CHAPTER 09

FIBER OPTIC SENSORS

INTRODUCTION: After the invention of LASER in 1960 a new branch in fiber optics developed in parallel with the communication which is also a well known and interesting topic in the field of research known as 'FIBER OPTIC SENSORS'. With the advancement in communication system via using fiber optics there was a great demand to measure and sense the rate of data transmission, change in phase, intensity, and wavelength and in the case of incentive conditions as noise, unstable environmental conditions, high vibration and extreme heat etc. These are the basic reasons for the birth of fiber optic sensors. Due to its small size, low cost and ease of fabrication leading it to replace traditional sensors which were used frequently before the birth of fiber optic sensors. Further there are many points why fiber optic sensors are used in place of traditional sensors which are listed below:

- Due to ease in fabrication in the form of different structures, including composite materials with least interference due to small size and cylindrical geometry.
- Due to its light weight.
- Due to its high sensitivity.
- Due to incapability to conduct electrical current the sensor is unaffected by electrical noise and the heat resistant type fiber units enables to detecting high temperature.
- Due to its free nature towards electromagnetic interference and radio frequency interference.
- Due to its ability towards remote sensing.
- It has also multiplexing capability to build up sensing network such as a fiber optic amplifier allows more than 100 types of special fiber units.
- It has flexibility also which enables easy installation in limited space such as space between machines.
- Extremely compact sensor head allows for easy detection of extremely small targets.
- It has a wide dynamic range.
- Due to its reliable operation.
- Due to its compact nature.
- Due to its capability to monitor a wide range of physical and chemical parameters.
- Due to its chemically inert nature.

FIBER OPTIC SENSOR PRINCIPLES: Fiber optic sensors consist of an optical source (LEDs, Lasers, Laser diodes etc.) optical fiber, sensing element (transducer), optical detector and electronic processing unit (Optical spectrum analyzer, wave analyzer, oscilloscope etc). A block diagram of fiber optic sensor system is shown in below figure

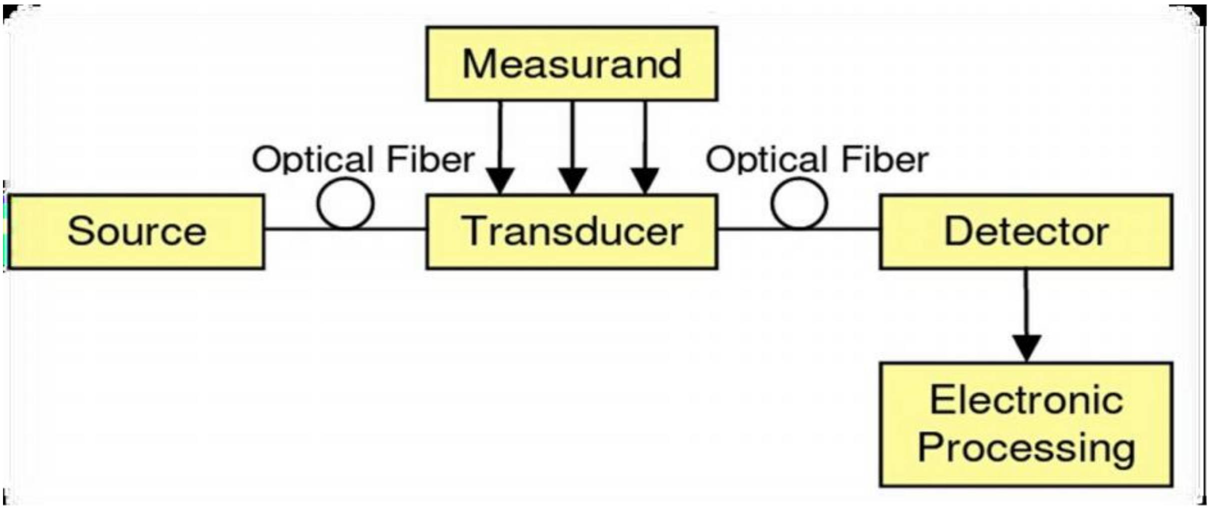


Fig: Block diagram of fiber optic sensor.

CLASSIFICATION OF FIBER OPTIC SENSORS:

Fiber optic sensors can be classified under three categories. On the basis of their

1) Sensing location.
2) Operating principle.
3) Application.

