Applications of Fiber-Optic Sensors

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FIBER OPTIC SENSORS AND THEIR APPLICATIONS

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Abstract

Beside advantages; recent advances, and cost reductions has stimulated interest in fiber optical sensing. So, researchers combined the product outgrowths of fiber optic telecommunications with optoelectronic devices to emerge fiber optic sensors. Numerous researches have been conducted in past decades using fiber optic sensors with different techniques. Intensity, phase, and wavelength based fiber optic sensors are the most widely used sensor types. In this paper, an overview of fiber optic sensors and their applications are presented.

Keywords: Fiber optics, optical fiber sensing, fiber Bragg gratings (FBGs), interferometry, microbending, smart structures

1. Introduction

With the invention of the laser in 1960's, a great interest in optical systems for data communications began. The invention of laser, motivated researchers to study the potential of fiber optics for data communications, sensing, and other applications. Laser systems could send a much larger amount of data than microwave, and other electrical systems. The first experiment with the laser involved the free transmission of the laser beam in the air. Researchers also conducted experiments by transmitting the laser beam through different types of waveguides. Glass fibers soon became the preferred medium for transmission of light. Initially, the existence of large losses in optical fibers prevented coaxial cables from being replaced by optical fibers. Early fibers had losses around 1000 dB/km making them impractical for communications use [1].

In 1969, several scientists concluded that impurities in the fiber material caused the signal loss in optical fibers. By removing these impurities, construction of low-loss optical fibers was possible. In 1970, Corning Glass Works made a multimode fiber with losses under 20 dB/km. The same company, in 1972, made a high silica-core multimode optical fiber with a 4 dB/km loss [1].

Recent advances in fiber optic technology have significantly changed the telecommunications industry. The ability to carry gigabits of information at the speed of light increased the research potential in optical fibers. Simultaneous improvements and cost reductions in optoelectronic components led to similar emergence of new product areas. Last revolution emerged as designers to combine the product outgrowths of fiber optic telecommunications with optoelectronic devices to create fiber optic sensors. Soon it was discovered that, with material loss almost disappearing, and the sensitivity for detection of the losses increasing, one could sense changes in phase, intensity, and wavelength from outside perturbations on the fiber itself. Hence fiber optic sensing was born [2].

In parallel with these developments, fiber optic sensor technology has been a significant user of technology related with the optoelectronic and fiber optic communication industry [3-7]. Many of the components associated with these industries were often developed for fiber optic sensor applications. Fiber optic sensor technology in turn has often been driven by the development and subsequent mass production of components to support these industries. As component prices have decreased and quality improvements have been made, the ability of fiber optic sensors to replace traditional sensors have also increased.

Fiber optic sensors are excellent candidates for monitoring environmental changes and they offer many advantages over conventional electronic sensors as listed below:

- Easy integration into a wide variety of structures, including composite materials, with little interference due to their small size and cylindrical geometry.
- Inability to conduct electric current.
- Immune to electromagnetic interference and radio frequency interference.
- Lightweight.
- Robust, more resistant to harsh environments.
- High sensitivity.
- Multiplexing capability to form sensing networks.
- Remote sensing capability.
- Multifunctional sensing capabilities such as strain, pressure, corrosion, temperature and acoustic signals.

To date, fiber optic sensors have been widely used to monitor a wide range of environmental parameters such as position, vibration, strain, temperature, humidity, viscosity, chemicals, pressure, current, electric field and several other environmental factors [8-13].

2. Optical Fiber Basics

An optical fiber is composed of three parts; the core, the cladding, and the 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].

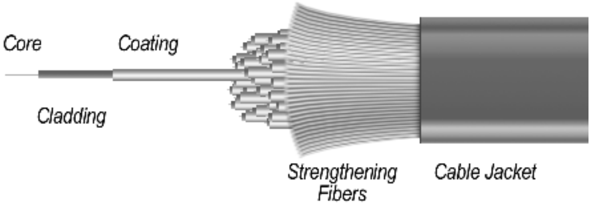

Figure 1. Basic structure of an optical fiber.

