Review Article

Fiber-Optic Sensors: Technology & Applications.

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Abstract:

Besides many advantages, cost reduction and quality enhancement have stimulated interest in fiber-optic sensors (FOSs). Inventors tactically synchronize 'fiber optic telecommunication' with 'opto-electronic devices' to fabricate innovative FOSs In this paper, classification and applications of Fiber-optic sensors (FOSs) are discussed. Particular emphasis is given to advances in Sagnac interferometric and polarization modulated FOSs with their application.

Key Words:

Optical-fiber Sensors, Sensitivity, Intrinsic, Extrinsic, Gyroscope Sensor, Kerr nonlinearities, Evanscent, Sagnac interferometric.

1. Introduction:

In 1960's, after invention of Laser, researchers were motivated to study the potential of optical-fibers for data transfer, communications, sensing and some other applications because a laser systems can send larger data than microwave or electrical systems. The ability to interact with and/or control the properties of light propagating in optical fibres is of fundamental importance in both optical fibre sensor and optical telecommunication technologies. An FOS uses optical-fiber either as the sensing element i.e. "Intrinsic Sensors", or as a means of transmitting signals from a remote sensor to the electronic-circuit that processes the signals i.e. "Extrinsic Sensors". Optical-fibers have many uses in remote sensing.

An FOS measures a physical quantity based on its modulation on the intensity, spectrum, phase, or polarization of light traveling through an optical-fiber. This device converts light rays into electronic signals. Similar to a photo-resistor, it measures physical quantity of light and translates it into the data which can be observed. Since optical sensors have many applications, they are found in everything and everywhere from computers to motion detectors. For example, when the door to dark cavity inside of a photo-copier is opened, light controls the sensor by increasing in electrical productivity and triggering the electric response and stopping the photo-copier machine for safety. Distinction is often made in the case of FOSs as to whether they act externally or internally on the optical-fiber. Where the transducers are external and the optical-fiber simply registers and transmits the sensed data of the measurand quantity, they are termed as ‘extrinsic sensors’. Where the FOSs are embedded in or are part of the optical-fiber; and for this type, there is often some modification to the optical-fiber itself, such FOSs are termed as ‘intrinsic sensors’.

FOSs are immune to electromagnetic interferences because they do not conduct electricity and can be used where there is high voltage electricity or inflammable material such as jet fuel. FOSs can be designed to endure high temperatures as well.

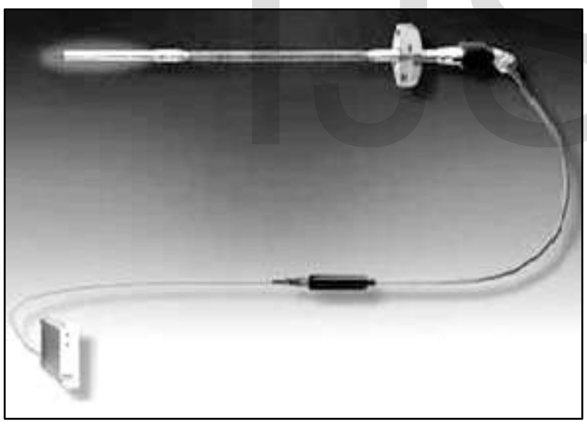

Figure 1: A simple kind of FOS.

FOSs have been one of the most benefited technologies of the remarkable developments, which are achieved by optoelectronics and optical-fiber communications industries. Primarily, an FOS works by modulating the properties of a propagating light wave, including wavelength, phase, intensity and polarization in response to the environmental parameters being measured [1]. Today, optical-fiber devices, including fiber gratings, play a major role in optical communication sensor applications, which include civil, mechanical, electrical, aerospace, automotive, nuclear, biomedical and chemical sensing technologies [2]. ***Figure 1*** shows a simple kind of FOS. The FOSs have been used in various applications ranging from monitoring of natural structures for estimation of seismic vibrations, earthquakes or volcanic activity [3] to medical systems like blood oxygen monitoring [4]. For structural applications, they are used for strain sensing and damage detection [5-7]. FOSs are also used for sensing force, pressure, temperature, velocity, acceleration, rotation, magnetic field, vibration [8-11], chemical [12-14] and biological species[16-17], pH level, acoustic waves, environmental [18] sensing and many other physical parameters.

An FOS is a device by which a chemical, physical, biological [40-43] or other measurand interacts with the light guided in a optical-fiber or guided to an interaction region by a optical-fiber to produce an optical signal correlated to the parameter of interest. It measures anything which alters the properties of light. Diagrammatically, an FOS is illustrated in ***Figure 2*.**

The light beam is taken to a modulation region within an optical-fiber and modulated therein by physical, chemical, or biological phenomena, and the modulated light is transmitted back to the receiver; detected and demodulated there.

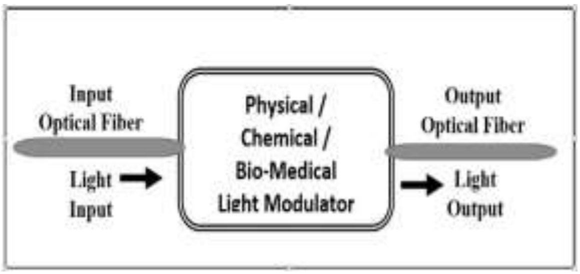

Figure 2 : Basic OFS system consists of an optical fiber and a light *modulating arrangement*

2. Optical-Fiber Basics:

An optical-fiber is composed of three parts:

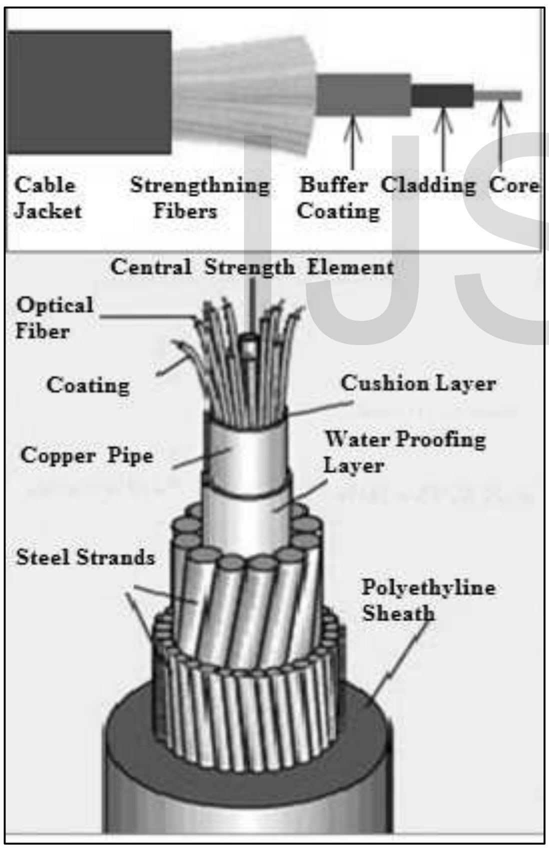

Figure 3: Basic structure of the optical fiber.

(a) The core.
(b) The cladding.
(c) The buffer coating.

A basic structure of optical-fiber and a cable of bunch of many optical-fibers is shown in ***Figure 3.*** The core is a glass like dialectic cylindrical rod. Mainly light propagates along core of optical-fiber. Though, core and cladding – both are made up of dielectric material, refractive index of core is higher than that of cladding. The cladding executes such functions as reducing loss of light from core into the surrounding air, reducing scattering loss at the core surface, shielding the fiber from absorbing surface contaminants and adding mechanical strength. The buffer coating is a layer of plastic type elastic material used to protect the optical-fiber from physical damage and abrasions.

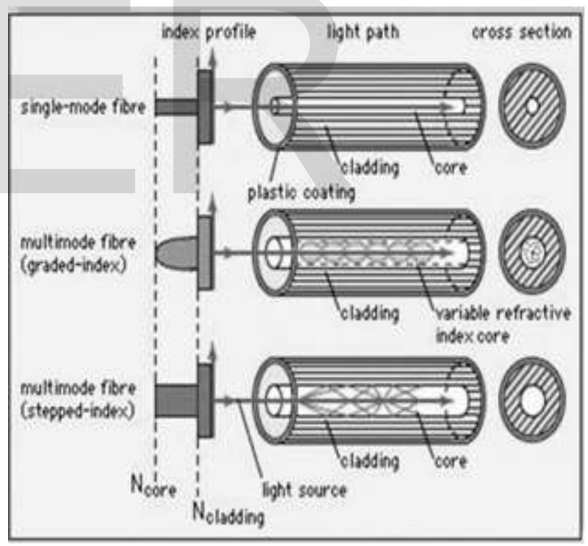

Figure 4: Different types of optical-fibers.

Optical-fibers are divided into two categories:

(i) Single mode optical-fibers.
(ii) Multimode optical-fibers.

Again, optical-fibers are differentiated according to the refractive index profile, as:

(i) Step index optical-fibers.
(ii) Gradient index optical-fibers.

Step index optical-fibers have a constant index profile over the entire cross section. Gradient index fibers have a nonlinear but rotationally symmetric refractive index profile, which falls off gradually from the center of the optical-fiber outwards. **Figure 4** shows the different types of optical-fibers.

3. Working Principle of Optical-Fiber Sensors:

Basically, an FOS system is composed of a light source (Laser, LED, Laser diode etc), an optical-fiber; a sensing or modulating element or transducer (which transduces the measurand to an optical signal), an optical detector and the processing electronic unit (oscilloscope, optical spectrum analyzer etc.). **Figure 5** shows the working principle of OFSs.

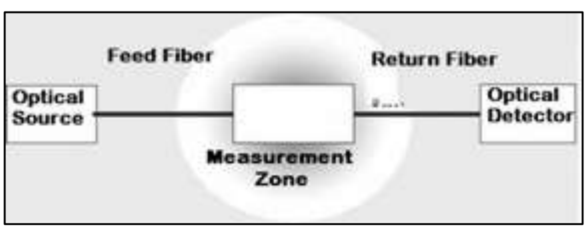

Figure 5: Working principle of OFS.

Light beam changes by the phenomena that is being measured. The principle of operation of an FOS is that a transducer modulates certain parameters of the optical system (wavelength, intensity, phase, polarization etc.) which causes a change in the characteristics of optical signal received by the detector. **Figure 6** shows the general structure of the FOS system.

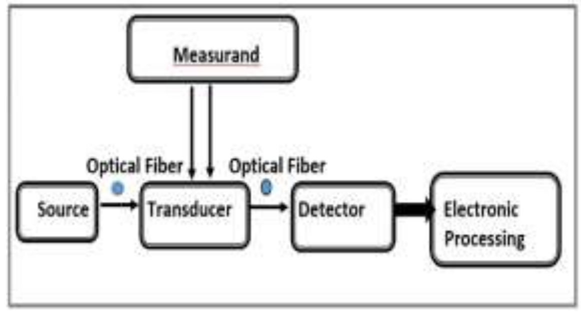

Figure 6: General structure of OFS system.

4. Classification Of Optical-Fiber Sensors:

FOSs are classified under three categories described below.

(i) The sensing location.
(ii) The operating principle.
(iii) The application.

4.1 Classification of optical-fiber sensors according to the sensing location:

Based on the sensing location and operation mode, FOSs are categorized under two titles [19-20].

(a) Extrinsic Fiber-optic Sensors.
(b) Intrinsic Fiber-optic Sensors.

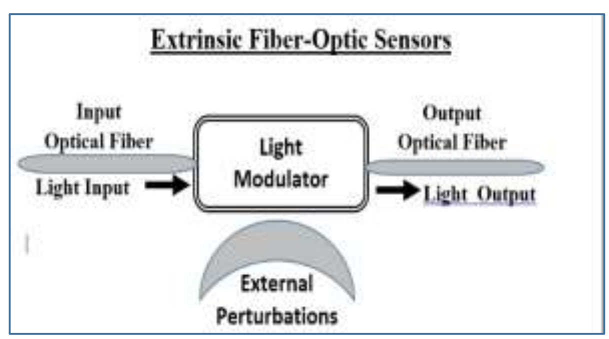

Figure 7: Extrinsic OFS System

In an extrinsic FOS, as shown in **figure 7**, the optical-fiber is basically used to carry light to and from an externally sensing optical device. Here, optical-fiber is a means of getting the light to the sensing location.In an intrinsic optical-fiber sensor, as shown in **figure 8**, one or more of the physical properties of the optical-fiber undergo a change. Perturbations act on the optical-fiber, which in turn changes some characteristic of the light inside the fiber.

