1.1 Historical Developments of Fiber Optic Sensors

Through a long process of evolution, the development of human society has now entered a highly information-oriented era. The information technology has become the major trend of contemporary development. With more and more high technology products going into peoples’ lives, there is more demand for high-speed and large-capacity information carriers. These have been the targets for many researchers. In past forty years, revolution is brought out in information technology due to developments in optoelectronics and telecommunication industries. Improvements in quality and cost reduction in optoelectronic components led the industry to bring out high performing devices such as compact disc, players, bar code scanner, high end lasers, laser printers, CCD camera, LCD projector, stable photodiodes, high sensitive photodetectors, phototransistors, etc. Ultra fast development in telecommunication was due to developments in fiber optics communication industry by providing high performance and more reliable telecommunication links, larger bandwidth for information carriage at low cost.

The invention of lasers in 1960’s opened new window for researchers to study the optical fibers for data communication, sensing and other applications in the next decade. Researchers conducted experiments by transmitting the laser beam in different waveguides. In the beginning large losses in optical fibers prevented the replacement of co-axial cables by optical fibers. Early fibers had losses of 1000dB/km, means only 1% of light transmitted in 20m fiber, making them impractical in communication use. Charles Kao who won Nobel Prize in 2009 for his contributions along with his co-worker G. A. Hockham investigated fundamental properties of optical fibers in detail way back in 1966 for optical communication and came to conclusion that – the losses in dielectric media were mostly caused by
absorption and scattering. The latter was predominantly caused by impurities, in particular iron ions present. Fibers with glass of higher purity could be a good candidate for optical communication. As coated by C. Kao - “Compared with existing coaxial cable and radio systems, this form of waveguide has a larger information capacity and possible advantages in basic material cost. The realization of a successful fiber waveguide depends, at present, on the availability of suitable low-loss dielectric material. The crucial material problem appears to be one which is difficult but not impossible. Certainly, the required loss figure of around 20dB/km is much higher than the lower limit of loss figure imposed by the fundamental mechanisms ,” [1]. Later in 1969 C. Kao along with other co-workers, showed that fused silica (SiO$_2$) had purity for good optical communication. An intense worldwide research with aim to produce low loss optical fibers began. In 1970, research team from the Corning Glass Works in the United States consisting of F. P. Kapron, D. B. Keck, P. C. Schultz, F. Zimar, under the leadership of R. D. Maurer, succeeded in making glass fibers of fused silica with low losses as C. Kao had envisioned. The team fabricated fiber by chemical method called chemical vapor deposition (CVD). To make a core and cladding with very close refractive indices, they doped titanium in the fused silica core and used pure fused silica in the cladding. A few years later (in 1974), loss even reached 4dB/km at 850nm using germanium instead of titanium. Several other technologies were developed in Japan, USA and UK. In that direction J. B. MacChesney and co-workers at Bell Laboratories developed a modified CVD technique, allowing efficient production of optical fibers. Within a few years, attenuation less than 1dB/km was achieved, which was even far below the target set by C. Kao. Today, attenuation of light around 1.55µm wavelength in fibers is below 0.2dB/km [2]. Modern optical fibers are extraordinarily transparent media, with more
than 95% light transmitted after 1km propagation [3]. Later advances in fiber optic technology have significantly changed the telecommunication industry. The ability to carry gigabits of information at the speed of light increased the research potential in optical fibers. Improvements and cost reductions in optoelectronic components led to emergence of new product area.

With improved technologies of manufacturing, optical fiber material loss almost disappeared and the sensitivity for detection of the losses increased. With development in low power measurement detectors, one could even sense small changes in phase, intensity and wavelength of a light carried by an optical fiber due to outside perturbations on the fiber. Optical fiber being physical medium is subjected to perturbation of one or the other kind. Therefore it experiences geometrical (size, shape, strain) or optical (RI, mode conversion) changes depending upon the nature and magnitude of the perturbation. In telecommunication applications, one tries to minimize such effects so that signal transmission and reception is reliable. On the other hand, in fiber optic sensor (FOS) field, the response to external perturbation is deliberately enhanced, so that the resulting change in optical radiation can be used as measure of external perturbation. In FOS, the fiber acts as modulator. It also serves as transducer and converts measurement data like temperature, stress, strain, rotation or electrical and magnetic currents into corresponding change in optical radiation. This sub branch of optical fiber technology soon saw an intense R&D activities around the world, which led to the emergence of the new field called ‘Fiber Optic Sensors’.

Development of optical fiber sensors started in 1977 even though some isolated demonstrations were made in earlier days. Many laboratories entered into the field resulting into rapid progress. In the beginning fiber optics sensors were developed for sensing sound [4-6], pressure [7-9], temperature [10], magnetic field [11, 12], rotation
Introduction to Fiber Optic Sensors and Fiber Gratings

[13, 14], current [15, 16], acceleration, fluid level, torque, photo acoustics, current, displacement etc [17].

Light is characterized by phase, polarization, frequency, wavelength and intensity (amplitude). Any one or more of these parameters may undergo a change due to external perturbation. Our ability to measure and quantify the change reliably and accurately is state of art of sensor design. In fiber optic sensors, information is conveyed by change either in phase, polarization, frequency, wavelength, intensity or combination of above properties of optical fiber. But the photodetector, being semiconductor device only senses the intensity of light at the detector surface. Hence, the art of sensing with phase, frequency or polarization modulation involves interferometric or grating based signal processing optical circuits.

