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Fiber Optic Sensors: A Leading Trend in Sensor Technology

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Akshaya Dhingra*[1], Vikas Sindhu[2], Anil Sangwan[3], Fiber Optic Sensors: A Leading Trend in Sensor Technology- Palarch's Journal Of Archaeology Of Egypt/Egyptology 17(9). ISSN 1567-214x, Keywords: EMI, FOS, Fiber Bragg Gratings (FBG), Optical Path Length Difference (OPD), Refractive Index (RI), State of Polarization (SOP)

Abstract: Fiber Optic Sensors (FOS) are being used in a variety of application since last few decades. Technological research in the field has made it more attractive and viable. Fiber optic sensing is a field in which multi-parameter measurements are made by either using optical fiber itself or with the help of an external transducer. FOS exhibit higher sensitivity, immunity to Electromagnetic Interference (EMI), smaller size, longer lifetime and amenability to multiplexing. These sensors can be deployed for varying applications i.e. Physical, Chemical, Electrical, Water, Transportation, Agriculture and Industrial fields. FOS can be further classified based on location, spatial distribution and operating principle. In the present paper study of various sensors based on Fiber optics has been presented in detail. This will enrich the researchers to find the gap areas and motivate them to undertake the research work towards the advancement in the field.

I. INTRODUCTION

With the immense growth in telecommunications sector the optical fiber cables are mainly being deployed for data communication since 1960's while providing higher performance, reliability and reduced bandwidth. The field of fiber optic communication has been developing since last few decades. With the evolution of low loss optical fiber and LASER diode, several researchers started their work on fiber optic sensing [1].

The FOS is optical sensor that converts light rays into an electric signal [2]. They use an optical fiber or external transducer to detect temperature, pressure, strain, chemical changes, position, humidity, vibration, viscosity, liquid level, light intensity, color, and rotation [3]. With the growth in area of fiber optics, it has been evinced that light-based systems are superior to any other electronic/electrical system. Therefore, optical sensor based systems have become an essential part of industrial, social, military and environmental processing fields [4].

There are numerous advantages of optical sensors in comparison to the traditional sensor based systems. Some of the distinct advantages FOS offers are high sensitivity, immunity to EMI, light in weight, small in size, can be

operated in remote areas, resistant to harsh environmental conditions, electrically isolated, can perform multi-parameter measurements, have a wider dynamic range, can be

multiplexed easily and are used for distributed monitoring of composite structures [5].

Figure 1 exhibits the basic structure of a FOS consisting of 5 elements i.e. optical source (LED or LASER), optical fiber, sensing/modulating element, an optical detector(PIN or APD) and end-processing devices (optical-spectrum analyzer, oscilloscope).

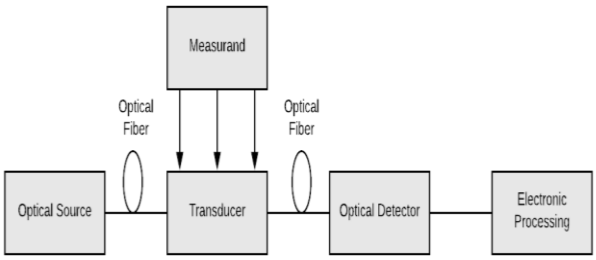

Fig. 1. Fiber Optic Sensor

The operating principle of FOS is to convert a physical quantity into an optical signal to perform sensing operation. The optical source generates a light signal that propagates through fiber and goes to transducer block. The transducer converts physical quantity in the form of measurand into an optical signal and performs modulation (depending upon the change in intensity, phase, color, state of polarization). The variation in characteristics of the received signal is detected by the optical detector. Therefore, it is more flexible to use a FOS as it covers the gap of conversion between electronics and photonics at the sensing site [6].