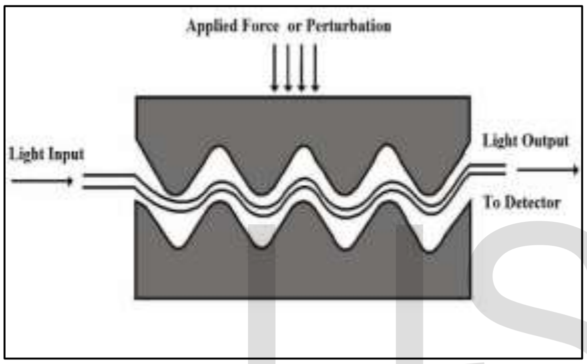

Figure 8: Intrinsic Fiber-Optic Sensor System.

4.1.1 Intrinsic Fiber-Optic Sensors:

In an intrinsic sensor, the optical-fiber itself is the sensing element. The light transmission takes place in the core of the optical-fiber itself as transducer. The light beam does not leave the optical-fiber but is changed whilst it contained within.

Intrinsic FOSs differ from extrinsic FOSs, where the light beam does not have to leave the optical-fiber to accomplish the sensing function as shown in **Figure 9**

In the intrinsic FOSs, the optical-fiber structure is such modified that the optical-fiber itself plays an active role in the sensing function, so, light-modulation takes place inside the optical-fiber to measure a specific parameter [29-33].

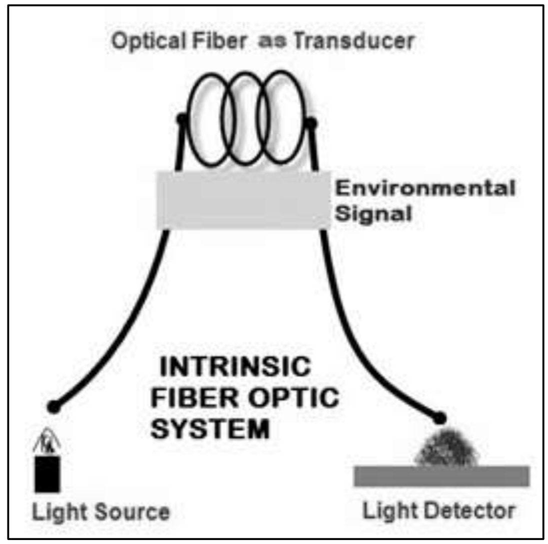

Figure 9: Intrinsic Fiber-Optic Sensor System.

FOSs measure force, pressure, strain, temperature and other quantities by modifying an optical-fiber so that the quantity to be measured modulates the wavelength, intensity, Phase, polarisation or transit time of light in the optical-fiber. The simplest type of optical-fiber requires only a simple source and a detector. A characteristically useful feature of intrinsic FOSs is that they can, provide distributed sensing over large distances.

Temperature is measured by using an optical-fiber that has evanescent loss that varies with temperature, or by analyzing the Raman scattering, Rayleigh Scattering or Brillouin Scattering. Electrical voltage is sensed by nonlinear optical in specially doped optical-fiber, which alters the polarization of light as a function of voltage or electric field. Angle measurement sensors are created on the Sagnac effect. Special optical-fibers like long-period optical-fiber grating (LPG) [40-43] are used for direction recognition. Optical-fibers can be made into interferometric sensors such as optical-fiber gyroscopes which are used in the aircrafts and in some car models for navigation purposes. They are also used to make hydrogen sensors.

The FOSs have been developed to measure co-located temperature and strain simultaneously with high accuracy using optical-fiber Bragg's grating. This is useful when acquiring information from small or complex structures [22]. Optical-fiber Bragg grating sensors are well suited for remote monitoring because they can be interrogated at nearly 250 km away from the monitoring station using an optical-fiber cable. Brillouin scattering effects can also be used to detect strain and temperature over large distances up to 120 kilometers [23-24, 40-43].

4.1.2 Extrinsic Fiber-Optic Sensors:

In an extrinsic FOSs, the optical-fiber simply carries light to or from the sensing element or it carries light from source and to detector but, modulation occurs outside the optical-fiber transducer. Extrinsic optical-fiber sensors mostly use a multimode type optical-fiber cable to transmit modulated light from either a non-optical-fiber sensor, or an electronic sensor connected to an optical transmitter. A chief advantage of extrinsic FOSs is their ability to reach the places which are inaccessible otherwise. Extrinsic FOSs are used in the same way to measure the internal temperature of electronic transformers where extreme electromagnetic fields present make other measurement techniques impossible. Extrinsic FOSs provide excellent protection to measurement of signals against noise corruption.

Extrinsic sensors are used to measure physical quantities like vibrations, revolutions, displacement, velocity, acceleration, torque, temperature etc. The distinguished characteristics of the extrinsic FOS is that the sensing occurs outside the optical-fiber as shown in **Figure 10.**

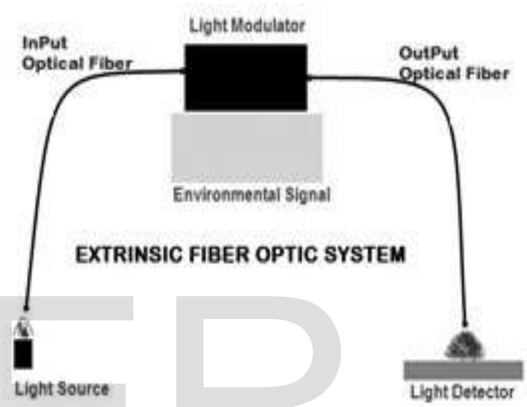

Figure 10: Extrinsic FOS System.

