

# Fiber Optic Sensors and Their Applications

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**Abstract: Photonic sensors signal processors and communication technologies have emerged as viable alternatives to electronics. Fibre optic sensors have advanced to an extent that they can be readily made use of in many applications. The different types of fibre optic sensors, components used in optical fibre sensing, sensor design and analysis, distributed\ multiplexed sensor schemes and the roles of optical sensors are highlighted.**

## I. INTRODUCTION

With the advent of lasers and semiconductor optoelectronics, a great revolution in modern optics took place. Rapid developments in fibre optics gave an additional impetus to this. Holography and Fourier Optics are well known photonic techniques. The above developments have led to the birth of a new discipline, popularly called Photonics. In photonics, photons play a role akin to electrons in electronic materials, devices and circuits. As a result, a large number of activities which were traditionally in the electronic domain are now shifting to the photonics. To mention a few, progress in the use of photonics in sensing, signal processing, communication and computing has been rapid. The main advantages are in terms of speed and security. It is also well known that in addition to the high-tech and scientific activity, a whole range of mass items like compact discs, photo copiers and laser printers have been the result of photonic technologies. Gigabit transmission networks and information super highways are currently pushing the society to greater heights. Processing and computing using massively parallel architectures are on the verge of success. A wide range of fibre optic sensors are fast reaching the market place. Freedom from electromagnetic interference and unprecedented speed and bandwidth are prime reasons for all the success in photonics. Impressive though the development in photonics till date is, it is yet to reach its full potential especially in terms of the market exploitation. One of the exciting fields wherein photonics is expected to play a significant role is smart structures and intelligent systems of interest in engineering. This is where the real challenge lies even in the case of fibre optic sensors and photonic communication and control schemes. In smart structure applications, composite materials, fibre optic sensing and telemetry systems, piezoelectric actuators and microprocessor based control schemes seem to offer the best advantages as of now.

## II. FIBER OPTIC SENSORS

The technology and applications of optical fibres have progressed very rapidly in recent years. Optical fibre, being a physical medium, is subjected to perturbation of one kind or the other at all times. It therefore experiences geometrical (size, shape) and optical (refractive index, mode conversion) changes to a larger or lesser extent depending upon the nature and the magnitude of the perturbation. In communication applications one tries to minimize such effects so that signal transmission and reception is reliable. On the other hand in fibre optic sensing, the response to external influence is deliberately enhanced so that the resulting change in optical radiation can be used as a measure of the external perturbation. In communication, the signal passing through a fibre is already modulated, while in sensing, the fibre acts as a modulator. It also serves as a transducer and converts measurands like temperature, stress, strain, rotation or electric and magnetic currents into a corresponding change in the optical radiation. Since light is characterized by amplitude (intensity), phase, frequency and polarization, any one or more of these parameters may undergo a change. The usefulness of the fibre optic sensor therefore depends upon the magnitude of this change and our ability to measure and quantify the same reliably and accurately.

The advantages of fibre optic sensors are freedom from EMI, wide bandwidth, compactness, geometric versatility and economy. In general, FOS is characterized by high sensitivity when compared to other types of sensors. It is also passive in nature due to the dielectric construction. Specially prepared fibres can withstand high temperature and other harsh environments. In telemetry and remote sensing applications it is possible to use a segment of the fibre as a sensor gauge while a long length of the same or another fibre can convey the sensed information to a remote station. Deployment of distributed and array sensors covering extensive structures and geographical locations is also feasible. Many signal processing devices (splitter, combiner, multiplexer, filter, delay line etc.) can also be made of fibre elements thus enabling the realization of an all-fibre measuring system. Recently photonic circuits (Integrated Optics) has been proposed as a single chip optical device or signal processing element which enables miniaturization, batch production, economy and enhanced capabilities.

There are a variety of fibre optic sensors. These can be classified as follows.

- A) Based on the modulation and demodulation process a sensor can be called as intensity (amplitude), a phase, a frequency, or a polarization sensor. Since detection of phase or frequency in optics calls for interferometric techniques, the latter are also termed as interferometric sensors. From a detection point of view the interferometric technique implies heterodyne detection/coherent detection. On the other hand intensity sensors are basically incoherent in nature. Intensity or incoherent sensors are simple in construction, while coherent detection (interferometric) sensors are more complex in design but offer better sensitivity and resolution.
- B) Fibre optic sensors can also be classified on the basis of their application: physical sensors (e.g. measurement of temperature, stress, etc.); chemical sensors (e.g. measurement of pH content, gas analysis, spectroscopic studies, etc.); bio-medical sensors (inserted via catheters or endoscopes which measure blood flow, glucose content and so on). Both the intensity types and the interferometric types of sensors can be considered in any of the above applications.
- C) Extrinsic or intrinsic sensors are another classification scheme. Extrinsic fibre optic sensors consist of optical fibres that lead up to and out of a 'black box' that modulates the light beam passing through it in response to an environmental effect.