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].

The light-guiding principle along the fiber is based on the "total internal reflection". The angle at which total 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 (see Figure 2). The critical angle of incidence is determined by using Snell's Law. Optical fiber is an example of electromagnetic surface waveguide [1].

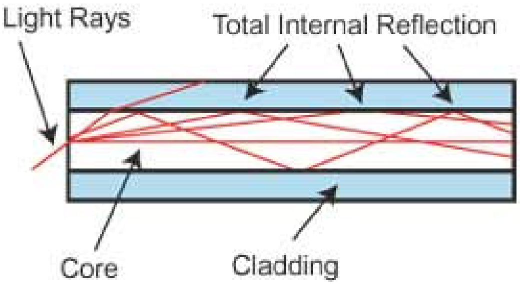

Figure 2. Total internal reflection in an optical fiber.

Optical fibers are divided into two groups called single mode and multimode. In classifying the index of refraction profile, we differentiate between step index and gradient index. Step index fibers have a constant index profile over the whole cross section. Gradient index fibers have a nonlinear, rotationally symmetric index profile, which falls off from the center of the fiber outwards [14]. Figure 3 shows the different types of fibers.

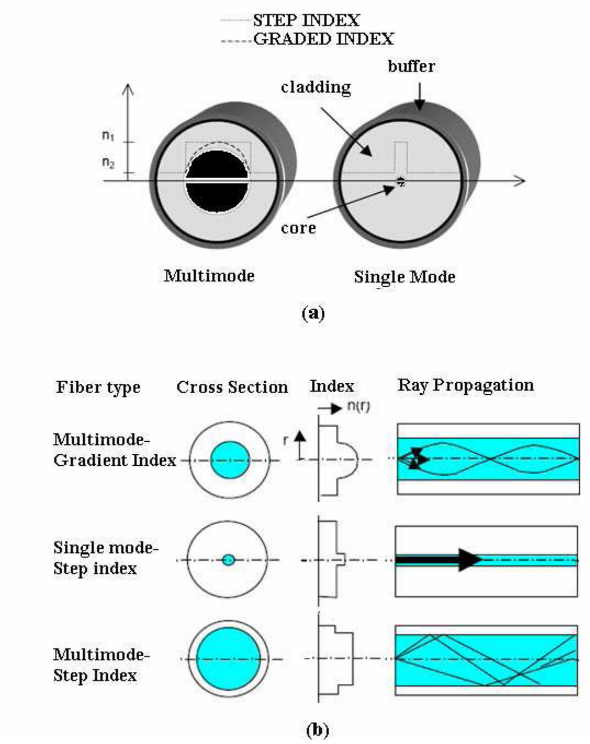

Figure 3. Different types of optical fibers.

3. Fiber Optic Sensor Principles

The general structure of an optical fiber sensor system is shown in Figure 4. It consists of an optical source (Laser, LED, Laser diode etc), optical fiber, sensing or modulator element (which transduces the measurand to an optical signal), an optical detector and processing electronics (oscilloscope, optical spectrum analyzer etc).

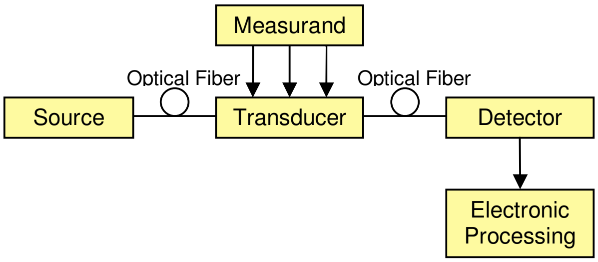

Figure 4. Basic components of an optical fiber sensor system.

Fiber optic sensors can be classified under three categories: The sensing location, the operating principle, and the application.

Based on the sensing location, a fiber optic sensor can be classified as extrinsic or intrinsic. In an extrinsic fiber optic sensor (see Figure 5), the fiber is simply used to carry light to and from an external optical device where the sensing takes place. In this cases, the fiber just acts as a means of getting the light to the sensing location.