The present work provides a broad review of FOS explaining its features, operating principle, types, and applications in detail. The rest of paper organisation is done as follows. Section II. describes the FOS classification based on the sensor location, modulation, and spatial distribution. The application areas of FOS are discussed in Section III., Section IV. describe the latest works and achievements followed by the conclusion and future trends in Section V.

II. CLASSIFICATION OF FOS

FOS are mainly classified into three broad categories i.e. based on sensor location, based on spatial distribution and based on the operating principle [7]. Figure 2 depicts a flowchart for classification of FOS.

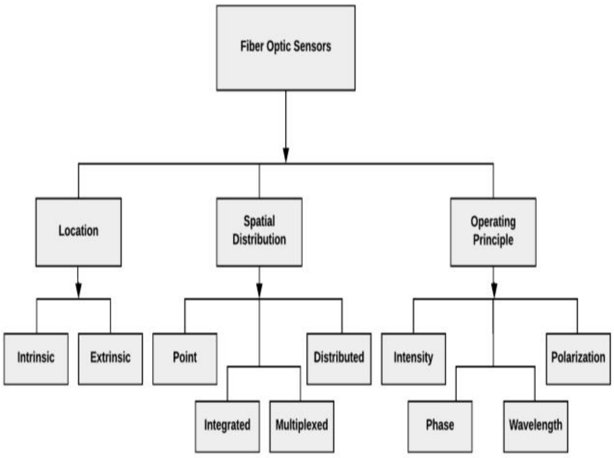

Fig. 2. Fiber Optic Sensors classification

A. Sensor Location

Based on sensor location, the FOS are categorized as (i) Intrinsic Sensors (in which fiber act as the sensing element), (ii) Extrinsic Sensors (in which external transducer is used as sensing element) [8].

1) Intrinsic FOS (IFOS): This type of FOS uses fiber as a transducing element. The IFOS are also called "Internal Sensors", as fiber is used for sensing operation as well as for transmitting light to the end-user. Direct modulation is performed in IFOS. As the light enters into the guided medium from one end and remains in it till detection [9].

With the use of intrinsic sensor the physical properties like phase, frequency, intensity, the transit time of light, SOP, etc. changes during the modulation. The IFOS makes use of Multi-mode fiber for intensity modulation while Single-mode fiber is used for modulation of other properties. In IFOS, the characteristics of light signal changes due to the perturbations occurring inside the fiber. An intrinsic sensor with a light source, optical fiber and a light detector is as depicted in figure 3.

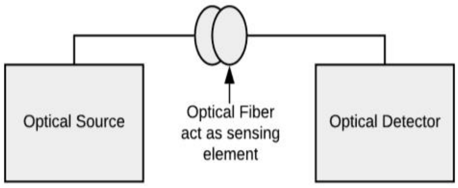

Fig. 3. Intrinsic Sensor

IFOS can also provide distributed sensing for a distance up to 1m. One of the major demerits of IFOS is that any physical perturbation caused during transmission in fiber may change characteristics of the light signal sent over it. Some of the IFOS are FBG Sensors, Long FBG sensors, interferometric sensors, special doped fiber sensors [10].

2) Extrinsic FOS (EFOS): These types of FOS are also called "external sensors" because it uses an external transducer element to perform sensing operation. The optical fiber is only used to guide the light signal from optical source to the external sensor and then from the sensor to the light detector. Therefore, one optical fiber cable is used for transmission of light energy from source to the sensor and another fiber cable is used to guide light to the detector after performing appropriate modulation. Figure 4 depicts an EFOS that utilizes an external sensor/ transducing element for modulating properties of light with respect to change in physical perturbations according to environmental conditions.

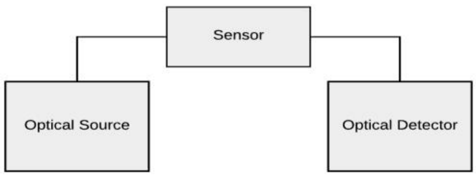

Fig. 4. Extrinsic Sensor

Generally, EFOS uses multi-mode fiber for transmitting light signals. These sensors can be used for measuring signals in harsh environmental conditions. The main advantage of EFOS is its capacity to reach far distant inaccessible places. An EFOS can be used for measuring internal temperature of the electric transformers in region of high radiation [11].