1.2 Advantages of Fiber Optic Sensors

The main drive of research in FOS area today is to produce a range of optical-fiber based techniques which can be used to measure different physical parameters, providing a foundation for an effective measurement technology, strengthen the technology that can compete with conventional methods and tackling difficult measurement situations where conventional sensors are not well suited to use in a particular environment. The resulting sensors have a series of characteristics those are significantly advantageous compared to conventional electrical sensors. Following are some advantages of FOS compared to conventional electrical sensors. Following are some advantages of FOS compared to conventional electrical sensors [18].

1. Sensed signal is immune to electromagnetic interference (EMF) and radio frequency interference (RFI).

2. Intrinsically safe in explosive environments.
3. Highly reliable and secure with no risk of fire/spark.
4. High voltage insulation and absence of ground loops and hence avoid any necessity of isolation devices like optocouplers.
5. Low volume and light weight (1 kilometer of 200µm silica fiber weighs only 70 grams and occupies volume of nearly 30 cm³).
6. As point sensors, they can be used to sense parameters in inaccessible regions without perturbation of the transmitted signals.
7. They be easily interfaced with low-loss optical fiber telemetry and hence affords remote sensing by locating the control electronics for LED/lasers and detectors far away from the sensor head.
8. Large bandwidth and hence offer possible multiplexing a large number of individually addressed point sensors in a fiber network or distributed sensing.
9. Chemically inert and they can be readily employed in chemical processes and biomedical instrumentation due to their smaller size and mechanical flexibility.
10. Multifunctional sensing capabilities such as strain, pressure, corrosion, temperature and acoustic signals.
11. Robust, more resistant to harsh environments.

These advantages were sufficient to attract intensive research and development activities around the world to develop new class of sensors based on fiber optics. This has eventually led to the emergence of variety of fiber optic sensors for accurate sensing and measurement of physical parameters [18].

Some of the disadvantages of FOS were also noticed during different sensor developments. One is the poor elastic property that makes optical fiber extremely brittle. This is not particularly desired for sensing applications. Consequently, the
handling, treatment and operation of FOS require extreme care. In addition, each process requires technical skills. With the current technology, in situ assembly of the optical system is a cumbersome and exhaustive process, since the measurement setup of the optical fiber sensor system is comprised of different modules (for example, light source, coupler and receiver), difficult splicing process and the constant need for careful treatment. Although the method of manufacturing fiber gratings has improved considerably, current technology only manages to produce one at one time and most of the process still requires manual handling. In addition, the cost of running fiber grating writing facilities is high due to expensive laser, masks (both phase mask and amplitude masks) and the requirement for a highly skilled operator. The lifespan of optical fiber is considered long for telecommunications, between 20 to 25 years, it may be not enough for some of sensing applications. Typical civil engineering structures such as buildings, bridges and dams typically have lifespan of more than 70 years where FOS is used for structural health monitoring. Therefore, packaging FOS is next big task after a sensor design [19-23].

### 1.3 Basic Principle of Fiber Optic Sensor

Although light is trapped within the dielectric medium of the optical waveguide, the radiation that propagates inside the waveguide can be perturbed by the external environment and this perturbation can be used to draw useful information for sensing purposes. In fact, the interaction of the physical parameter of interest that is measured with the waveguide produces a modulation in the propagation constants of the guided light beam. This modulation is a sensitive function of the measurand of interest. Following are basic elements constituting a fiber optic sensor [19-21].
1. Optical sources: Commonly used light sources in visible or infra red range are applicable. E.g. Laser, LED, Laser diode etc

2. Optical fiber: A sensing or modulator element (which transduces the measurand to an optical signal). Varieties of optical fibers - both multimode and single mode fibers - are used.

3. Optical detector and processing electronics: High resolution detector compatible to detect light from above mentioned light sources are used. E.g. oscilloscope, optical spectrum analyzer etc).

The general structure of an optical fiber sensor system is shown in Fig.1.1.

![Figure 1.1: Basic components of optical fiber sensing system.](image)

1.4 Design of FOS

A fiber optic sensor can be designed in different ways based on the requirement. A schematic of the three most common sensing designs - point, distributed and quasi-distributed sensing is illustrated in Fig.1.2 (a-c).

1.4.1 Point Sensor

The measurement of any particular measurand at a particular location is basic need of a sensor system. This is achieved with a point sensor. Here, tip of the fiber is allowed to sense the change (Fig. 1.2 (a)). Most of fiber optic sensors such as those
used in the monitoring of temperature, acceleration, pressure or chemical parameters use this design [22].

1.4.2 Distributed Sensor

With some sensors, the whole length of the fiber can be used as a sensing element. The measurand action is sensed along the length of the fiber itself and process is termed distributed sensing, illustrated in Fig. 1.2(b). This principle has been employed widely in the measurement of temperature using non-linear effects in fibers, such as Brillouin or Raman scattering or in some types of strain sensing. This yields either an enhanced sensitivity if the fiber is wrapped up to form a single sensing point or it can be used for spatial averaging of the signal [22].

1.4.3 Quasi Distributed Sensor

A style of sensor that is somewhat in between these two types of sensors is termed quasi-distributed. As shown schematically in Fig. 1.2(c), the measurand information is obtained at different pre-determined points along the length of a fiber network. Here, the fiber has been sensitized or special materials have been introduced into the fiber loop to allow the measurement to be taken and this technique has been applied to temperature and chemical sensing, e.g., using different fiber types [22]

Figure 1.2: Scheme of three most common fiber optic sensor designs: (a) Point sensor, (b) Distributed Sensor, (c) Quasi distributed sensor.
1.5 Types of Fiber Optic Sensors

Varieties of fiber optic sensors were developed in the direction to full fill the needs of human society. Optical fiber sensors are classified into different classes based on different categories: the sensing location, the operating principle, the applications etc [18, 20].