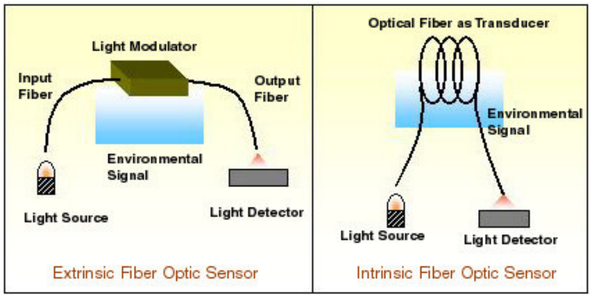

Figure 5. Extrinsic and intrinsic types of fiber optic sensors.

On the other hand, in an intrinsic fiber optic sensor one or more of the physical properties of the fiber undergo a change (see Figure 5). Perturbations act on the fiber and the fiber in turn changes some characteristic of the light inside the fiber [9].

Based on the operating principle or modulation and demodulation process, a fiber optic sensor can be classified as an 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 [10].

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

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

4. Fiber Optic Sensor Types

4.1 Intensity Based Fiber Optic Sensors

Intensity-based fiber optic sensors rely on signal undergoing some loss. They are made by using an apparatus to convert what is being measured into a force that bends the fiber and causes attenuation of the signal. Other ways to attenuate the signal is through absorption or scattering of a target. The intensity-based sensor requires more light and therefore usually uses multimode large core fibers [5]. There are a variety of mechanisms such as microbending loss, attenuation, and evanescent fields that can produce a measurand-induced change in the optical intensity propagated by an optical fiber. The advantages of these sensors are: Simplicity of implementation, low cost, possibility of being multiplexed, and ability to perform as real distributed sensors. The drawbacks are: Relative measurements and variations in the intensity of the light source may lead to false readings, unless a referencing system is used [15].

One of the intensity-based sensors is the microbend sensor, which is based on the principle that mechanical periodic micro bends can cause the energy of the guided modes to be coupled to the radiation modes and consequently resulting in attenuation of the transmitted light. As seen in Figure 6, the sensor is comprised of two grooved plates and between them an optical fiber passes. The upper plate can move in response to pressure. When the bend radius of the fiber exceeds the critical angle necessary to confine the light to the core area, light starts leaking into the cladding resulting in an intensity modulation [16].

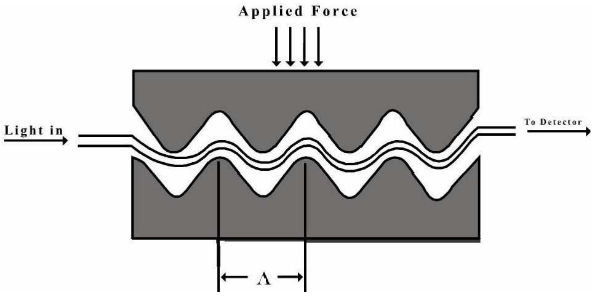

Figure 6. Intrinsic fiber optic sensor.

Another type of intensity based fiber optic sensor is the evanescent wave sensor (see Figure 7) that utilizes the light energy which leaks from the core into the cladding. These sensors are widely used as chemical sensors. The sensing is accomplished 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. Measurements can also be performed in a similar method by replacing the cladding with a material such as an organic dye whose optical properties can be changed by the chemical under investigation [17].

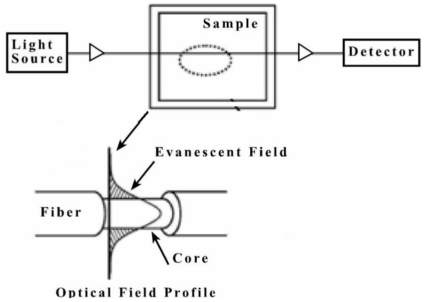

Figure 7. Evanescent wave fiber optic chemical sensor.