B. Spatial Distribution

Based on spatial distribution the FOS are classified as (i) Point sensors, (ii) Integrated sensors, (iii) Multiplexed sensors and (iv) Distributed sensors.

1) Point Sensors: These sensors are used where a single point space is to be measured. Some of the point sensors are FBG sensors and Fabry-Perot Sensors [12]. These sensors are used in some valuable applications i.e. for bend measurements in one plane and not being utilized for typical shape sensing or complex measurement of more than one DOF (Degree of Freedom). Figure 5 shows a single point FOS.

Fig. 5. Single Point FOS

2) Integrated Sensors: In this type, a single value is obtained by measuring and averaging a physical parameter over the spatial section. In this type of sensors, the sensing element is integrated inside the fiber. Measurement of strain with respect to length using a deformation sensor and temperature using interferometric sensors [13].

3) Quasi- Distributed / Multiplexed Sensors: This type of sensors provides a fixed number of discrete points with respect to single optical fiber cable for which measurand is calculated along the cable. There are distinct types of multiplexed sensors used for optical sensing depending upon different multiplexing techniques [14]. Figure 6 shows multiplexing based FOS.

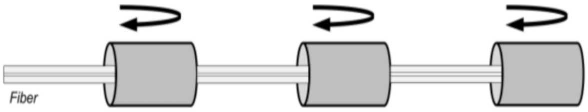

Fig. 6. Multiplexed FOS

4) Distributed Sensors: This type of sensors enables continuous and real-time monitoring of data across the optical fiber cable. Distributed sensors are mainly employed in multi-directional jointing applications. These can be easily deployed in harsh environmental conditions like systems affected by Rayleigh, Brillouin, and Raman-scattering [15]. The Brillouin scattering based FOS used for measuring temperature and absolute strain. And the sensors based on Rayleigh scattering used for measuring relative changes within fiber. The distributed sensing is used in remote areas with the help of FBG sensors [16]. Figure 7 shows a distributed FOS in which fiber act as a sensing element.

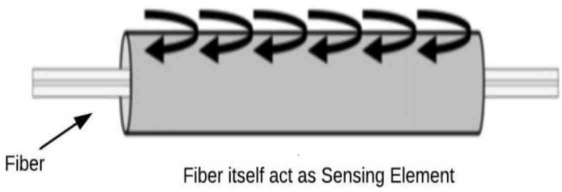

Fig. 7. Distributed FOS

C. Principle/ Modulation

Based on the principle of operation FOS are classified as (i) Intensity, (ii) Phase, (iii) Wavelength, and (iv) Polarization modulated sensors [17].

1) Intensity Modulated Fiber Optic Sensors (IM-FOS): This is one of the simplest and oldest types of FOS in which the intensity of light is modulated through fiber. IM-FOS requires more light that's why mostly uses a multi-mode fiber for transmission of a signal [18]. The normalized modulation index for IM-FOS is given by Eq. (1)

$$m = \frac{\Delta I}{(I_o\, P)} \quad \ldots (1)$$

(Where ΔI represent variation in optical power due to modulation by the measurand, I_o denotes the optical power reached at detector in case of absence of modulation, and P is the perturbations caused during transmission)

The transmitted signals from the sensors undergo some loss due to a various phenomena. That includes fiber bending, absorption, scattering, reflection, and change in medium. The response of an IM-FOS is given by Eq. (2)

$$S = qI_o\, Rm \quad \ldots (2)$$

Here, q is responsivity of the detector in (A/W), R is the load resistance and m is the normalized modulation index.

The first IM-FOS is used to measure displacement by putting two fibers in series. Another type of IM-FOS is a reflective sensor in which fibers are positioned in parallel to each other. [19]. A simple extrinsic reflective IM-FOS can be used to measure stress, distance, and liquid level as depicted in figure 8.