The optical-fiber performs light delivery and collection only. The propagating light leaves the optical-fiber in a way that can be detected and collected back by another or the same fiber.

Extrinsic FOSs can be found in systems such as Fabry–Perot interferometers which exploits only some of the advantages of optical-fibers offered over competing technologies. Intrinsic FOSs such as optical-fiber gyroscope, optical-fiber Bragg gratings, long period gratings micro-bend and coated or doped FOSs exploit most of the advantages offered by this technology. Intrinsic FOSs can be embedded within composite structures. This has attracted attentions of many researchers. A comparison of Extrinsic FOSs & Intrinsic FOSs is given below:

- Extrinsic FOSs are less expensive than intrinsic FOS.
- Extrinsic FOSs are less sensitive than intrinsic FOS.
- Extrinsic FOSs can be easily multiplexed while intrinsic FOSs are tougher to be multiplexed.
- Extrinsic FOSs have ingress/egress connection problems while intrinsic FOSs reduces connection problems.
- Intrinsic FOSs have more elaborate signal demodulation than the extrinsic one.
- Extrinsic FOSs include applications like temperature, pressure, liquid level and flow while intrinsic FOSs include applications like rotation, acceleration, strain, acoustic pressure and vibration.

4.2 Classification of FOSs based on their applications.

According to their applications, FOSs are classified as follows:

(a) Physical sensors: Used to measure physical properties like temperature, stress, etc.

(b) Chemical sensors: Used for pH measurement, gas analysis, spectroscopic studies, etc.

(c) Bio-medical sensors: Used in bio-medical applications like measurement of blood flow, glucose content etc.

4.3 Classification of FOSs based on the operating system.

Based on the operating principle or modulation-demodulation process, a FOS is classified as :

(a) Intensity based optical-fiber sensors.
(b) Wave length (or Frequency) modulated optical-fiber sensors.
(c) Phase Modulated Fiber Optic Sensors.
(d) Polarization Modulated Fiber Optic Sensors.

4.3.1 Intensity modulated optical-fiber sensors:

Intensity based FOSs uses multi-mode type large-core optical-fiber which requires more light. **Figure 11** shows arrangement of optical-fiber to work as a vibration sensor and how does the light intensity work as a sensing parameter. When there is vibrations, the light propagated from one end to another gets changed and the vibrations of amplitude is measured.

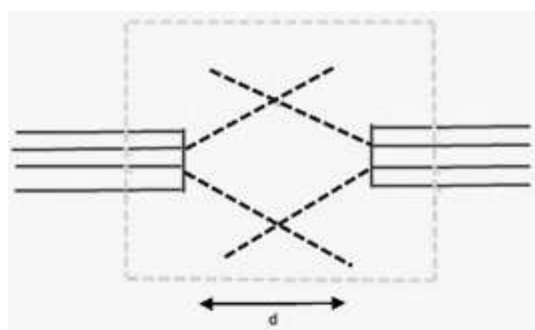

Figure 11 : Intensity modulated FOS system.

There are different mechanisms such as microbending loss, attenuation, and evanescent fields which produce a measurand induced change in the optical intensity propagated by the optical-fiber. The

Microbend sensor is one of the intensity-based OFSs. It is created on the principle that mechanical periodic micro bends produces the energy of guided modes to be coupled with radiation modes resulting in attenuation of transmitted light. In this FOS, an optical-fiber passes between two grooved plates.

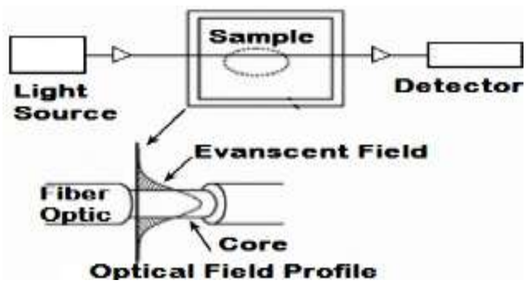

Figure 12: Evanscent Fiber-Optic Sensor

Evanescent wave Optical-fiber sensor ***(Figure: 12)*** utilizes the light energy leaked from core to cladding. They are usually used as chemical sensors. The sensing is achieved by stripping the cladding from a section of optical-fiber and using a light source that is absorbed by the chemical that is to be detected.

The resulting variation in light intensity gives a measure of the chemical concentration. Similarly, the measurements is performed by replacing the cladding with a material like an organic dye whose optical properties can be changed by the chemical under investigation.

Intensity based FOSs have several limitations due to variable losses due to spliced junctions, micro & macro bending losses, connections or joints loses etc. in the system that do not occur in environment. The examples are intensity-based microbend FOS and evanescent wave FOS [38]. The advantages of intensity based FOSs include simple operation, low cost, real distributed sensors ability, simple implementation, easy multiplexing etc. it's disadvantages are variations in light intensity, relative measurements etc.

4.3.2 Polarisation modulated Fiber-Optic sensors:

Polarization is modified by various external variables. Polarization based FOSs are used in a variety of measurements, signal processing and communication applications. The polarization state of the light field means the direction of polarization of electric component portion of the light field. Different forms of polarization include linear, elliptical, and circular polarization states. For the linear polarization state, direction of electric flied components is in the same line during the light propagation. For the elliptical polarization state, the direction of electric field components changes during the light propagation and when the trace of all possible electric fields are plotted is in elliptical shape. Whenever an optical-fiber is exposed to strain or stress, the refractive index is changed. The induced phase difference between different polarization directions exists, so called photo elastic effect. Respective change in refractive index due to strain or stress is known as induced refractive index. Thus, there is an induced phase difference between different polarization directions.

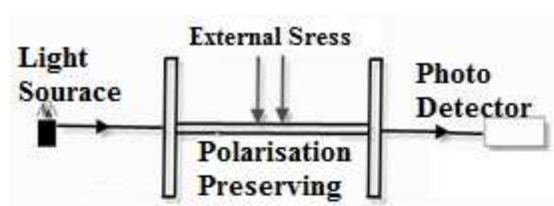

Figure 13: polarization modulated FOS

Figure 13 shows the optical setup for a polarization based FOS. Light is polarized by a polarizer that can be a length of polarization-preserving fiber.