4.2 Wavelength Modulated Fiber Optic 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 wavelength-modulated sensors. Fluorescent based fiber sensors are being widely used for medical applications, chemical sensing and physical parameter measurements such as temperature, viscosity and humidity. Different configurations are used for these sensors where two of the most common ones are shown in Figure 8. In the case of the end tip sensor, light propagates down the fiber to a probe of fluorescent material. The resultant fluorescent signal is captured by the same fiber and directed back to an output demodulator [18].

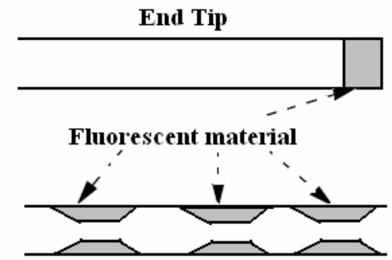

Figure 8. Fluorescent fiber optic sensor probe.

One of the simplest wavelength based sensor is the blackbody sensor as shown in Figure 9. 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 are then used to determine the profile of the blackbody curve. This type of sensor has been successfully commercialized and has been used to measure temperature to within a few degrees centigrade under intense RF fields.

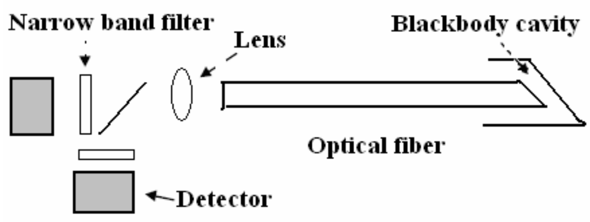

Figure 9. Blackbody fiber optic sensor.

The most widely used wavelength based sensor is the Bragg grating sensor. Fiber Bragg gratings (FBGs) are formed by constructing periodic changes in index of refraction in the core of a single mode optical fiber. This periodic change in index of refraction is normally created by exposing the fiber core to an intense interference pattern of UV energy. The variation in refractive index so produced, forms an interference pattern which acts as a grating.

The Bragg grating sensor operation is shown in Figure 10 where light from a broadband source (LED) whose center wavelength is close to the Bragg wavelength is launched into the fiber. The light propagates through the grating, and part of the signal is reflected at the Bragg wavelength. The complimentary part of the process shows a small sliver of signal removed from the total transmitted signal. This obviously shows the Bragg grating to be an effective optical filter [13].

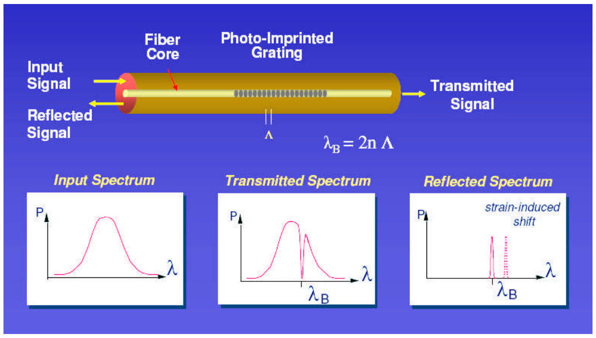

Figure 10. Bragg grating response.

4.3 Phase Modulated Fiber Optic Sensors

Phase modulated sensors use changes in the phase of light for detection. The optical phase of the light passing through the fiber is modulated by the field to be detected. This 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 [5].

Mach-Zehnder, Michelson, Fabry-Perot, Sagnac, polarimetric, and grating interferometers are the most commonly used intereferometers. The Michelson and Mach-Zehnder interferometers are shown in Figures 11 (a) and 11 (b), respectively.

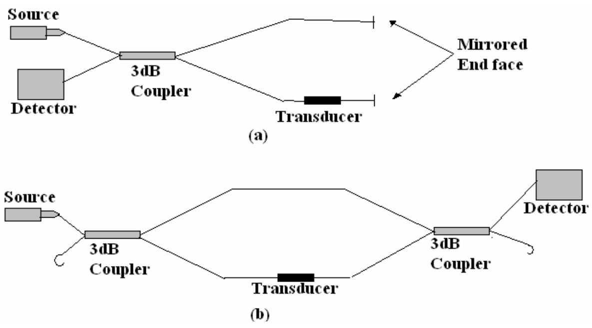

Figure 11. Shematic diagrams of (a) Michelson, and (b) Mach-Zehnder interferometers.