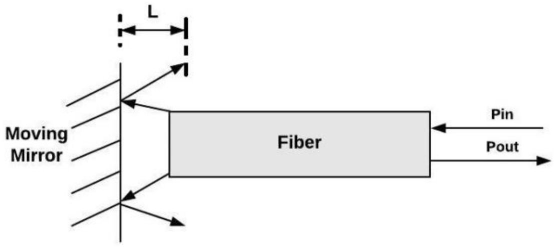

Fig. 8. Simple extrinsic IM-FOS

Other types of IM-FOS are Micro bend and Evanescent field-based. Micro bend FOS is a type of IM-FOS extrinsic sensors. Micro bending occurs due to mechanical perturbations occurring in multi-mode fiber due to which light redistributes among various modes of the fiber. Due to micro bends in fiber, the intensity of light decreases with increase in size of mechanical perturbations. Figure 9 depicts the structure in which a fiber is squeezed between two corrugated plate/teeth blocks due to which multiple micro bends occur [20].

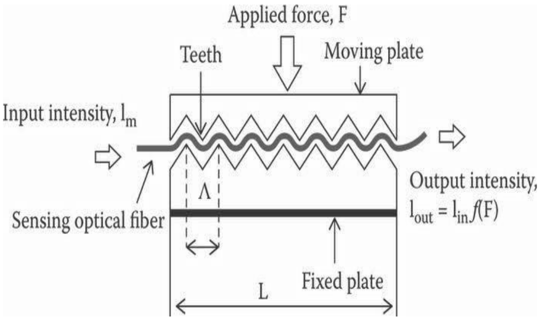

Fig. 9. Micro bend FOS

Evanescent field-based sensors utilize surface-specific detection but can't be used for efficient sensing due to its small penetration depth. To overcome this problem, micro-structured fibers, tapered fibers are used for changing the incident angle. Interaction techniques are used with the evanescent field for sensing [21]. These sensors are used for the chemical investigation to match the optical properties of the source with the chemical under test. An evanescent field-based chemical sensor is depicted in figure 10 below.

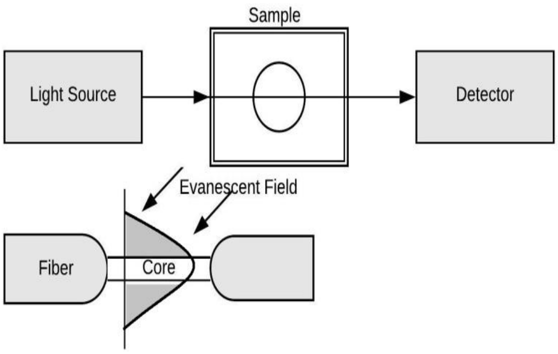

Fig. 10. Evanescent field-based FOS for Chemical Investigation

The IM-FOS offers many advantages like simple fabrication, lower costs, signal processing requirements, distributed sensing, multiplexing, etc. One of the disadvantages of using IM-FOS is that light variations may cause an error while taking readings without reference [22]. IM-FOS also suffers from a large amount of signal attenuation caused by fiber bends, evanescent fields, fiber misalignments, fluctuation in source power, which makes it less reliable to perform sensing. To solve these problems a reference intensity signal along with the sensor head branch is transmitted for measuring input power which is as depicted in figure 11 below [23].

