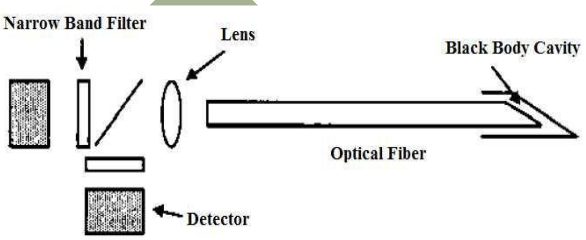

Figure 6 Blackbody Sensor

This type of sensor has been successfully commercialized and used to measure temperature to within a few degrees centigrade under intense fields.

Another sensor is the Bragg grating sensor which is most widely used wavelength based sensor. In-fiber, Bragg gratings are sensor elements which are photo-written into optical fiber using intense ultra-violet laser beams and have the potential for the measurement of strain/deformation and temperature with applications reported including monitoring of highways, bridges, aerospace components and in chemical and biological sensors.

Bragg grating sensors make use of the transmission/reflection of light as determined by a series of regular refractive index variations along the axis of a fiber core. . Whenever a broad-spectrum light beam impinges on the grating, a portion of its energy transmitted through, and another reflected off as depicted in Figure 7.

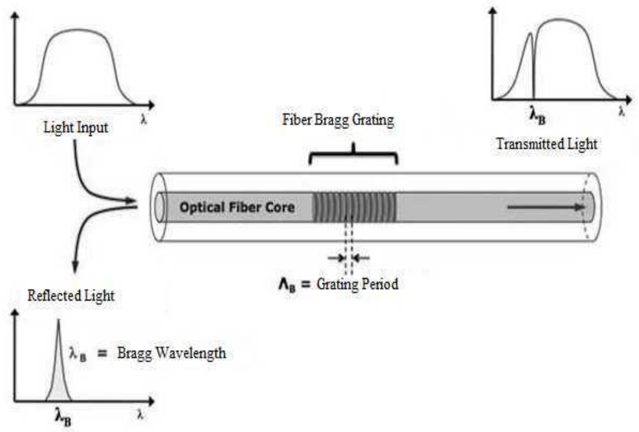

Figure 7 Fiber Bragg Grating & its response

The reflected light signal will be very narrow (few nm) and will be centered at the Bragg wavelength which corresponds to twice the periodic unit spacing $\wedge_B$. Any change in the modal index or grating pitch of the fiber caused by strain, temperature of polarization changes, will result in a Bragg wavelength shift [5].

VII. POLARIZATION BASED SENSORS

The direction of the electric field portion of the light field is defined as the polarization state of the light field. Linear, elliptical, and circular polarization are different types of polarization states of the light. The refractive index of a fiber undergoing a certain stress or strain is called induced refractive index. The induced refractive index changes with the direction of applied stress or strain. Thus, there is an induced phase difference between different polarization directions. This phenomenon is called photoelastic effect. In other words, under the external perturbation, such as stress or strain, the optical fiber works like a linear retarder. Therefore, by detecting the change in the output polarization state, the external perturbation can be sensed [6]. Figure 8 shows the optical setup for the polarization based fiber optic sensor.

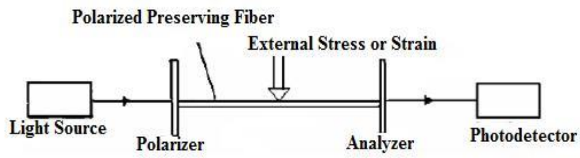

Figure 8 Polarization-based optical fiber sensor

It is formed by polarizing the light from a light source via a polarizer that could be a length of polarization-preserving fiber. The polarized light is launched at 45 degrees to the preferred axes of a length of bi-refrigent polarization-preserving fiber. This section of fiber is served as sensing fiber. Under external perturbation such as stress or strain, the phase difference between two polarization states is changed. Then, the output polarization state is changed according to the perturbation. Hence, by analyzing the output polarization state at the exit end of the fiber, the external perturbation can be detected.

VIII. PHASE BASED SENSORS

In this case, the external physical phenomenon to be measured modifies the phase shift between two coherent propagating beams having different paths. The phase modulation is then detected interferometerically, by comparing the phase of the light in the signal fiber to that in a reference fiber. In an interferometer, the light is split into two beams, where one beam is exposed to the sensing environment and undergoes a phase shift and the other is isolated from the sensing environment and is used for as a reference. Once the beams are recombined, they interfere with each other as shown in Figure 9. Mach-Zehnder, Michelson, Fabry-Perot, Sagnac, polarimetric, and grating interferometers are the most commonly used intereferometers.

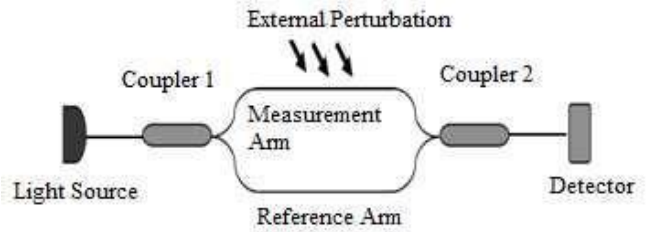

Figure 9 Mach-Zehnder optical fiber interferometer

The fiber has to be monomode, otherwise each mode would have a different phase shift linked to its eigen propagation constant. The coherence length of the light source has to be larger than the maximum possible difference of the optical path between the two arms. The phase shift will be linked to a refractive index change in the measurement arm. This refractive index modulation can take place in the optical fiber core or cladding due to a large range of possible phenomena (thermal, mechanical, chemical, electromagnetical etc.).

IX. APPLICATIONS

Fiber optic sensors are used in various areas. Specifically:

- Chemical & Biological Sensing
- Mechanical Measurements such as rotation, acceleration, electric and magnetic field measurement, temperature, pressure, linear and angular position, strain, humidity, chemical measurements etc.
- Monitoring the physical health of structures in real time.
- Buildings and Bridges: Concrete monitoring during setting, crack (length, propagation speed) monitoring, spatial displacement measurement, long-term deformation (creep and shrinkage) monitoring etc.
- Dams: Foundation monitoring, joint expansion monitoring, spatial displacement measurement, leakage monitoring, and distributed temperature monitoring.
- Heritage structures: Displacement monitoring, crack opening analysis, post-seismic damage evaluation, restoration monitoring, and old-new interaction.
- Tunnels: Multipoint optical extensometers, convergence monitoring, prefabricated vaults evaluation, and joints monitoring damage detection.

CONCLUSION

This paper has reviewed the main optical fiber sensors. There are various unique advantages of optical fiber sensors which include their ability to be light in weight, small in size, easy to launch light, low ISI, resistance to electromagnetic interference, high sensitivity, wide bandwidth and environmental ruggedness make them widely used in different areas. All these mentioned characteristics make best use of optical fiber as sensor and opening new research fields.

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