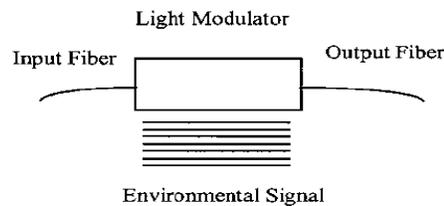


Figure1 Extrinsic fiber optic sensor

Intrinsic fibre optic sensors rely on the light beam propagating through the optical fibre being modulated by the environmental effect either directly or through environmentally induced optical path length changes in the fibre itself.

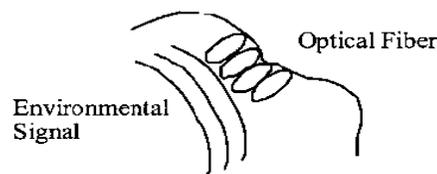


Figure2 Intrinsic fibre optic sensor

### III. BASIC COMPONENTS:

**3.1 Optical fibres:** These are thin, long cylindrical structures which support light propagation through total internal reflection. An optical fibre consists of an inner core and an outer cladding typically made of silica glass, although, other materials like plastics are sometimes used. Three types of fibres are in common use in FOS. The multimode (MM) fibre consists of a core region whose diameter ( $\sim 50 \mu\text{m}$ ) is a large multiple of the optical

wavelength. The index profile of the core is either uniform (step-index) or graded (eg. parabolic). Plastic fibres have a step index profile and a core size of about 1mm. The micro bend type or the evanescent type intensity sensors use MM fibres. MM fibre has the advantage that it can couple large amount of light and is easy to handle, both the advantages arising from its large core size.

Single mode (SM) fibre is designed such that all the higher order waveguide modes are cut-off by a proper choice of the waveguide parameters as given below.

$$V = \frac{2\pi a}{\lambda} \sqrt{n_1^2 - n_2^2}$$

Where,  $\lambda$  is the wavelength,  $a$  is the core radius,  $n_1$  and  $n_2$  are the core and cladding refractive indices, respectively. When  $V < 2.405$ , single mode condition is ensured. SM fibre is an essential requirement for interferometric sensors. Due to the small core size ( $\sim 4 \mu\text{m}$ ) alignment becomes a critical factor.

The SM fibre mentioned above is not truly single mode in that two modes with degenerate polarization states can propagate in the fibre. This can lead to signal interference and noise in the measurement. The degeneracy can be removed and a single mode polarization preserving fibre can be obtained by the use of an elliptical core fibre of very small size or with built in stress. In either case light launched along the major axis of the fibre is preserved in its state of polarization. It is also possible to make a polarizing fibre in which only one state of polarization is propagated. Polari metric sensors make use of polarization preserving fibres. Thus, multimode fibre, single mode fibre and polarization preserving fibre are the three classes of fibres which are used in the intensity type, the interferometric type and the Polari metric type of sensors, respectively.

**3.2 Sources:** In FOS semiconductor based light sources offer the best advantages in terms of size, cost, power consumption and reliability. Light emitting diodes (LEDs) and laser diodes (LDs) are the right type of sources for FOS although in laboratory experiments the He-Ne laser is frequently used. Features of LED include very low coherence length, broad spectral width, low sensitivity to back reflected light and high reliability. They are useful in intensity type of sensors only. LDs on the other hand exhibit high coherence, narrow line width and high optical output power, all of which are essential in interferometric sensors. Single mode diode lasers are made using distributed feedback or external cavity schemes. High performance Mach-Zehnder and Fabry-Perot type sensors need single mode lasers. LDs in general are susceptible to reflected (feedback) light and temperature changes. They are also less reliable and more expensive. Coupling of light from source to fiber is an important aspect and may call for special optical devices. Use of pigtailed source can alleviate this problem but such devices cost more. Fiber lasers and amplifiers are fast becoming commercial products and may play an important role in future FO sensors.

**3.3 Detectors:** Semiconductor photodiodes (PDs) and avalanche photodiodes (APDs) are the most suitable detectors in FOS. APD can sense low light levels due to the inherent gain because of avalanche multiplication, but need large supply voltage typically about 100 V. The various noise mechanisms associated with the detector and electronic circuitry limit the ultimate detection capability. Thermal and shot noises are two main noise sources and need to be minimized for good sensor performance. Detector response varies as a function of wavelength. Silicon PD is good for visible and near IR wavelengths. Generally there is no bandwidth limitation due to the detector as such, although the associated electronic circuits can pose some limitation.