4.3.3 Phase Modulated Fiber Optic Sensors:

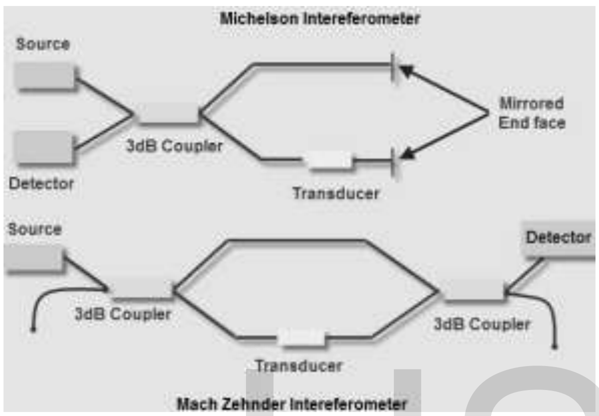

Figure 14:Phase Modulated Finber-Optic Sensor.

Phase modulated FOSs follow changes in phase of light for detection. The optical phase of light passing through the optical-fiber is modulated by the field to be detected. Then, phase modulation is sensed interferometerically, by comparing the light phase in the signal optical-fiber to that in a reference optical-fiber. When light beam is passed through interferometer, it is split into two beams. The first beam is exposed to the sensing environment and it undergoes a phase shift. The second beam is isolated from the sensing environment and it is used as a reference beam. When the two beams are recombined, they interfere with each other. e.g. Mach-Zehnder, Michelson, Fabry-Perot, Sagnac, polarimetric, and grating interferometers. The Michelson interferometer and Mach-Zehnder interferometer are compared in **Figure 14** [39-44].

Another interferometer based FOS is the Fabry-Perot interferometric sensor (FFPI), which is classified into two manners: Extrinsic Fabry-Perot interferometer (EFPI) sensor and Intrinsic Fabry-Perot interferometer (IFPI) sensor. In an EFPI sensor, the Fabry- Perot cavity is outside the optical-fiber. Optical-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 fabricated within the fiber. Since, the cavity between two mirrors acts both as sensing element as well as waveguide, the light never leaves the optical-fiber. **Figure 15** shows an EFPI sensor, based on capillary tube.

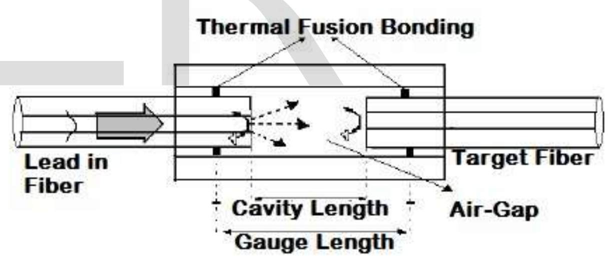

Figure 15: EFPI sensor based on capillary tube.

One cleaved optical-fiber end (lead-in) is inserted into a glass capillary tube while another cleaved optical-fiber end (target) is inserted into the tube from the other end. Both lead-in optical-fiber and target optical-fiber are thermally fusion-bonded with the tube. The cavity between the two fibers is controlled by using a precision optical positioner prior to the thermal fusion-bonding. One of the advantages in this EFPI strain sensor is that its cavity length and gauge length can be different. The strain sensitivity is determined by the gauge length. The temperature sensitivity is determined by cavity length since the fiber and tube have the same thermal expansion coefficients. So, by making gauge length longer than cavity length, the temperature sensitivity of the sensor becomes lesser than the strain sensitivity. Hence, temperature compensation is not required.

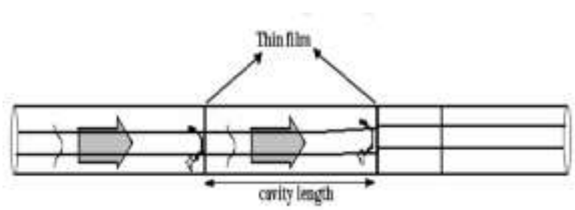

Figure 16: Thin film based IFPI sensor.

In IFPI sensor, two mirrors are separated by the distance within core of a optical-fiber. The IFPI sensor is the joined TiO2 thin film coated optical-fiber IFPI sensor. Here, internal mirror is introduced in optical-fiber by thin film deposition on the cleaved fiber end followed by fusion splicing as shown in **Figure 16**. Some other methods like vacuum deposition, magnetron sputtering, or e-beam evaporation are used to produce the internal mirror.

Sagnac interferometric sensors are built on the optical-fiber gyroscopes that are used to sense angular velocity.

Optical-fiber gyroscopes are based on the principle that application of force changes light-wavelength because it travels around an optical-fiber coil. It measures time varying influences such as acoustics and vibrations. There are two types of fiber optic gyroscopes: Closed loop fiber-optic gyroscope and Open loop fiber-optic gyroscope. In an open loop gyroscope, a broadband light source is used to inject light into an input / output fiber coupler. The input light beam passes through a polarizer which certain the mutuality of the counter propagating light beams through the optical-fiber coil. The second central coupler shares the two light beams into the optical-fiber coil where they pass through a modulator. It is used to produce a time varying output signal showing rotation. The modulator is offset from the center of optical-fiber coil for emphasizing a proportional phase difference between the counter propagating light beams. After light beams propagate from modulator, they recombine before passing through the polarizer. Lastly, light beams are guided onto the output detector.

The closed loop fiber optic gyroscope is aimed at vacuum to high accuracy navigation applications. They have high turning rates. They need high linearity and large dynamic ranges.

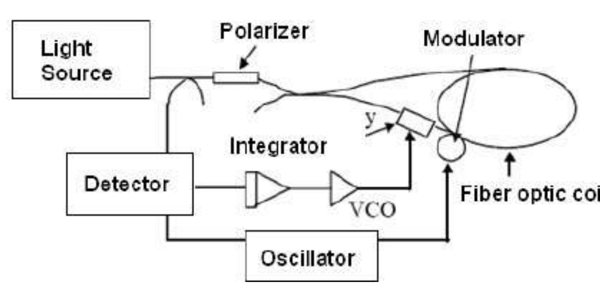

Figure 17:Closed loop Optical-Fiber Gyroscope.