1.5.1 Based on Sensing Location

In FOS, the light may be modulated either inside or outside the optical fiber i.e. sensing location may be inside or outside the fiber. Hence, based on sensing location FOSs are classified broadly as intrinsic and extrinsic sensors. This is the simplest classification of fiber optic sensors.

1.5.1.2 Intrinsic Sensor

In intrinsic fiber optic sensor, the interaction occurs within an element of optical fiber itself and light never leaves the waveguide. External environment acts on the fiber and the fiber in turn changes some characteristic of the light inside the fiber that is measured using the detector. One or more of the physical properties of the guided light, e.g., intensity, phase, polarization or wavelength is modulated by the measurand. A schematic illustration of intrinsic sensor can be seen in Fig. 1.3. Examples for intrinsic sensors are pressure sensor, temperature sensor, strain sensor, etc. [18, 20, 23, 25].
1.5.1.2 Extrinsic Sensor

In extrinsic fiber optic sensor, the optical fiber is used to couple light, usually to and from the region where the light beam is influenced by the measurand (or external environment). In this case, the fiber just acts as a means of getting the light to the sensing location and to detector as shown in Fig 1.4. Common examples of this type of sensors are optical fiber endoscopy, displacement sensor and fiber-optic fluorescence sensor. In fiber-optic fluorescence sensor the light is coupled out of the fiber and excites the analyte. The light emitted by fluorescence of the analyte is collected by the second fiber and guided to the detector [18-21].

1.5.2 Based on Modulation Technique

Based on the operating principle or modulation and demodulation process, a fiber optic sensor can be classified into 4 groups

1. Intensity modulated sensor
2. Wavelength modulated sensor
3. Polarization modulated sensor

4. Phase modulated sensor

All these parameters may be subject to change due to external perturbations. Thus, by detecting these parameters and their changes, the external perturbations can be sensed.

1.5.2.1 Intensity Modulated Sensor

Intensity modulation is simplest and cheapest method of detecting different parameters using optical fiber. Intensity-based fiber optic sensors are based on intensity undergoing change. In intensity modulated fiber optic sensors, measurand modulates the intensity of light transmitted through the optical fiber and variations in the intensity are measured at the output end of the optical fiber using a detector. Intensity modulated sensors are analogue in nature and have significant usage in digital applications for switches and counters [23]. These require more light and therefore usually use multimode optical fibers. Intensity modulated FOS can be found in variety of intrinsic and extrinsic configurations. The intensity modulation can be achieved through variety of methods or mechanisms such as transmissive, reflective, microbending, attenuation and evanescent fields that can produce a measurand induced change in the optical intensity propagated by an optical fiber [23].

The advantages of these sensors are: Simplicity of implementation, low cost, possibility of being multiplexed and ability to perform as real distributed sensors. The drawbacks are: Relative measurements and variations in the intensity of the light source may lead to false readings, unless a reference system is used [20].

1.5.2.2 Wavelength Modulated Sensors

Wavelength modulated fiber optic sensors are based on changes in the wavelength of a light for detection. Fluorescence sensors [24, 25], black body sensors [26] and the fiber grating sensor [27-29] are examples of wavelength-modulated sensors. Fiber
Grating sensors will be discussed in next chapters in detail. Fluorescent based fiber sensors are being widely used for medical applications, chemical sensing and physical parameter measurements such as temperature, viscosity and humidity. Different configurations are used for these sensors. One of the simplest wavelength based sensor is the blackbody sensor as shown in Fig.1.5. A blackbody cavity is placed at the end of an optical fiber. When the cavity rises in temperature it starts to glow and act as a light source. Detectors in combination with narrow band filters are then used to determine the profile of the blackbody curve. This type of sensor has been successfully commercialized and has been used to measure temperature to within a few degrees centigrade under intense RF fields. Because of better signal to noise ratio, this sensor performance is good at higher temperatures – above 200°C and falls off below 200°C [20, 30].

![Blackbody Fiber Optic Sensor](image)

**Figure 1.5: Blackbody Fiber Optic Sensor.**

### 1.5.2.3 Phase Modulated Fiber Optic Sensors

Phase modulated sensors use modulation in phase of the light being transmitted in an optical fiber for detection. The optical phase of the light passing through the fiber is changed by the physical quantity to be measured. Phase modulated FOS are highly sensitive to measurand. Hence they are employed when extreme sensitivity is required. Most of phase modulated FOS use single mode fiber and are of intrinsic
type. The phase angle ($\phi$) for lightwave traveling in the fiber of length $L$ is defined as

\[ \phi = \frac{2\pi n L}{\lambda} \]  

(1.1)

where ‘$n$’ is refractive index of the core and $\lambda$ is the wavelength of light. A change in length or refractive index under the influence of external physical parameter will cause a phase change as defined by the equation

\[ \Delta \phi = \frac{2\pi}{\lambda} (n \Delta L + n L) \]  

(1.2)

The expression $n\Delta L + nL$, is called optical path difference (OPD). The optical intensity at the output of a interferometer is function of OPD. Very small change in length produces large phase difference. Similarly, very small changes of refractive index at longer sections of fiber produce large phase differences. When phase shift is integral multiple of wavelength, lights from the two arms of the interferometer are in phase providing constructive interference and maximum intensity at the output. If the phase shift is integral multiple of half of the wavelength, lights from the two arms of the interferometer are out of phase providing destructive interference and minimum intensity [23].