#### IV. DESIGN AND ANALYSIS OF FIBER OPTIC SENSORS

##### 4.1 Intensity (amplitude) sensors

In this case, the signal to be measured (the measurand); intensity (amplitude) modulates the light carried by an optical fibre. For this class of sensors a normalized modulation index ( $m$ ) can be defined as

$$m = \Delta I / I_0 P$$

Where,  $\Delta I$  = change in optical power as a result of modulation by the measurand;  $I_0$  = optical power reaching the detector when there is no modulation; and  $P$  = perturbation.

The sensor response expressed as a differential voltage per unit change in measured is given by,

$$S = q I_0 R_m$$

Where  $q$  = detector responsivity (A/W)

$R$  = load resistance

The limiting performance is reached when the signal voltage (power) is equal to the noise voltage (power). There are many noise sources within the detector as also in the processing circuits. For purposes of estimating the sensor performance, one usually considers the quantum limit of detection i.e.; the fluctuations in the photon field being detected is the ultimate limit.

#### 4.2 Micro bends Sensor

The modulation due to a measurand can be brought about in the form of a microbend loss modulation, moving fibre modulation or an absorbing layer modulation. Microbend sensor is an example of an intensity modulation sensor. A microbend sensor is shown in Fig.1.

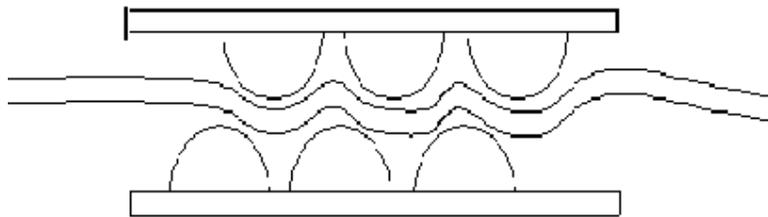


Figure3

It is designed using multimode fibre of a few meters in length which is placed between two rigid plates having an optimum corrugation profile such that the fibre experiences multiple bends. Due to the microbending induced losses, the lower order guided modes are converted to higher order modes and are eventually lost by radiation into the outer layers resulting in a reduction of the optical intensity coming out of the fibre. A displacement of the plates (due to say, pressure) causes a change in the amplitude of the bends and consequently an intensity modulated light emerges from the fibre core. The use of microbend sensors in some smart structure applications is explained in a later section.

#### 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 interferometrically, 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 is used for as a reference. Once the beams are recombined, they interfere with each other. Mach-Zehnder, Michelson, Fabry-Perot, Sagnac, polarimetric, and grating interferometers are the most commonly used interferometers. An interferometric sensor is based on the detection of changes in the phase of light emerging out of a single mode fibre. In the case of a fibre the phase change in general is given by,

$$\Delta\phi = \Delta\phi_L + \Delta\phi_n + \Delta\phi_g$$

Where  $\Delta\phi_L$  = Phase due to length,

$\Delta\phi_n$  = Phase due to index

$\Delta\phi_g$  = Phase due to guide geometry variation

The phase change is converted into an intensity change using interferometric schemes (Mach-Zehnder, Michelson, Fabry-Perot or Sagnac forms). In a simple scheme only the sensing and reference arms are made of fibres, while the rest are made of bulk optic components. However the use of either all-fiber or integrated optic components can provide better stability and compactness compared to their bulk counterparts. Interferometric fibre optic sensors are the most commonly used sensors since they offer the best performance. They have found application as acoustic (e.g. hydrophones), rotation (eg. gyroscope), strain, and temperature, chemical, biological and a host of other types of sensors.

The phase change of light propagating through a fibre of length  $l$  and propagation constant  $\beta = k_0 n$ , is given by

$$\phi = \beta k_0 n l$$

The change in phase due to a unit perturbation such as pressure change is given by,

$$\Delta\phi = \beta\Delta l + l\Delta\beta = \beta\Delta l + l [k_0\Delta n + (\delta\beta/\delta a)\Delta a]$$

Where  $n$  = refractive index, and  $a$  = radius of the fibre.