Figure 17, illustrates a closed loop fiber optic gyro. It is used as a modulator in the optical-fiber 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 is similar to open loop fiber optic gyroscope described as above.

4.3.4 Wavelength modulated optical-fiber sensors :

Wavelength based optical-fiber sensors use changes in the light-wavelength generated according to change in the measuring parameter. Fluorescence sensors, black body sensors and Bragg grating sensors are wavelength modulated optical-fiber sensors. Fluorescence based fiber sensors ***(Figure: 18)*** are useful in medical applications, chemical sensing and physical parameter measurements such as temperature, humidity, viscosity etc. In case of the end-tip sensors, light propagates down the optical-fiber to a probe of fluorescent material. The resultant fluorescent signal is grasped by the same optical-fiber and directed back to an output demodulator.

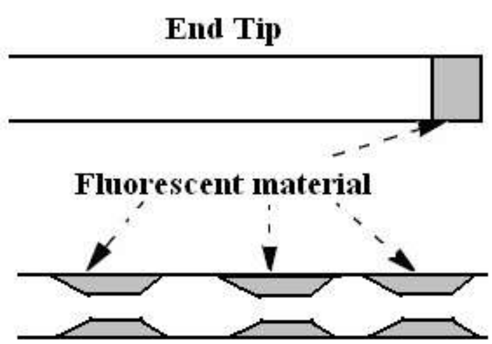

Figure 18: Fluorescence based Optical-Fiber Sensor.

The blackbody sensor, as shown in **Figure 19,** is one of the simplest wavelength modulated sensor. A blackbody cavity is placed at the end of an optical-fiber. When the cavity temperature rises, it glows like a light source. Detectors with narrow band filters are used to conclude the blackbody curve profile. The blackbody wavelength modulated sensor is used to measure precise temperature under strong fields.

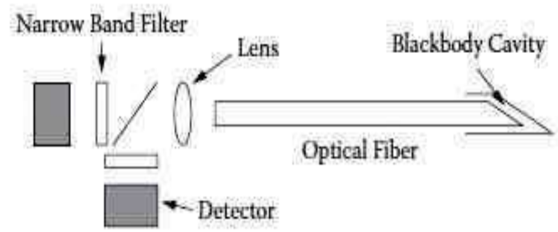

Figure 19: Blackbody FOS.

The common Fiber-optic Bragg gratings are prepared by periodic changes in in the core refractive index of the mono-mode optical-fiber. Such periodic changes in the core refractive index is made by exposing core to an intense U.V. interference pattern. In the Bragg's grating sensor, as in **figure 20,** the broadband light source (LED), whose central wavelength closer to the Bragg wavelength, is launched into the optical-fiber.

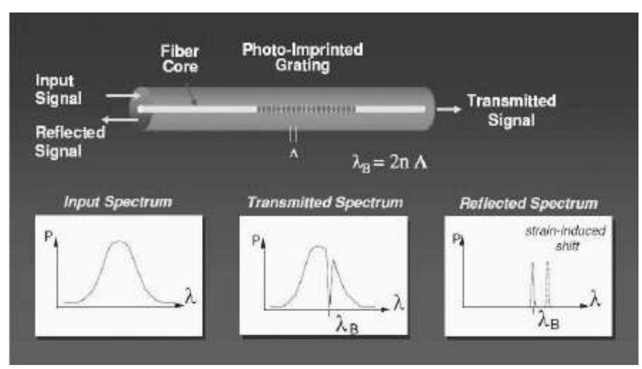

Figure 20: Bragg grating response

5. Examples Of Optical-Fiber Sensors:

A optical-fiber A.C./D.C. voltage sensor in the middle or high voltage range (100–2000 V) can be prepared by inducing measurable amounts of Kerr nonlinearity in the mono-mode optical-fiber by exposing a calculated length of fiber to the external electric field [25]. The measurement technique is based on polarimetric-detection where, high accuracy is achieved in a hostile industrial environment.

Electrical power is measured by a specially designed bulk optical-fiber ampere sensor coupled with proper signal processing in a polarimetric detection system [27].

An FOS in electrical switchgears transmits light from an electrical arc-flash to a digital protective relay, enables quick tripping of a breaker and reduces the arc blast energy.

Fiber Bragg grating (FBG) based optical-fiber sensors significantly increase performance, efficiency and safety in many industries. With FBG integrated technology, sensors provide complete analysis and detailed reports on insights with good resolution. These type of sensors are used extensively in industries like telecommunication, automotive, aerospace, energy, etc. FBGs are sensitive to the compression, static pressure, mechanical tension and temperature changes. The efficiency of FBG based FOS is provided by means of central wavelength adjustment of light emitting source according to the current Bragg gratings reflection spectra [28].

6. Advantages of Optical-fiber Sensors :

The FOSs have inherent superiorities that are difficult to achieve by other conventional electrical, electronic or hybrid sensors.

(i). Insensitivity to electromagnetic interferences and non-conductor of electric current.

(ii). Remote sensing: A segment of optical-fiber can be used as a sensor gauge with a long segment of another or the same optical-fiber transmitting the sensing information to a remote station. Optical-fiber transmission cables offer significantly lower signal loss, as compared to signal transmission in conventional sensors, and maintain a high signal to noise ratio (SNR).

(iii). Small size and light weight: Intrinsically small-size of optical-fiber helps to build a compact system suitable for installing or embedding into sensor device.

(iv). Operation in hazardous environments: Optical-fiber sensors can function under extreme conditions like high temperature, high pressure, corrosive and toxic environments, high radiation, large electromagnetic fields, highly inflammable medium and other harsh environments.

(v). High sensitivity and wide bandwidth: An FOS is sensitive to small perturbations of environment.

(vi). Distributed measurement: An optical-fiber communication network allows measurements at different points along the transmission line without significant loss to signal passes through it and provides a technique to monitor, analyse and control the parameters over an extended length or area.