In phase modulated sensors, this sensitive phase change of the light is encashed to design sensor. But the difficulty is optical phase change cannot be directly detected (optical waves have frequencies in the range of few hundred THz). The optical phase change of the light is detected by comparing the phase with reference fiber which is identical to measuring fiber but unperturbed by the measurand. In order to detect phase difference, it is necessary to convert phase difference to optical intensity change which can be measured by a detector. This is achieved by combining two optical signals – one from sensing fiber and other from reference fiber. In an interferometer, the light is split into two beams, where one beam is exposed to the sensing
environment and undergoes a phase shift. The other is isolated from the sensing environment, which is used as a reference. The whole system is called interferometer. This phase modulation is then detected interferometrically, by comparing the phase of the light in the signal fiber to that in a reference fiber. Once the beams are recombined, they interfere with each other. There are four most commonly used interferometric configurations. They are - Michelson, Mach-Zehnder, Fabry-Perot and Sagnac interferometers [22, 23, 32-35].

**Michelson Interferometer:** Experimental configuration of Michelson interferometer is shown in the Fig.1.6. One 2X2 coupler (3dB coupler) that splits input light into exactly two parts is used in the Michelson interferometer. The coherent laser light launched in one arm of the coupler is split and injected into two arms on the other side of the coupler. One of these two arms is allowed to be perturbed by a physical parameter to be measured and reference arm is protected. These two arms (sensing and reference) have mirrored ends to reflect the beam back through the same fibers and coupler to a detector. Any perturbation due to physical change at sensing arm varies phase of light in that arm.

![Michelson Interferometer Configuration](image)

**Figure.1.6: Michelson interferometer configuration.**

The phase shift is then detected. Because the light passes both through the sensing and reference fibers twice, the optical phase shift per unit length of fiber is doubled. Michelson interferometer can intrinsically have better sensitivity. Another clear
advantage of the Michelson interferometer is that the sensor can be designed with a single coupler between the source-detector module. However, good-quality reflection mirrors are required. The disadvantage of Michelson interferometer is that the coupler feeds light into both the detector and laser. Feedback into the laser is source of noise, especially in high performance systems [23].

**Mach-Zehnder Interferometer:** Mach-Zehnder interferometer uses two identical 2X2 couplers. The experimental configuration is shown in the Fig.1.7. Light launched into one of the arm of the 1st coupler is split into two identical beams and launched into other two arms considered one as sensing and other as reference arm. These beams are combined using another coupler and phase shift is measured. The phase shift results from changes in the length or refractive index of the sensing fiber. If the path lengths of the sensing and reference fiber are same or differ by an integral multiple of wavelengths, the combined beams are exactly in phase and the beam intensity is maximum. However, if the two beams are out of phase by $\frac{\lambda}{2}$, the recombined beam is at its minimum value of intensity. A modulation of 100% occurs over $\frac{\lambda}{2}$ change in fiber length. With this sensitivity, movements as small as $10^{-3}$ meters can be detected [23].

![Figure 1.7: Mach-Zehnder interferometer configuration.](image)

**Fabry-Perot Interferometer:** Fabry-Perot interferometer is type of multi beam interferometer. It is again classified into intrinsic Fabry-Perot interferometer (IFPI)
and extrinsic Fabry-Perot interferometer (EFPI). The experimental configuration of IFPI shown in the Fig. 1.8. It consists of two partial reflecting fiber mirrors. The injected coherent beam is partially reflected back and partially transmitted into interferometer. At second partial reflecting mirror, again the beam is partially reflected and partially transmitted. In this type of interferometers, the light bounces back and forth many times in the cavity, increasing the phase delay many times. This transmitted light is detected through the detector at the other end. Successive reflection sequences will reduce the detection beam. The multiple passage of light along the fiber magnifies the phase difference resulting into highly sensitive sensor [23, 36].

![Figure 1.8: Fabry-Perot Interferometer configuration.](source)

**Fiber Optic Gyroscopes:** The principle of fiber optic gyroscope is based on Sagnac interferometry. Hence, they are also called as Sagnac interferometers. Gyroscopes are principally used to measure rotation and are replacement for ring laser gyros and mechanical gyros. Fiber optic gyroscopes are also used to measure time varying effects such as angular velocity, acoustics, vibrations and slowly varying strain. Fiber optic gyroscopes are most developed FOS. Several manufacturers worldwide are producing them in large quantities to support automobile navigation systems, pointing
and tracking of satellite antennas, inertial measurement systems for commuter aircraft and missiles and as the backup guidance system for the Boeing 777. [20, 23, 26].

![Figure 1.9: Configuration of Fiber optic gyroscope.](image)

The basic configuration of fiber optic gyroscope is shown in Fig. 1.9. The fiber optic gyroscope consists of loop of fiber. Light from the laser is split into two beams and launched simultaneously into both end of the fiber loop. Both beams travel in counter propagating directions around the loop of fiber and recombined to analyze at a detector. In non-rotating loop, clockwise and anticlock wise beams arrive at same time in phase and form constructive interference. If the loop is rotated in clockwise direction, the entire coil is displaced slightly increasing the time it takes light to traverse the fiber optic coil. Thus, the clockwise propagating light beam has to go through a slightly longer optical pathlength than the counter-clockwise beam, which is moving in a direction opposite to the motion of the fiber coil. Two beams reach the detector at different times and phase difference is introduced. These differences in arrival time and phase difference are directly proportional to the rotation rate and can be conveniently measured as phase differences with great sensitivity and accuracy [37-39]. Fiber optic gyroscopes are used in two configurations - open loop fiber optic gyros and closed loop fiber optic gyros.