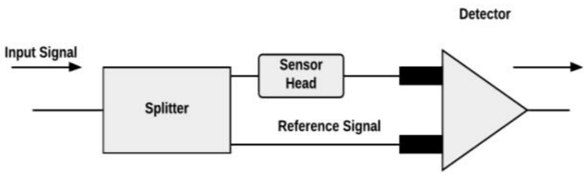

Fig. 11. Measurement of power through intensity reference

2) Phase Modulated Fiber Optic Sensors (PM-FOS): The PM-FOS measures the variation in phase of the received light signal. The PM sensors are also known as interferometric sensors because their operating principle is based on measurement of the phase-difference between two fibers i.e. signal fiber and reference fiber. In this sensor, a light beam is divided into two light rays one is kept isolated from environmental perturbations while other sensing light rays may provide phase shift due to external environmental conditions. Types of PM-FOS are mainly (i) Mach Zehnder, (ii) Michelson and (iii) Fabry-Perot [24].

Mach Zehnder Interferometers (MZIs) are mainly employed in various sensing applications like temperature, RI and strain, etc. The flexible structure of MZI with sensing and reference arms is depicted in figure 12. The light signal at the transmitter is first splitted and goes into two independent arms. At the receiver side, a coupler is used to add up the signal coming from both the arms. According to Optical Path Length Difference (OPD), coupled signal at the receiver side contains the interference component between the arms. Presently the conventional MZI’s are replaced by In-line waveguide interferometers. The MZI's can also be employed for interrogation as multi-point arrays in a TDM scheme [25].

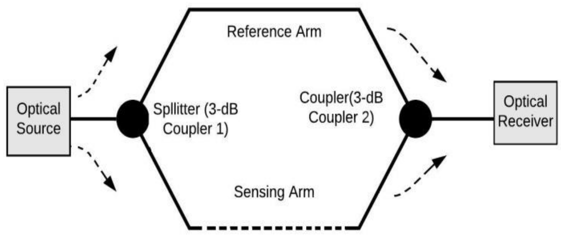

Fig. 12. Mach Zehnder Interferometer

Michelson Interferometers (MIs) are the interferometers works on the principle of reflection. It measures interference between two light rays and each ray is reflected at the end of each arm as shown in figure 13. MI’s works similar to that of MZI's but represented like half of an MZI in the configuration. Therefore, according to the fabrication and principle of operation MI's and MZI's are similar to each other.
The MI's consist of reflectors which makes it different from that of MZI’s. The MI's are light in weight and smaller in size because of the use of reflection modes these are being employed in many practical and installation applications. In-line MI’s are employed in many FOS for measuring temperature and liquid level [26].

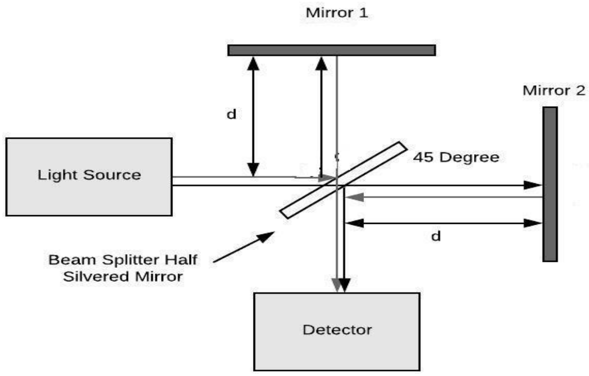

Fig.13. Michelson Interferometer

Fabry-Perot Interferometer (FPI) is another type of PM-FOS which consists of two parallel reflectors with separation distance equal to cavity length (L). The cavity can be formed by an optical fiber or any other medium. Hence, the FPI reflectance and transmittance versus the mirror reflection coefficient is given by Eq. (3)

$$R_i = \left(\frac{n_i - n_{i+1}}{n_i + n_{i+1}}\right)^2 \quad \dots (3)$$

Here i =1, 2, 3…. and so on.
And n_i is the RI of cavity and surrounding medium.
The interference between two dielectrics i.e. parallel reflectors in the FPI sensor takes place by multiple super positions of transmitted as well as reflected light rays. In these interferometers, the reflected and transmitted spectrum is a function of RI of the medium, cavity length (L) and mirror reflectivity [27]. Therefore, the ∂_{FPI} (phase-difference of an FPI sensor) is given by Eq. (4)

$$\partial_{FPI} = \frac{2\pi}{\lambda} n2L \quad \dots (4)$$

Where λ represent the wavelength of light, L is the cavity length and n is the RI of the cavity.
Therefore, if there are any environmental perturbations caused in the FPI sensor, ∂_{FPI} changes along with OPD variation.