#### 4.4 Fibre Optic Polari meter

The birefringence property arising from optical anisotropy is used in the study of photo elastic behaviour. The anisotropy may be due to naturally occurring crystalline properties or due to stress induced birefringence. It is the latter that is used in a photo elastic fibre optic strain gauge. In a simple setup two lead fibres are used to illuminate and collect light passing through a photoelastic specimen. A pair of linear polarizers is used in the crossed form to obtain a conventional polariscope. In such a case the intensity at each point on the specimen is given by

$$I = I_0 \sin^2 2\theta \sin^2 \frac{\alpha}{2}$$

Where  $I_0$  is the total light intensity and  $\theta$  is the angle that the principal stress directions make with respect to the axes of the polarisers. Due the stress birefringence the orthogonally polarized light waves travel with a phase difference  $\alpha$  given by

$$\alpha = \frac{2\pi}{\lambda} (n_1 - n_2) d = \frac{2\pi}{f_a} (\sigma_1 - \sigma_2) d$$

where  $\lambda$  is wave length,  $n$  is the index of refraction,  $d$  is the thickness in the direction of light propagation,  $C$  is stress-optic coefficient and  $f_a = (\lambda / C)$  is known as material fringe value. When the polarisers are oriented  $45^\circ$  w.r.t. principal stress directions, the equation is

$$I = I_0 \sin^2 2\theta \sin^2 \frac{\alpha}{2}$$

Simplify to

$$I = I_0 \sin^2 \frac{\alpha}{2}$$

With  $\alpha = (2\pi / f_a) \sigma d$  where the applied load is assumed to produce a uniaxial stress. By taking the derivative of the above equation we obtain

$$\Delta I = I_0 \Delta \left( \frac{\alpha}{2} \right) \sin \alpha$$

This has a maximum sensitivity when  $\alpha = \pi / 2$  (quadrature condition). Under this condition  $(\Delta I / I_0) / \Delta \epsilon = \pi E d / f a$ , where  $E$  is the elastic modulus and  $\epsilon$  is the strain in the direction of applied load. The photo-detector output current which is expressed in terms of voltage sensitivity can be written as

$$I_p = R_1 P_0$$

Where  $I_p$  is the output photo current,  $P_0$  is the incident optical power,  $R_1$  is the sensitivity.

It may be noted that in this case the output current of a photo detector depends upon the incident optical power and the sensitivity of the photo detector.

## V. APPLICATION

A common use for fiber optic sensors includes advanced intrusion detection security systems. The light is transmitted along a fiber optic sensor cable placed on a fence, pipeline, or communication cabling, and the returned signal is monitored and analyzed for disturbances. This return signal is digitally processed to detect disturbances and trip an alarm if an intrusion has occurred.

Fibers are widely used in illumination applications. They are used as light guides in medical and other applications where bright light needs to be shone on a target without a clear line-of-sight path. In some buildings, optical fibers route sunlight from the roof to other parts of the building (see nonimaging optics). Optical fiber illumination is also used for decorative applications, including signs, art, toys and artificial Christmas trees. Swarovski boutiques use optical fibers to illuminate their crystal showcases from many different angles while only employing one light source. Optical fiber is an intrinsic part of the light-transmitting concrete building product, LiTraCon.



Figure 4: Light reflected from optical fiber illuminates exhibited model

Optical fiber is also used in imaging optics. A coherent bundle of fibers is used, sometimes along with lenses, for a long, thin imaging device called an endoscope, which is used to view objects through a small hole. Medical endoscopes are used for minimally invasive exploratory or surgical procedures. Industrial endoscopes (see fiberscope or borescope) are used for inspecting anything hard to reach, such as jet engine interiors. Many microscopes use fiber-optic light sources to provide intense illumination of samples being studied.

In spectroscopy, optical fiber bundles transmit light from a spectrometer to a substance that cannot be placed inside the spectrometer itself, in order to analyze its composition. A spectrometer analyzes substances by

bouncing light off of and through them. By using fibers, a spectrometer can be used to study objects remotely.<sup>[31][32][33]</sup>

An optical fiber doped with certain rare earth elements such as erbium can be used as the gain medium of a laser or optical amplifier. Rare-earth doped optical fibers can be used to provide signal amplification by splicing a short section of doped fiber into a regular (undoped) optical fiber line. The doped fiber is optically pumped with a second laser wavelength that is coupled into the line in addition to the signal wave. Both wavelengths of light are transmitted through the doped fiber, which transfers energy from the second pump wavelength to the signal wave. The process that causes the amplification is stimulated emission.

The iron sights for handguns, rifles, and shotguns may use short pieces of optical fiber for contrast enhancement. Optical fiber can be used to supply a low level of power (around one watt)<sup>[citation needed]</sup> to electronics situated in a difficult electrical environment. Examples of this are electronics in high-powered antenna elements and measurement devices used in high voltage transmission equipment.

Using a micro bend sensor, pressure, load and displacement measurement can be made on civil structures such as buildings and bridges. Such a sensor is attractive because it is simple to use, low cost and very rugged. Initial calibration could be done with a compression testing machine.

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