(vii). The passive dielectric characteristic: As Optical-fiber is unable to conduct electric current, it eliminates the conductive paths in high voltage environments.

Some of the Advantages of FOSs over Conventional Electronic Sensors are:

- Freedom from electromagnetic interference (EMI) and radio frequency interference.
- Inherent safety and suitability for extreme vibration and explosive environments.
- Tolerant of high temperatures (>1450 C) and corrosive environments, Greater Sensitivity.
- Lightweight and compact size.
- Multifunctional ability.
- Multiplexing capabilities.
- Resistant to harsh environment.
- Wide Dynamic Range.
- Remote sensing capability.
- Multifunctional sensing capabilities such as rotation, acceleration, electric and magnetic field measurement, temperature, pressure, acoustics, vibration, linear and angular position, strain, humidity, viscosity, chemical measurements.
- Large Bandwidth.

7. Disadvantages of Optical-fiber Sensors:

Some of the disadvantages of using FOSs are:

- Detection systems may be complex and expensive.
- High cost.
- Unfamiliarity to the end user. Especially, skilled operator is required.
- Requirement for precise installation procedures.
- Development of usable measuring systems is complex.

8. Applications of Optical-fiber Sensors:

Optical-fiber sensors are used in several areas, specifically:

- Mechanical Measurements such as rotation, speed, acceleration etc.
- Electric field and magnetic field measurement,
- Temperature, pressure, flow rate, acoustics vibration, linear position-angular position, strain, humidity, viscosity and chemical measurements etc.
- Electrical & Magnetic Measurements, electromagnetic field measurement etc,
- Chemical & Biological Sensing.
- Monitoring the physical health of structures in real time.
- Buildings and Bridges: Concrete monitoring while setting, crack length and crack enlargement speed monitoring, spatial displacement measurement, neutral axis evolution, creep and shrinkage type long term deformation monitoring, concrete-steel interaction and post-seismic damage evaluation etc.
- Tunnels: Multipoint optical extensometers, convergence monitoring, shotcrete / prefabricated vaults evaluation and joints monitoring damage detection etc.
- Dams: Foundation monitoring, joint expansion monitoring spatial displacement and leakage monitoring, distributed temperature monitoring etc.

9. Conclusion and Future Trends:

An overview of fiber optics sensors and their applications is presented in which key sensors are discussed. The following are the future trends.

Special waveguides such as photonic crystal fibers will enable many new sensing mechanisms with different configurations.

Improved technologies will continue to improve sensor performance, functionality, capability and reliability under harsh environment operation. Advanced signal processing and network technology will enable high density FOS networks.

	References :
1	S. Yin, P. B. Ruffin and F. T. S. Yu, "*Optical-fiber sensors*", 2nd edn, Taylor & Francis Group, CRC Press (2008).
2	B. Culshaw and J. Dakin, "*Optical-fiber Sensors System and pplications"*, Vol 2, Artech House (1989).
3	E. Udd, R. G. Blom, D. Tralli, E. Saaski and R. Dokka, "*Application of the Sagnac Interferometer Based Strain Sensor to an Earth Movement etection System"*, Proceedings of the SPIE, 2191, pp. 126-136 (1994)
4	J. R. Griffiths and S. P. Robinson "*The OxyLite: a Fiber- Optic oxygen ensor"*, TheBritish Journal of Radiology, pp. 627-630 (1999)
5	K. Hotate and S. L. Ong, "*Distributed dynamic strain measurement using a correlation-based Brillouin sensing system*", IEEE Photonics Technology Letters, 15, pp. 272–274 (2003).
6	S. Villalba and J R Casas, "*Application of optical-fiber distributed sensing to health monitoring of concrete structures*", Mechanical Systems and Signal Processing, 39, pp. 441–451 (2013).
7	C. K. Y Leung, N. Elvin, N. Olson, T.F. Morse and H. Yi Fei, "*A novel distributed optical crack sensor for concrete structures"*, Engineering Fracture Mechanics, 65, pp. 133-148 (2000).
8	Y. Dong, X. Bao, L. Chen, "*Distributed temperature sensing based on brief ringence effect on transient Brillouin grating in a polarization-maintaining photonic crystal fiber*", Optics Letters, 34, pp. 2590–2592 (2009).
9	D. Zhou, Z. Qin, W. Li, L. Chen and X. Bao, "*Distributed vibration sensing with time-resolved optical frequency-domain reflectometry*", Optics Express, 20, pp.13138–13145 (2012).
10	Y. Dong, L. Chen and X. Bao, "*High-spatial-resolution simultaneous strain and temperature sensor using Brillouin scattering and birefringence in a polarization maintaining fiber*", IEEE Photonics Technology Letters, 22, pp. 1364–1366 (2010).
11	B. Culshaw and A.D. Kersey, *"Optical-fiber sensors: an historical perspective",* Journal of Light wave Technology, 26, pp. 1064-1078 (2008).
12	G. Stewart, W. Jin and B. Culshaw, "*Prospects for optical-fiber evanescent-field gas sensors using absorption in the near-infrared*", Sensors and Actuators B: Chemical,38, pp. 42-47 (1997).
13	F. B. Xiong, W. Z. Zhu, H. F. Lin, X. G. Merg, "*Optical-fiber sensor based on*

	evanescent wave absorbance around 2.7 µm for determining water content in polar organic solvents", Applied Physics B, 115, pp. 129-135 (2014).
14	H. Jiang, R. Yang, X. Tang, A. Burnett, X. Lan, H. Xiao and J. Dong, "*Multi layer optical-fiber sensors for in situ gas monitoring in harsh nvironments*", Sensors and Actuators B: Chemical, 177, pp. 205–212 (2013).
15	O. S. Wolfbeis, "*Optical-fiber chemical sensors and biosensors,*" Analytical Chemistry, 76, pp. 3269-3284 (2004).
16	J. A. Ferguson, T. C. Boles, C. P. Adams and D. R. Walt, "*A optical-fiber DNA biosensor microarray for the analysis of gene expression*", Nature Biotechnology, 14, pp. 1681-1684 (1996).
17	B. G. Healy, L. Li, and D. R. Walt, "*Multi analyte biosensors on optical imaging bundles*", Biosensors and Bioelectronics, 12, pp. 521-529 (1997).
18	A. M. Dietrich, J. N. Jensen and W. F. Da Costa, "*Measurement of pollutants: chemical species*", Water environmental research, 68, pp. 391-406 (1996)
19	K. T. V Grattan and B. T. Meggitt, "*Optical-fiber Sensor Technology: Applications and Systems*", 3, Kluwer Academic Publishers (1999).
20	B. D. Gupta, Gupta and Banshi Das, "*Optical-fiber Sensors: Principles and Applications*", New India Publishing (2006).
21	Strong, P. Andrew; Lees, Gareth; Hartog, H. Arthur.; Twohig, Richard; Kader, Kamal; Hilton, Graeme