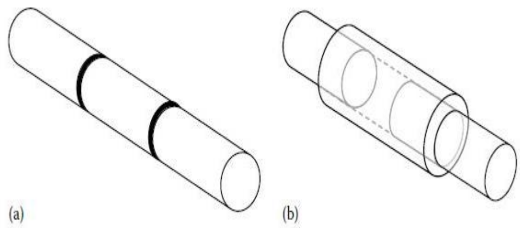

Fig. 14. (a) Intrinsic FPI Sensor (b) Extrinsic FPI Sensor

The FPI sensors are made up of reflectors inside and outside fiber that's why it is further divided into Intrinsic Sensors and Extrinsic Sensors. The Intrinsic FPI sensor consists of some reflecting components inside the fiber. Figure 14(a) shows the intrinsic FPI sensor with reflectors within the fiber formed with the help of techniques like chemical etching, thin film deposition, FBG's, micro-machining, etc. The Extrinsic FPI works based on reflections caused by an external cavity formed outside the fiber as shown in figure 14(b). The extrinsic sensors are mainly deployed because of its simple fabrication and low cost [28].

3) Wavelength Modulated Fiber Optic Sensors (WM-FOS): The wavelength modulated FOS works on the principle of change in optical wavelength when exposed to any environmental perturbations. Some common types of WM sensors are Fiber Bragg Grating (FBG), Black-Body and Fluorescence sensors.

The FBG sensors are engraved inside an optical fiber. The periodic changes in RI are formed by exposing UV light pattern over the core of fiber. This variation of RI forms an intense interference pattern known as grating. The operation of FBG is as depicted in figure 15. The light ray from the optical source is launched in the fiber having central frequency nearly equal to Bragg Wavelength [29]. The light transmitted over the fiber propagates through the gratings while some part is reflected. FBG can work as a filter because some part of the transmitted signal is reflected [30]. The reflected light w.r.t variation in RI provides λ_g (central wavelength) given by Eq. (5)

$$\lambda_g = 2n\Lambda \quad \dots (5)$$

Where n is the RI of core and Λ denotes periodicity of the RI modulation

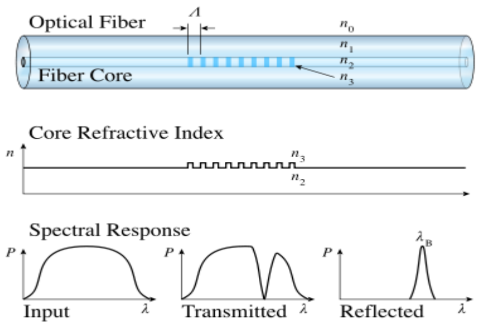

Fig. 15. Working of Fiber Bragg Grating

FBG's are employed in numerous applications to measure strain, temperature and pressure at multiple locations with the help of changes in RI of the core, grating period and wavelength of the light signal [31].

Black-body sensors are the simplest type of WM-FOS comprises of a cavity placed at one end of the fiber. These sensors act as a light source when it glows due to rise in temperature inside the cavity. Figure 16 depicts the structure of a black body sensor. These sensors are being employed commercially as optical fiber thermometers, since they can measure temperature in intense RF fields [32].

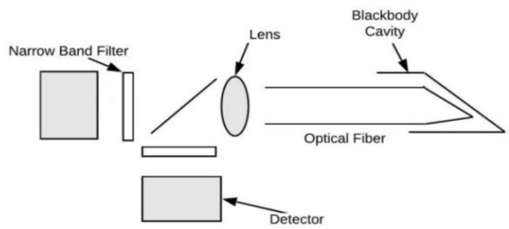

Fig. 16. Blackbody Sensor

Fluorescent WM-FOS are end-tip based sensors in which light propagates through the fiber to a fluorescent material probe. The captured signal is given to an output demodulator. The structure of fluorescent sensor is as depicted in figure 17. These sensors are mainly employed in physical, chemical, bio-medical sensing for the measurement of humidity, temperature, and viscosity [33].