1.5.2.4 Polarization Modulated Fiber Optic Sensors

Standard single mode fibers transmit light without regards to polarization. But
some special fibers known as polarization mainlined fibers maintain input polarization or transmit only one polarization state. The refractive index of a fiber changes when fiber undergoes stress or strain depending on the direction. The refractive index undergoing change due to stress or strain is called induced refractive index. Because of induced refractive index, there is an induced phase difference between different polarization directions. This phenomenon is called photoelastic effect. The induced refractive index changes with the direction of applied stress or strain. Thus, there is an induced phase difference between different polarization directions. Therefore, by detecting the change in the output polarization state, the external perturbation can be sensed. Fig. 1.10 shows the optical setup for the polarization based fiber optic sensor. It is formed by polarizing the light from a source via a polarizer. The polarized light is launched into polarization maintained fiber. This section of fiber is served as sensing fiber. Under external perturbation such as stress or strain, the phase difference between two polarization states is changed. Then, the output polarization state is changed according to the perturbation. Hence, by analyzing the output polarization state at the exit end of the fiber, the external perturbation can be detected [20].

Figure 1.10: Polarization based sensor.
1.6 Fiber Gratings

Even though the improvements in optical fiber manufacturing and advancements in the field were reality in late 1970’s; integrating optical components such as mirrors, wavelength filters and partial reflectors to optical fibers for various applications was a challenging job. However, all these hurdles were cleared with the discovery of fiber gratings [40] and further refinement of fiber gating inscription method externally, that was demonstrated by Meltz G., et. al. [41]. Fiber gratings were discovered by Hill et. al. in 1978 [40] where the team successfully altered the core refractive index of a single-mode optical fiber by optical absorption of UV light.

The change in core refractive index can be explained in terms of photosensitivity of optical fibers, that allows the fabrication of phase structures in the core of fibers. These phase structures or phase gratings are obtained by permanently changing the refractive index in a periodic pattern along the core of the fiber. The grating period and length together with the strength of the modulation of the refractive index determine whether the grating has a high or low reflectivity over a wide or narrow range of wavelengths. Therefore, these parameters determine whether the grating acts as a wavelength division multiplexer in telecommunications, a narrow-band high-reflectance mirror in laser or sensor applications or a wavelength-selective filter removing unwanted laser frequencies [42].

Fiber grating is periodic perturbation along the optical path. Fiber grating is an optical device with periodic perturbation along short section of the optical fiber core. This perturbation in the fiber may be either in the form of refractive index, thickness or density of glass. Most of the fiber gratings have periodic refractive index modulation in the core that poses perturbation to the optical path. When light propagates through periodically alternating regions of higher and lower refractive
index, it is partially reflected and partially refracted at each interface between those regions. This periodic perturbation in the optical path directs coupling of power from one mode to another and pitch of the perturbation selects coupling modes. [43, 44]. Fiber grating technology is widely applicable in optical communication systems and sensing field.

Fiber grating acts as common diffraction grating of period $\Lambda$. A light wave incident on the grating at an angle $\theta_1$ is diffracted out with an angle $\theta_2$ (Fig. 1.11). The grating equation is given as [45],

$$n\sin\theta_2 = n\sin\theta_1 + m\frac{\lambda}{\Lambda}$$  \hspace{1cm} (1.3)

‘$m$’ is diffraction order. Now considering that incident and diffracted rays correspond to bounded modes of optical fiber, the propagation constant $\beta$ can be defined as

$$\beta = \frac{2\pi}{\lambda} n_{\text{eff}}$$  \hspace{1cm} (1.4)

with $n_{\text{eff}} = n_{co} \sin\theta$, where $n_{\text{eff}}$ represents effective refractive index of the mode and $n_{co}$ represents refractive index of the core [46].

![Figure 1.11: Diffraction by grating.](image)

Now Eq. 1.3 can be written as

$$\beta_2 = \beta_1 - \frac{2\pi}{\Lambda}$$  \hspace{1cm} (1.5)
From this equation one can predict for which grating period the coupling occurs between two modes of propagation constant $\beta_1$ and $\beta_2$ at the wavelength $\lambda$.

In uniform gratings, grating planes are perpendicular to the fiber axis and are of a constant period. These grating periods are considered as fundamental building blocks of fiber gratings. In general fiber gratings consists of the periodic refractive index modulation in the optical fiber core. The pitch is called period of the grating ($\Lambda$) as shown in Fig.1.12.

Fiber gratings are broadly divided into two types based on the grating period and light coupling scheme.

– fiber Bragg gratings also called short period gratings or reflecting gratings

– long period gratings also called transmission gratings

The relative grating period of both types of fiber gratings can be realized by observing Fig.1.13 where there is large difference in grating period.
1.6.1 Fiber Bragg Grating (FBG)

Fiber Bragg gratings consists of periodic modulation of refractive index in the core of single mode fiber with grating period less than 100μm, practically submicron period. FBGs act as narrow band reflection filters. FBG couples forward coupling core mode to backward coupling core modes those scattered by grating planes, reflecting back a small band of source spectrum [42, 47]. Reflected spectrum can be observed in optical spectrum analyzer using 2x2 coupler or circulators. In transmitted spectrum of FBG, a narrow band will be missing as it is reflected back. Input and reflected spectra of typical FBG are shown in Fig.1.14. Advantages of FBGs is that in FBGs information is encoded in absolute parameter i.e. wavelength, they can act as point sources, any number of FBGs can be multiplexed in single line. More discussion on FBG will be continued in next the chapter.

![Figure 1.14: FBG action.](image)

1.6.2 Long Period Grating (LPG)

Long period gratings have grating period ranging between 100μm to 1mm. LPGs promotes coupling between forward coupling core mode and co propagating cladding modes. Hence, the transmitted spectrum of LPG consists of series of attenuation dips centered at discrete wavelengths. Each attenuation dip corresponds to each cladding mode [48]. These modes decay rapidly as they propagate along the fiber axis because
of scattering. LPG acts as band rejection filter [49]. For practical applications, transmitted spectrum of LPG is observed. Typical input and transmitted spectrum is shown in the Fig. 1.15.