There are similarities and differences between the Michelson and Mach–Zehnder interferometers. In terms of similarities, the Michelson is often considered to be folded Mach–Zehnder, and vice versa. Michelson configuration requires only one optical fiber coupler. Because the light passes both through the sensing and reference fibers twice, the optical phase shift per unit length of fiber is doubled. Thus, the Michelson can intrinsically have better sensitivity. Another clear advantage of the Michelson is that the sensor can be interrogated with only a single fiber between the source-detector module and the sensor. However, a good-quality reflection mirror is required for the Michelson interferometer [10].

Another commonly used interferometer based sensor is the Fabry-Perot interferometric sensor (FFPI) and is classified into two categories: Extrinsic Fabry-Perot interferometer (EFPI) sensor and intrinsic Fabry-Perot interferometer (IFPI) sensor. In an EFPI sensor, the Fabry-Perot cavity is outside the fiber. Fiber guides the incident light into to the FFPI sensor and then collects and the reflected light signal from the sensor. In an IFPI sensor, the mirrors are constructed within the fiber. The cavity between two mirrors acts both as sensing element and waveguide. In this case, the light never leaves the fiber [19]. Figure 12 shows a typical EFPI sensor [19] based on capillary tube.

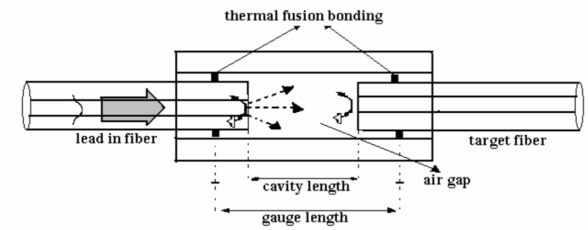

Figure 12. Capillary tube based EFPI sensor.

One cleaved fiber end (lead-in) is inserted into a glass capillary tube and another cleaved fiber end (target) is inserted into the tube from the other end. Both lead-in and target fibers are thermal fusion bonded with the tube. The cavity length between the two fibers is controlled using a precision optical positioner prior to the thermal fusion bonding. One of the advantages of this EFPI strain sensor is that its gauge length and cavity length can be different. The strain sensitivity is determined by the gauge length, while the temperature sensitivity is determined only by cavity length since the fiber and tube have the same thermal expansion coefficients. Hence, by making the gauge length much longer than the cavity length, the sensor temperature sensitivity becomes much less than the strain sensitivity. So, no temperature compensation is required.

An IFPI sensor contains two mirrors separated by a distance within a fiber core. The earliest IFPI sensor probably is the spliced TiO2 thin film coated fiber IFPI sensor. In this sensor internal mirror is introduced in fiber by thin film deposition on the cleaved fiber end followed by fusion splicing as shown in Figure 13. Several other methods are also used to produce internal mirror, such as using vacuum deposition, magnetron sputtering, or e-beam evaporation [19].

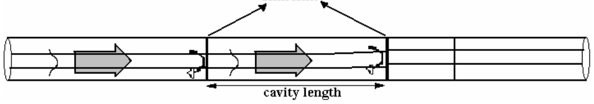

Figure 13. Thin film based IFPI sensor.

Sagnac interferometric sensors are based on fiber gyroscopes that can be used to sense angular velocity. Fiber gyroscopes are based on the principle that application of force changes the wavelength of light as it travels around a coil of optical fiber. It may also be occupied to measure time varying influences such as acoustics and vibration. Two types of fiber optic gyros have been developed: Open loop fiber optic gyro and closed loop fiber optic gyro.