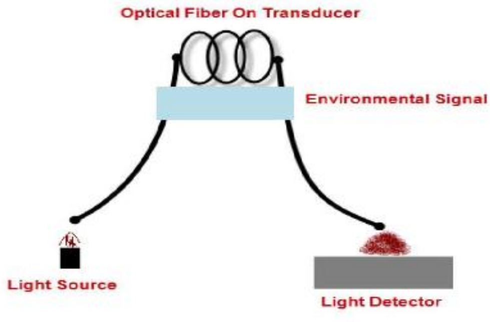
These three classes are further sub divided as following;

1) On the basis of sensing location-
(a) Intrinsic
(b) Extrinsic
2) On the basis operating principle-
(a) Based on intensity
(b) Based on phase
(c) Based on wavelength
(d) Based on polarisation
3) On the basis of their application –
(a) Physical sensor s
(b) Chemical sensors
(c) Bio-medical sensors
4) On the basis of response to the measurement point-
(a) Point to point sensors
(b) Multiplex sensors 5

(c) Distributed sensors

Each of these above mentioned classes of fibers in turns has many subclasses that consist of large number of fiber optic sensors.

INTRINSIC FIBER OPTIC SENSORS: In such type of sensors, sensing takes place within the fiber itself. These type of sensors have their dependency on the optical fiber properties itself to convert an environmental action into a modulation of the light beam passing through it. Virtually, any environmental effect can be converted to an optical signal to be interpreted .Each environmental effect may be measured by dozens of different fiber optic sensors approaches. It has been designed in such a way that it sensed only the environmental effects. • The most important characteristics of intrinsic fiber optic sensors is that it provides distributed sensing over long distances.



Intrinsic Type Fiber Optic Sensors

Some examples of intrinsic sensors are described below-

PRESSURE SENSOR:

In such type of sensors a fiber is sandwiched between a pair of toothed plates to induce micro bending .When pressure is applied to these toothed pairs, there is a redistribution of guided power between modes of fiber occurs, which changes the power at output end .Once we calibrate such change in optical power with applied pressure we can easily use such system as a pressure sensor. A schematic diagram of such type of sensor is shown below.

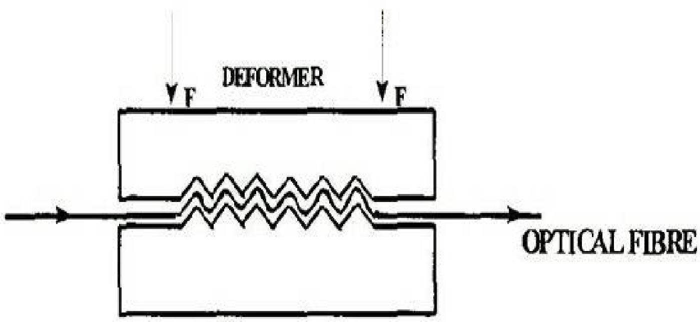
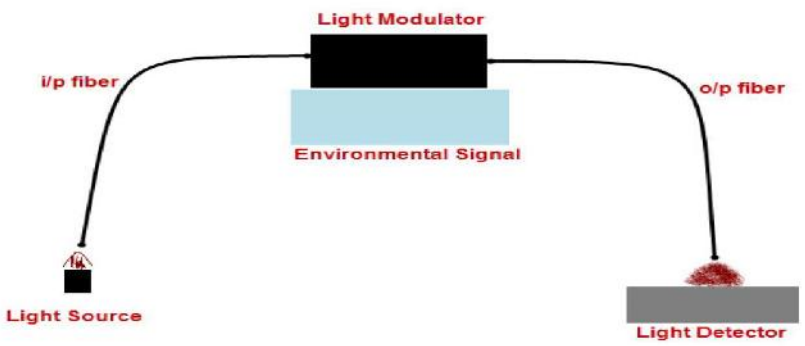


Fig: A schematic arrangement for pressure sensor

EXTRINSIC FIBER OPTIC SENSORS: In such type of sensors, sensing takes place in a region outside of the fiber and essentially fiber serves as a conduit for the to and fro transmission of light to the sensing region efficiently and in a desired form. These sensors may be used strictly as information carriers that lead up to a black box to impress information on a light beam that propagates to a remote receiver. The black box may contain mirrors, a gas or liquid cell ,a cantilevered arm or dozens of other mechanisms that may generate ,modulate or transform a light beam. The most important advantage of using these sensors is that their ability to reach places which seems to be unreachable.



Extrinsic Type Fiber optic Sensors

INTENSITY BASED FIBER OPTIC SENSORS: These type of sensors use multimode fibers having large core size. They require more light to gather into it.