![Image: Input and transmitted spectrum of LPG.]

**Figure 1.15: Input and transmitted spectrum of LPG.**

### 1.7 Lightwave Applications of FBG

An enthusiastic scenario where FBG’s are liberally applied to enhance the lightwave network all the way from the central office to the subscriber’s premise. Despite competitive technologies, many of these grating applications have matured, others are nearing commercialization and, as lightwave systems evolve to optical networks and fiber moves toward the home, the number of uses will increase. Some light wave applications of FBG are briefly discussed below.

**Laser Stabilization:** Fiber Bragg grating reflectors are used as feedback mirrors in wavelength-stabilized semiconductor lasers. Wavelength-stabilized 980nm pump lasers [50, 51] for erbium-doped fiber amplifiers are commonly deployed today, benefiting both pump laser yield and amplifier reliability. Grating stabilization of 1480nm pump lasers has also attracted attention [51]. Stabilization is achieved using weak, narrow-band FBG reflectors in the fiber pigtail to couple light back into a Fabry–Perot pump laser, creating an external laser cavity. Grating reflectivities of 1–10% are chosen to achieve robust stabilization and maximize the laser output. Having
a narrow reflection bandwidth of 0.2–3nm allows the pump wavelength to be accurately placed for optimum pumping of the fiber amplifier. This is particularly important with 980 nm pumping as the erbium absorption bandwidth is only 7–10 nm [52]; pump wavelength fluctuations from temperature, injection current and aging are then significant risks to optimum amplifier performance. The use of a single FBG reflector to simultaneously stabilize three pump lasers for use in multistage optical amplifiers has been demonstrated. This reduces the number of gratings and provides pump redundancy to increase the amplifier’s reliability [53, 54].

**Fiber Lasers:** Fiber lasers can be constructed using FBGs as wavelength-selective resonator mirrors and erbium-doped fiber as the gain medium. These fiber lasers are optically pumped, often directly without the use of pump wavelength division multiplexing (WDM) couplers. Narrow line width fiber lasers suitable as externally-modulated continuous wave sources have been demonstrated in gigabit/s transmission experiments [55] and short distributed-feedback fiber lasers having Er–Yb-doped gain sections have also exhibited robust single-frequency operation [56]. Low-cost configurations have been proposed using 650 nm lasers to pump the erbium doped gain region [53]. The output behavior is described by a simple above-threshold, two-mirror model of the erbium fiber laser derived from rate equations. The laser threshold and slope efficiency are easily calculated, whether pumped at 650, 980 or 1480 nm wavelength [57].

**Reflectors in Fiber Amplifiers:** Numerous fiber amplifier configurations have been proposed to utilize reflectors or filters to enhance performance. Reflecting only the pump light may increase the amplifier saturated output power in those cases of amplifiers having marginal pump power. FBG’s can be used as efficient wavelength-selective reflectors that discriminate between pump and signal light. A simple
analytical of the erbium-doped fiber amplifier [58] can be adapted to the idealized case of negligible amplified spontaneous emission and unity reflectance of the FBG reflector. Typically, reflecting the signal doubles the small-signal gain while reflecting the pump may yield a 1–3dB improvement in small-signal gain. Pump reflectors have been used to enhance performance of remotely pumped amplifiers in repeaterless systems. Span lengths were extended by placing remote sections of erbium doped fiber and pumping them at 1485 nm with light generated from high-power lasers located at a terminal station. Demonstrations of greater than 500 km repeaterless transmission at 2.5 Gb/s [59-60] and 352 km of 8 10 Gb/s [61] have been reported. In the 352 km transmission experiment, a preamplifier 123 km from the terminal station was remotely pumped with light from a 1.3-W source and residual pump light was reflected back into the amplifier with a FBG reflector [54].

**Raman-Shifted Lasers and Raman Amplifiers:** Raman-shifted lasers and Raman amplifiers enable efficient conversion of short-wavelength light into longer wavelengths suitable for long-distance fiber transmission. Raman gain is obtained through energy transfer from the pump light to the laser output or amplified signal as mediated by molecular vibrations in the silica fiber [62]. A high-power Raman-shifted pump laser was used to generate the 1485nm light used in the repeaterless experiments mentioned in the previous section. In those experiments FBG resonator mirrors enhanced the Raman amplification to convert 6 W of 1117nm light from a diode pumped Yb\(^{3+}\) cladding-pumped laser into more than 1.5W of 1485 nm. The 1117nm light was down converted through five stages of Raman gain. Having so many gratings and conversion stages requires that the grating reflectors exhibit low insertion loss (0.2dB) and low fiber loss for the Raman shifting process to be efficient.
Dispersion Compensators: Chromatic dispersion in transmission fiber can cause significant distortion of optical pulses, leading to system penalties. Upgrading existing lightwave systems to 10Gb/s channels usually requires dispersion compensators often using long lengths of dispersion-compensating fiber [63]. In the absence of optical nonlinearities, compensation is achieved by passing the distorted signal through a device whose dispersion is equal to that of the transmission fiber and of opposite sign. This compensating all-pass filter must also have sufficient optical bandwidth to accept the signal spectrum. The FBG is one such proposed filter [64]. In an idealized model, chirp in FBG dispersion compensators should be close to linear, resulting in a differential delay of reflected light. Disregarding optical nonlinearities and higher-order dispersion, the chirp is selected so that grating dispersion upon reflection cancels that of the fiber. The grating must also be long enough to ensure that the entire signal spectrum is accommodated.