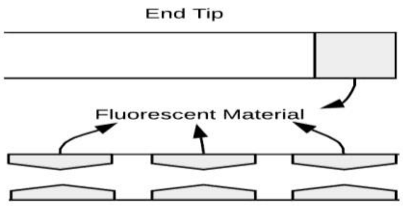

Fig.17. Fluorescent Sensor

4) Polarization Modulated Fiber Optic Sensors.

The polarization modulated sensors work on change in the State of Polarization (SOP) for measuring parameters like strain, pressure, stress, temperature, etc. acting on it. The changes in SOP can be classified as linear, elliptical and circular polarization. In linear SOP, the direction of the electric field is always in the same line the same w.r.t. propagation of light. While in elliptical SOP, the electric field direction changes w.r.t to the propagation of light and elliptical electric fields are obtained at the output [34].

The temperature variation in an SMF is measured depending upon β (propagation constant), L (change in the fiber length), RI's of core and cladding. Under the influence of ε (longitudinal strain)/ T (temperature) in case of SMF polarization modulated FOS, $\frac{\partial(\Delta\emptyset)}{\partial X}$ (change in the phase-difference) is given by Eq. (6).

$$\frac{\partial(\Delta\emptyset)}{\partial X} = \Delta\beta\frac{\partial L}{\partial X} + L\frac{\partial(\Delta\beta)}{\partial X} \quad ...(6)$$

Where X represents strain/temperature/pressure

A polarization modulated FOS made with the help of a polarizer, polarization preserving fiber and an analyzer is depicted in figure 18.

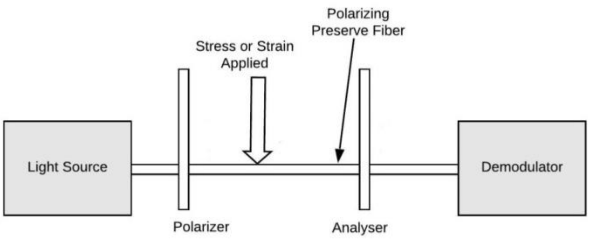

Fig. 18. Polarization Modulated Sensors

III. APPLICATIONS OF FOS

The FOS can be employed for multi-parameter measurements in areas of interest. The FOS offers numerous advantages like the smaller size, light in weight, electrically passive, immunity to EMI, remote sensing capabilities, etc. over the conventional sensors. Therefore, the FOS are mainly employed for sensing in variety of applications. Some of them are listed below:

(a) Physical Sensing: The FOS are used for the measuring various physical parameters like stress, strain, flow, acceleration, position, temperature, pressure, etc. in structures of distinct size or shape.

(b) Chemical Sensing: Extrinsic FOS are mainly employed for measuring a sample of a chemical depending upon measurement strategy and type of fiber used. Used for measuring RI, absorbance, evanescence, reflection, luminescence, fluorescence, dispersion, etc [35].

(c) Bio-Medical Sensing: The FOS are employed in numerous medical applications with the help of a physical transducer. The FOS are chemically inert, immune to EMI non-evasive in contact with organs so used for surgery. These are also used to sensing biological active elements i.e. measurements related to DNA, antibodies, etc [36].

(d) Petroleum Industry: The FOS like OTDR, OFDR, BOTDA, and BOTDR recently used for measuring flow, viscosity, leakage, pressure, etc of fossil fuel and gases in the petroleum sector [37].

(e) Civil Engineering: Some distributed FOS are being employed for the detection of geo-hazards (like landslides, earthquakes), dam monitoring, structural health monitoring [38, 39].