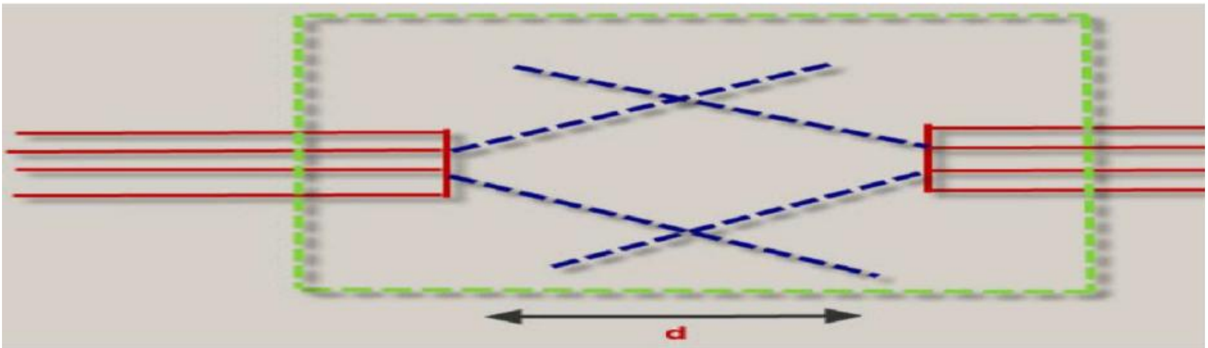


Fig: Vibration fiber optic sensor

Above fig. shows the vibration sensor that consists of two optical fibers held in close proximity to each other. When light is injected into one of the optical fiber, the light expand into a cone of light whose angle depends on their difference 'd'. These types of sensors faces many limitations regarding various losses such as losses due to connectors and splices, micro bending losses, macro bending losses and misalignment of light sources and detectors. To overcome these losses intensity based fiber optic sensors employ dual wavelength. One of the wavelengths is used for calibration of all the errors due to the undesired intensity variations by bypassing the sensing regions.

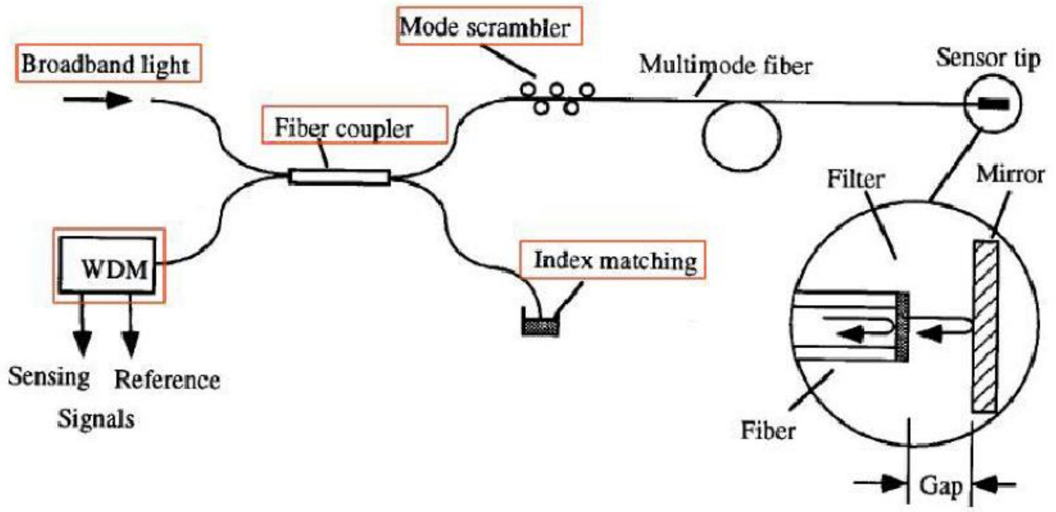


Fig: Intensity based optical fiber sensor

INTENSITY TYPE FIBER OPTIC SENSORS USING MICROBENDING: When a fiber is bent there may be losses arising due to this bending. This bending is called micro bending. Thus, the output light intensity is proportional to the amount of micro bending. Therefore, by detecting the changes of output light intensity, the micro bending can be measured so that sensor can be used proper.

INTENSITY TYPE FIBER OPTIC SENSOR USING EVANSCENT WAVE COUPLING: When light propagates along a single mode fiber , it is not totally confined to the core reason but extends into the surrounding cladding region, this phenomenon is called evanescent wave phenomenon. This phenomenon is used to fabricate fiber optic components, e.g. directional coupler. The coupling intensity between two fibers depends on the distance between the two fiber cores. When light is being launched into one of the fibers, it propagates towards the second fiber core which is placed close proximity so that the evanescent wave of the first fiber is within the region of second fiber. This makes the coupling of coupling of evanescent wave. Therefore, by monitoring the intensity change of the second fiber, the change in the environment can be sensed.