	(December 2009). "*An Integrated System for Pipeline Condition Monitoring"*. Doi:10.2523/ IPTC-13661 -MS.
22	S. Trpkovski, S.A. Wade, G.W. Baxter, S.F. Collins, "Dual temperature and strain sensor using a combined fiber bragg grating and fluorescence intensity ratio technique in Er3+-doped fiber". Review of Scientific Instruments. 74 (5):2880. doi. 10.1063/ 1.1569406. Retrieved 2008-07-04 (2003).
23	Fernandez-Vallejo, Montserrat (2011). "Remote (250 km) Fiber Bragg Grating Multiplexing System", Sensors. 11 (09):8711- 8720. doi:10.3390/s110908711
24	Marcelo A. Soto et. al. "*Extending the Real Remoteness of Long-Range Brillouin Optical Time-Domain Fiber Analyzers"* 32 (1). 2004: 152–162. doi:10.1109/JLT.2013.2292329.
25	Measures, Raymond M. (2001) "*Structural monitoring with optical fiber technology*", San Diego, California, USA. Academiuc Press. pp. Chapter 7. ISBN 0-12-487430-4.
26	Ghosh, S.K.; Sarkar, S.K.; Chakraborty, S. (2002). "*Design and development of an optical-fiber intrinsic voltage sensor"*. Proceedings of the 12th IMEKO TC4 international symposium Part 2. Zagreb, Croatia: 415–419.
27	Ghosh, S.K.; Sarkar, S.K.; Chakraborty, S. (2006). "*A proposal for single mode optical-fiber watt measurement scheme*". Journal of Optics (Calcutta). Optical Society of India. 35 (2): 118–124. ISSN 0972-8821.

28	Aleynik A.S.; Kireenkova A.Yu.; Mekhrengin M.V.; Chirgin M.A.; Belikin M.N. (2015). "*Central wavelength adjustment of light emitting source in interferometric sensors based on optical-fiber bragg gratings*". Scientific and technical journal of information technologies, mechanics and optics. 15 (5): 809-816.
29	M. Archenault, H. Gagnaire, J. P. Goure and N. Jaffrezic-Renault, "*A simple intrinsic optical-fiber refract meter*," Sensors and Actuators B: Chemical, 5, pp. 173-179 (1991).
30	J. Yuan and M. A. El-Sherif, "*Optical-fiber chemical sensor using polyaniline as modified cladding material*", IEEE Sensors, 3, pp. 5-12 (2003).
31	S. Trolier Mc Kinstry, G. R. Fox, A. Kholkin, C. A. P. Muller and N. Setter, "*Optical-fibers with patterned ZnO/electrode coatings for flexural actuators*", Sensors and Actuators A: Physical, 73, pp. 267-274 (1999).
32	C. Egami, K. Takeda, M. Isai and M. Ogita, "*Evanescent-wave spectroscopic optical-fiber pH sensor*", Optics Communications, 122, pp. 122-126 (1996).
33	H. Guo and S. Tao, "*An active core optical-fiber temperature sensor using an Eu(III)- doped sol-gel silica fiber as a temperature indicator*", IEEE Sensors Journal, 7, pp. 953-954 (2007)
34	Lee, C., Taylor, H., Choi, H-S. "*Optics letters*", Vol. 22, 1814, 1997.
35	Brooks et. al., J., "*Light wave technology*" Vol. 5, 1014, 1987.
36	Kersey, A.D., Dandridge, A. J. Inst. Electronic and Radio Eng., Vol. 58, S99, 1988.
37	Tracey, P. M., "*Intrinsic Optical-fiber Sensors*", IEEE Transactions on Industry Applications, 27, 1, 1991.
38	Eric Udd, William B. Spillman Jr. *"Fiber Optic Sensors: An Application to engineers and scientists*", Published by John Wiley and Sons, 2nd Edition, 2011
39	Francis T.S. Yu, Shizhuo Yin, "*Optical-fiber Sensors*", ISBN-0-8247-0732-X, 2002.
40	P. N. Patel, V. Mishra, A. S. Mandloi, "*Optical Biosensors: Fundamentals & Trends*", Journal of Engineering Research and Studies (JERS), vol. I, Issue I, pp. 15-34, Sept2010.
41	P. N. Patel, V. Mishra, A. K. Panchal, N. H. Maniya, "*Optical Sensing Of Ethanol Using Porous Silicon Photonic Bandgap Microcavity Structure*", Journal of International Academy of Physical Sciences, vol. 16, no.2 pp. 163-170, December-2012, ISSN: 19921950.
42	Sunita Ugale, Vivekanand Mishra., "*Fabrication and characterization of ultralong period reversible fiber gratings*", Journal of Optics, September 2014, volume 43, Issue 3, pp 169-172.
43	S. Agrawal, V. Mishra, "*Thinned fibre Bragg grating as a fuel adulteration sensor",* Simulation and experimental study of Opto-Electronics Review 23(4) December 2015
44	D. Yuan, Y. Dong, Y. Li and T. Li, "*Mach-Zehnder Interferometer Biochemical Sensor Based on Silicon-on-Insulator Rib Waveguide with Large*

	Cross Section," Sensors, 2015, 15 (9), 21500-21517; doi:10.3390/s150921500.