(f) Agricultural Engineering: FOS like fiber-optic reflection spectroscopy sensors are employed in monitoring the quality of soil, air, and water to improve crop yields and productivity in agricultural engineering.

(g) Manufacturing Industry: FOS like FBG, pyrometer, etc. are used for monitoring environmental properties of extreme manufacturing processes like drilling and turning.

(h) Energy Field: FBG sensors are mainly used to monitor structures which generate, produce, distribute and convert electric power. FOS have also employed in EMI resistant environments and for the detection of partial discharges in electrical transformers.

(i) Biometric Applications: FOS are employed for capturing biometrics like face, eyes, and fingerprint detection in many government agencies.

(j) Transportation industry: It uses FOS for improving fuel efficiency and reduced emissions with the help of FBG sensors in ships, aircraft, railways, automobiles, etc.

FOS are being employed for Multi-parameter measurements. They are being used in applications like physical sensing, structural monitoring, transport infrastructure, temperature measurements, chemical sensing, electrical grids, healthcare solutions, water distribution systems, distributed remote sensing using FBG and many more industrial works.

IV. LATEST WORK AND ACHIEVEMENTS

Author and Year	Work Done	Advantages	Disadvantages	Application
L. Fan, et al.[40]	Study of new method to investigate the concrete deterioration under steel corrosion with the use of a distributed fiber optic sensor.	Distributed Optical sensor is feasible to be used in real time conditions	3 stage Strain measurement rate increases for different stages.	Engineering Structures
J. Alvarez-Montoya et al[41]	Implementation of in-flight strain monitoring, remote sensing and automatic damage detection in an operating composite aircraft structure	FBG sensors used for data monitoring gives enhanced results. New technologies like data fusing, various clustering techniques employed to increase efficiency.	System can be improved by updating capabilities	Aerospace Vehicles
José Roberto, Tenório Filho et.al.[42]	Assessment of autogenous strain with the help of two methods i.e. mechanical strain gauge and long gauge deformation based optical sensor	Optical sensor performs better as don't require additional tests.	Traditional Sensor requires two different exposure conditions that were used as specimen for measurement.	Construction and Building Materials
G.S. Serovaev et al[43]	Study of influence of embedded optical sensors on structure of composite materials.	FBG are embedded into composite material for accurate measurements of strain.	For effective and reliable system several factors are required.	Manufacturing of composite material.
Andrew J. Boulanger et.al.[44]	Measurement of various parameters of fluid i.e. temperature between -192°C to 70°C ,fluid pressure up to 20 MPa and heat flux	System is basically safe, non intrusive and have self monitoring capabilities.	System can used to measure parameters upto given range.	Oil/gas, aerospace and nuclear industries.
M. Shanafield et.al.[45]	Study of FOS for distributed temperature sensing and future	FBG's, Optical frequency domain reflectometry and	High frequency, accurate and	Hydrology, Hydrogeology, Geophysics, And

	applications.	acoustic sensing techniques used for exploration	highly spatial measurements are required.	Other Environment Fields

V. CONCLUSION AND FUTURE TRENDS

This paper covers a detailed study of FOS, its features, types, applications, latest work and achievements. The three distinctive types of FOS based on location, spatial distribution and operating principle have thoroughly examined. The structure of different modulation techniques used by FOS namely: IM, PM, WM, and polarization modulated sensors, have also been evaluated and presented. In coming years, the FOS can be used in AON (All Optical Networks) as there is no requirement of O-E-O conversion using this technology. Also, these can be deployed in DWDM technology to increase the available wavelength. Besides that FOS can be used in conjunction with smart sensing devices

and communication networks for extensive implementation in M-2-M (Machine-to-Machine) communication and IoT (Internet of Things). The IoT implementation with FOS will create efficient and smart systems. Hence, this study describes all the aspects related to FOS. This will motivate the researcher's to undertake further research in the field of FOS technology.

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