PHASE MODULATED FIBR OPTIC SENSORS: External perturbations changes the phase of the light field. This phase change could be taken into account at the time of formation of fiber optic sensors so that the detection should be made .The field which is being detected modulate the optical phase of light passing through the fiber .On comparing the phase of the light in the signal fiber to that in reference fiber one may detect the phase modulation interferometrically. The relation between the change in phase and optical path can be given by $\varphi(r,t) = (2\quad)L(r,t)$ where   is wavelength of light and L(r,t) represent the change in optical path. Since, optical wavelength is very small, a small change in optical path may cause a large change in phase. Since optical phase cannot be detected directly by the optical detectors. So interferrometric techniques are required to convert phase change into intensity change. The most commonly used interferometers are Mach-Zehnder, Michelson, Fabry Perot, Sagnac polarimetric and grating interferometers. Here, in an interferometer light is spitted into two beams where one beam is exposed to the sensing environment and undergoes a phase shift and other one is used as a reference because it is isolated from the sensing environment. Once these two separated beams recombine they interfere with each other.

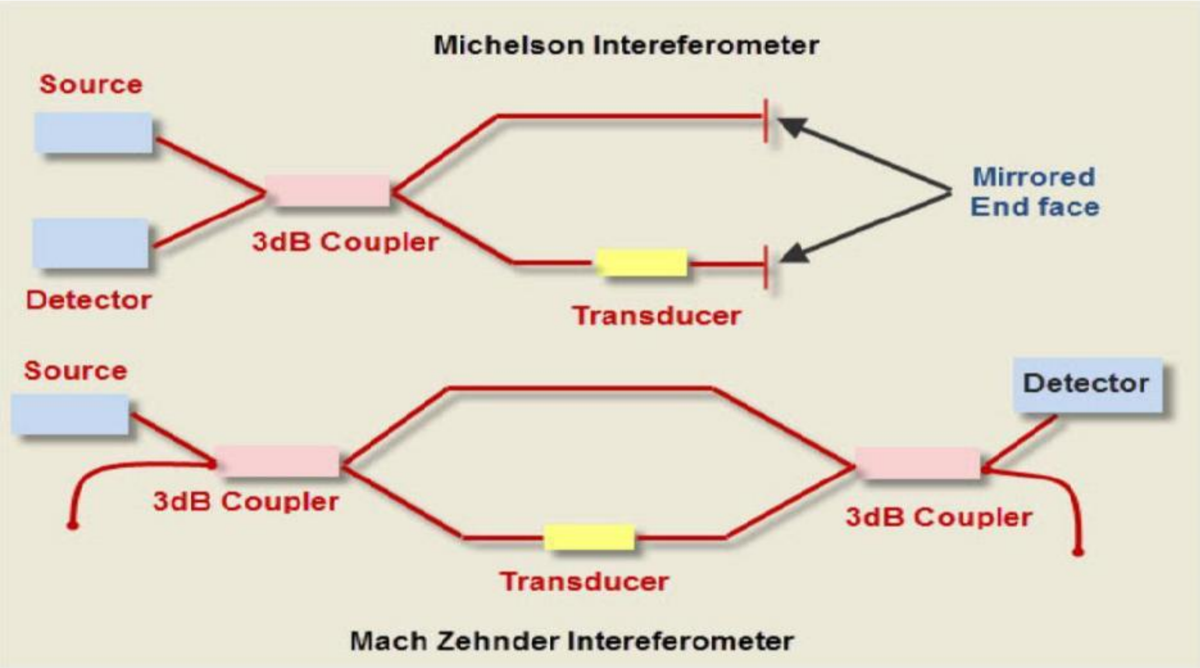


Fig: two basic phase based fiber optic sensors

FIBER OPTIC GYROSCOPE: Single mode fiber optic interferometric sensor which is finding wide scale application is the 'Fiber Gyroscope'. This device is based on the classical Sagnac ring interfrometer. The Sagnac effect, i.e. the phase shift induced between two light beams travelling in opposite direction around a fiber coil. When the coil is rotating about an axis perpendicular to the plane of the coil.