The open loop fiber optic gyro is shown in Figure 14. A broadband light source is used to inject light into an input or output fiber coupler. The input light beam passes through a polarizer which is used to make certain the mutuality of the counter propagating light beams through the fiber coil. The second central coupler shares the two light beams into the fiber optic coil where they pass through a modulator. It is used to produce a time altering output signal indicative of rotation. The modulator is offset from the center of the coil for emphasizing a proportional phase difference between the counter propagating light beams. After light beams propagate from modulator, they rejoin and pass through the polarizer. Finally, light beams are guided onto the output detector [8].

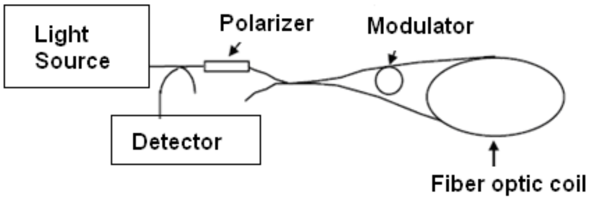

Figure 14. Open loop fiber optic gyro.

The second type is the closed loop fiber optic gyro that is primarily aimed at vacuum to high accuracy navigation applications. They have high turning rates and need high linearity and large dynamic ranges. In Figure 15, a closed loop fiber optic gyro is illustrated. This type of sensor is used as a modulator in the fiber optic coil to produce a phase shift at a certain rate. When the coil is rotated, a first harmonic signal is contributed with phase which depends on rotation rate. This manner is similar to open loop fiber optic gyro which is described before [18].

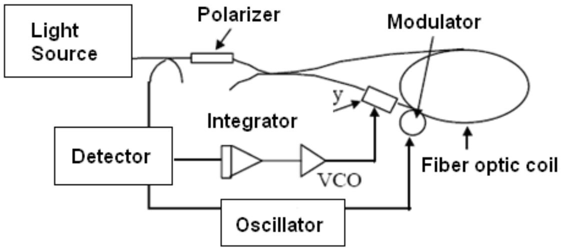

Figure 15. Closed loop fiber optic gyro.

4.4 Polarization Modulated Fiber Optic Sensors

The direction of the electric field portion of the light field is defined as the polarization state of the light field. Different types of polarization states of the light field are linear, elliptical, and circular polarization states. For the linear polarization state, the direction of the electric field always keeps in the same line during the light propagation. For the elliptical polarization state, the direction of the electric field changes during the light propagation. The end of the electric field vector forms an elliptical shape; hence, it is called ‘‘elliptical polarized light”.

The refractive index of a fiber changes when it undergoes stress or strain. Thus, there is an induced phase difference between different polarization directions. This phenomenon is called photoelastic effect. Moreover, 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. 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 [10].

Figure 16 shows the optical setup for the polarization-based fiber optic 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 [10].

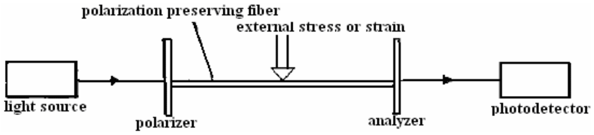

Figure 16. Polarization-based fiber optic sensor.

5. Applications of Fiber Optic Sensors

Fiber optic sensors are used in several areas. Specifically:

- Measurement of physical properties such as strain, displacement, temperature, pressure, velocity, and acceleration in structures of any shape or size.
- Monitoring the physical health of structures in real time.
- Buildings and Bridges: Concrete monitoring during setting, crack (length, propagation speed) monitoring, prestressing monitoring, spatial displacement measurement, neutral axis evolution, long-term deformation (creep and shrinkage) monitoring, concrete-steel interaction, and post-seismic damage evaluation.
- Tunnels: Multipoint optical extensometers, convergence monitoring, shotcrete / prefabricated vaults evaluation, and joints monitoring damage detection.
- 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.

6. Conclusions

An overview of fiber optics sensors and their applications has been presented. The major types of sensors discussed included microbending sensors, evanescent wave sensors, FBGs, optical fiber interferometers,and polarization modulated fiber optic sensors.

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