Gain Equalizers: The useful optical bandwidth of amplified lightwave systems is limited because of gain-narrowing through concatenated optical amplifiers. Erbium-doped silica fiber amplifiers in particular show gain peaking at 1530 and 1560nm and the useful gain bandwidth may be reduced to less than 10nm. Pre-emphasis of the WDM channels at the transmitter increases the available bandwidth by equalizing the signal-to noise ratio of the received WDM channels, but is only suited for point-to-point systems [65]. The loss spectrum of the gain-equalizing filter must match the erbium-gain spectrum at the nominal operating condition of the amplifier. Placing a gain-equalizing filter inside the optical amplifier flattens the gain-spectrum and with appropriate design, may have minimal effect on the amplifier noise figure or saturated output power. A blazed Bragg grating has been used as a gain equalizing element, but has not led to widespread use [66].
1.8 Lightwave Applications of LPG

Long period grating which acts as wavelength dependent loss elements has many applications in both communication and sensors. Even though, LPG applications in various fields are under research, lot of R&D work is under the progress. Researchers demonstrated many applications of LPG. Following are some of LPG applications in lightwave networks already demonstrated.

**Optical filters:** An LPG band pass filter has been demonstrated by darkening the fiber core in the middle section of an LPG with a focused UV beam [67] or by insertion of a section of a hollow-core fiber between two identical LPGs [68]. Introducing \( \pi \)-phase shifts along an LPG also results in special band pass filters [69], which have found applications in actively mode-locked fiber ring lasers. LPGs can also form multi-port couplers. It has been demonstrated both theoretically and experimentally that the light energy coupled to the cladding mode can be collected by using two parallel LPGs [70-73]. The transmission spectra from the two parallel gratings are complementary to each other, one showing band rejection characteristics and the other showing band pass characteristics. The structure of two parallel LPGs thus operates as an all-fiber broadband add/drop multiplexer and has potential applications in WDM systems. Recently, a broad-band optical coupler based on three parallel identical LPGs has been demonstrated [74]. A total power transfer efficiency of 85% at the resonance wavelength has been achieved. Other implementations include placing a tapered fiber in parallel to an LPG [75] and writing an LPG in a two-core fiber with slightly different cores [76]. The structure of two cascaded LPGs has been demonstrated as a multi-channel filter for multi wavelength signal generation in WDM systems [77]. The transmission spectrum of the filter has a
sinusoidal fringe pattern with an envelope governed by the shape of the rejection band of the individual grating and the channel spacing can be controlled by changing the physical separation of the two gratings [78]. A technique of generating high-repetition-rate pulses based on cascaded LPGs has also been demonstrated [79]. When an LPG is written in a birefringent fiber, two resonance dips appear in the transmission spectrum, which correspond respectively to the two principal polarizations of the fiber. Such a grating has been used to realize a wavelength-selective fiber polarizer [80]. An extinction ratio \( > 30 \text{dB} \) and an insertion loss \( < 0.5 \text{dB} \) have been achieved. LPG polarizers have also been implemented with few-mode fibers [81]. Using the polarization-dependent spectrum of an LPG, a wavelength-switchable erbium-doped fiber ring laser has been demonstrated, where dual-wavelength operation is accomplished by rotating the polarization plane of the fiber laser cavity [82].

**Gain flatteners for optical amplifiers:** LPG filters can be considered as wavelength-selective attenuators and therefore used as gain flatteners for erbium-doped fiber amplifiers (EDFAs) [83, 84]. By careful control of the filter spectrum and fiber length, the EDFA gain has been flattened to within 1dB over 40nm while producing a noise figure below 4.0dB and an output power of nearly +15dBm [84]. Another method of achieving broad-band gain flattening is to use a phase shifted LPG [85]. To flatten a gain spectrum that contains several peaks, a compact module based on using different cladding modes of a number of concatenating LPGs has been proposed [86]. More recently, an EDFA gain spectrum flattened to within 0.35dB over 30nm has been realized by using an optimized design of step changed LPGs [87]. Other gain-flattening schemes include etching [88] and UV trimming [89] of LPGs. Dynamic
gain flattening has been demonstrated with bending of two cascaded gratings [90] or twisting of a grating [91, 92].

**Fiber coupling:** Fiber-to-fiber coupling via the cladding mode of the fiber can relax the alignment tolerances substantially [93, 94]. A lens-free fiber-to-fiber connector that has a long working distance and a wide alignment tolerance has been implemented by using two matched LPGs written in a double-cladding fiber [95]. Lateral alignment tolerances of ~450µm and ~3mm for coupling losses less than 1dB and 3dB respectively have been achieved. Laser-to-fiber coupling based on an LPG and a lens has also been demonstrated. A working distance longer than 100µm and a lateral tolerance of 2.5µm have been obtained [94]. Fiber-to-waveguide coupling has also been demonstrated with a CO₂-laser-induced LPG. [95, 96].

**Dispersion compensation:** LPGs in dispersion-tailored few-mode fibers have been employed in dispersion compensation. Higher-order mode (HOM) dispersion compensation using the LP02 mode can offer dispersion-slope matching to practically any transmission fibers [97]. An HOM fiber having a propagation loss of 0.44dB/km and a dispersion coefficient of −210ps/nm/km has been fabricated [98]. Using the HOM dispersion-compensation scheme, a 40Gb/s hybrid Raman/erbium-amplified system with a transmission distance of 1700km has been demonstrated [99]. A tunable dispersion compensator that utilizes an HOM fiber and switchable LPGs has also been made, which provides a dispersion tuning range of 435ps/nm over a bandwidth of 30nm [100].
1.9 Potable Water

Water is most fundamental building block of life. Most of us are fortunate to be living in a place where water is easily available. Most of the earth surface is covered with water, there is much more water than there is land. About 70% of the earth's surface is covered with water. Water also exists in the air as vapour and in aquifers in the soil, as groundwater. Oceans store most of the earth's water, this is apparently 97% of the total amount of water on earth, 2% of which is frozen. Of all the water on earth only 2.59% is freshwater. Of this, about 2% is trapped in ice caps and glaciers. The rest of the freshwater is either groundwater (0.592%) or readily accessible water in lakes, streams, rivers, etc. (0.014%). From the above statistics, one can conclude that less than 1% of water on earth can be used as drinking water. This includes both surface and ground water [101, 102].

Over large parts of the world, humans have inadequate access to potable water and use sources contaminated with disease vectors, pathogens or unacceptable levels of toxins or suspended solids. Drinking or using such water in food preparation leads to widespread acute and chronic illnesses and is a major cause of death and misery in many countries. Reduction of waterborne diseases is a major public health goal in developing countries.

With increasing world population and run for the high profile life, it is becoming difficult to supply safe drinking water. Industries are growing to supply the demands of population which is also the reason for the growing water difficulty. Industries demand more water and pollution will increase if the industrial effluents are not managed properly. Other factors such as fertilizer runoff and leaking from septic tanks can further contaminate water. Just because one has water source (lake, river, well or bore well) that yields plenty of water doesn't mean you can go ahead and just
take a drink. Because water is such an excellent solvent that it can contain lots of dissolved chemicals. Since, ground water moves through rocks and subsurface soil, it has a lot of opportunity to dissolve substances as it moves. For that reason, ground water will often have more dissolved substances than surface water. Even though the ground has an excellent mechanism for filtering out matter such as leaves, soil, bugs, dissolved chemicals and gases can still occur in large enough concentrations in ground water to cause problems. As ground water flows through sediments, metals such as iron, manganese, potassium, calcium, manganese, lead, cadmium, mercury, organic compounds etc are dissolved and may later be found in high concentrations in the water. If water is badly polluted (like raw sewage) it might be obvious from its appearance or odor. It might be colored or turbid (cloudy) or have solids, oil or foam floating on it. Even though water appears clean, clear and odor less it may not be fit to drink. Many harmful and beneficial materials in water are invisible and odorless. Higher concentration of these dissolved chemicals in water may cause serious health problems in human by prolonged intake. A number of chemical contaminants have been shown to cause adverse health effects in humans as a consequence of prolonged exposure through drinking-water. In water, many radicals such as iron, manganese, copper, cadmium, mercury, arsenic, lead, zinc, cyanides, fluorides etc are present in ppm / ppb level. Slight increase in the concentration of these chemicals in water may cause significant problems; even crises can occur on prolonged use of such water.

Many research and analysis were taken up in the past to recommend the minimum level of these dissolved chemicals in the drinkable water and these recommendations are known as standards of drinking water or guidelines for drinking water. Every country has its own drinking water standards based on geographical condition. World Health Organization (WHO) is universal body that regularly
releases guidelines for drinking water. The WHO Guidelines for Drinking-water Quality (GDWQ) provide a point of reference for drinking water quality regulations and standards all over the world.

Hence, regular monitoring of the water quality-level of dissolved chemicals present in the water is very important. There are many methods of analysis such as colorimetric, gravimetric, electrochemical, chromatography, mass spectrometry, etc. But to determine metal radicals present in very low concentrations (ppm level), specialized equipments are required such as atomic absorption spectrometer (AAS), inductively coupled plasma (ICP) spectrometer, flow injection method. These all instruments are laboratory based (not portable), expensive and require special technical person to handle the instrument. In AAS every elemental analysis requires respective light source (E.g. Iron source for Fe analysis). ICP spectrometer experiences lot of interference of other elements while analyzing particular one [103]. Flow injection method requires preprocessing of a test sample. To avoid all these methods, in the present work we present very simple, low cost method based on fiber grating technology. Here, we present highly sensitive fiber grating sensor to determine the concentration of manganese and nitrate present in water at ppm level. Our fiber grating sensors are sensitive, robust and reliable. Results obtained by grating sensors are confirmed by AAS and ICP methods. Later sensitivity of the sensor is enhanced by coating sensor region with gold nanoparticles synthesized in the laboratory.

1.10 Optical Fibers in Nuclear Environment

Since optical fibers and optical fiber components have excellent features such as low-loss large information capacity, compactness, low insertion loss and little
influence by electromagnetic induction compared with conventional copper cable systems, those have been applied to not only in public telecommunication, but also space applications [104], in nuclear industry [105] and in high energy physics experiments [106]. Hence, it has become essential to investigate the influence of ionizing radiation on the characteristics of optical fibers and many fiber-optic components. Radiation effects in bulk optical glasses and in optical fibers have been extensively studied in the last decades. In bulk silica glass, different effects have been seen such as radiation-induced attenuation, luminescence and refractive index changes [107-111]. Transmission loss is considered to be the most affected parameter of the optical fiber. Radiation induced changes in transmission characteristics of optical fibers depend upon type of radiation, intensity (flux), rate of flux, total exposure, optical fiber composition, wavelength of transmission etc. Radiation resistivity of various types of optical fibers was therefore noted. Numerous investigations about the resistivity and sensitivity of optical fiber are being undertaken all over the world [112]. We studied the optical properties of plastic optical fiber and silica fiber under nuclear radiation of gamma radiation emitted by Amerisium-241 and FBG characteristics under radiation emitted by Na$^{22}$ and Tl$^{204}$. 
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