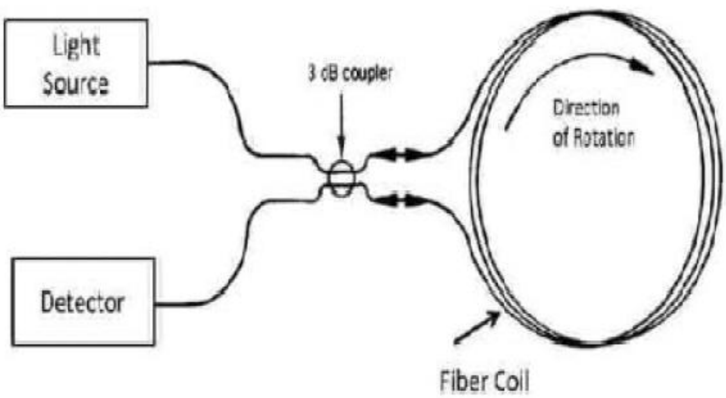


Fig: Sagnac interferometer configuration

FIBER OPTIC CURRENT SENSOR: For the measurement of direct current we use fiber optic current sensors. A single ended optical fiber around the current carrying conductor which utilizes the magneto-optic effect (Faraday Effect) is being used. FOCS measures unidirectional or bidirectional current up to 6000A within 1% of the measured value.

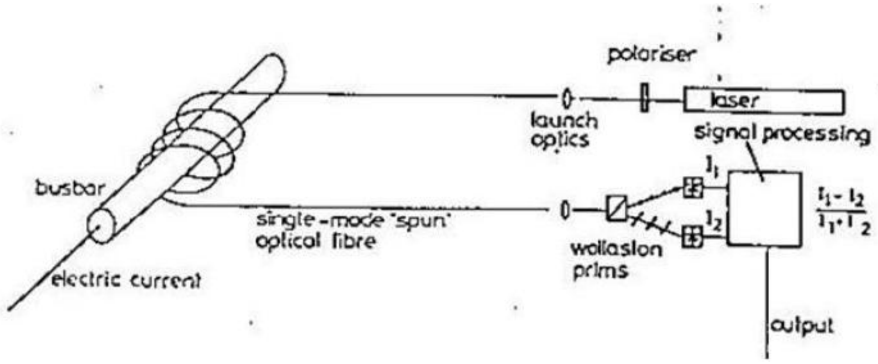


Fig: An optical fiber electrical current probe using Faraday rotation as the modulation process.

One area was such a sensor has proved valuable, is in the monitoring of large current in electricity generating stations.

WAVELENGTH MODULATED FIBER OPTIC SENSORS: Such type of sensors based on the detection of change in wavelength of light. It uses a broadband source, a wavelength modulator or measurend (i.e. analyte), a form of spectrometer (using prisms, gratings or interference filters), a detector (single photo diode or array) and signal processing unit. The sensitivity characteristics of the detector, the inherent resolution of the spectrometer, mechanical stability of the modulation unit and the spectrometer, and the capability of the signal processing unit are required in this type of sensors. Wavelength detection is relatively easy if the spectral changes results from the changes in chemical indicator dyes, fluroescence, phosphorescence or black body radiations. In these cases, the incident and emitted wavelength are far apart therefore, detection is easy. The examples of wavelength modulated sensors are fluorescence sensors, black body sensors and Bragg's grating sensors.

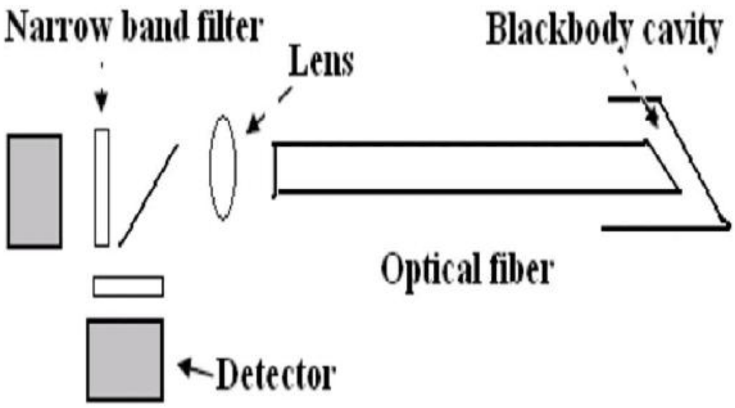


Fig: Wavelength based (black body) fiber optic sensor

The above figure shows the wavelength based fiber optic sensors i.e. black body sensor. In this sensor a black body cavity is placed at the end of an optical fiber. When the temperature rises inside the cavity it starts to glow and act as a light source. The combination of narrow band filters with detectors are then used for profile determination of black body curve .These sensors have been widely used in temperature measurement of few degree centigrade under intense R F fields. The most important characteristics of such type of sensors is high sensitivity towards temperature. Such sensors are much sensitive towards vibration hence can be used in gravitational wave detectors.

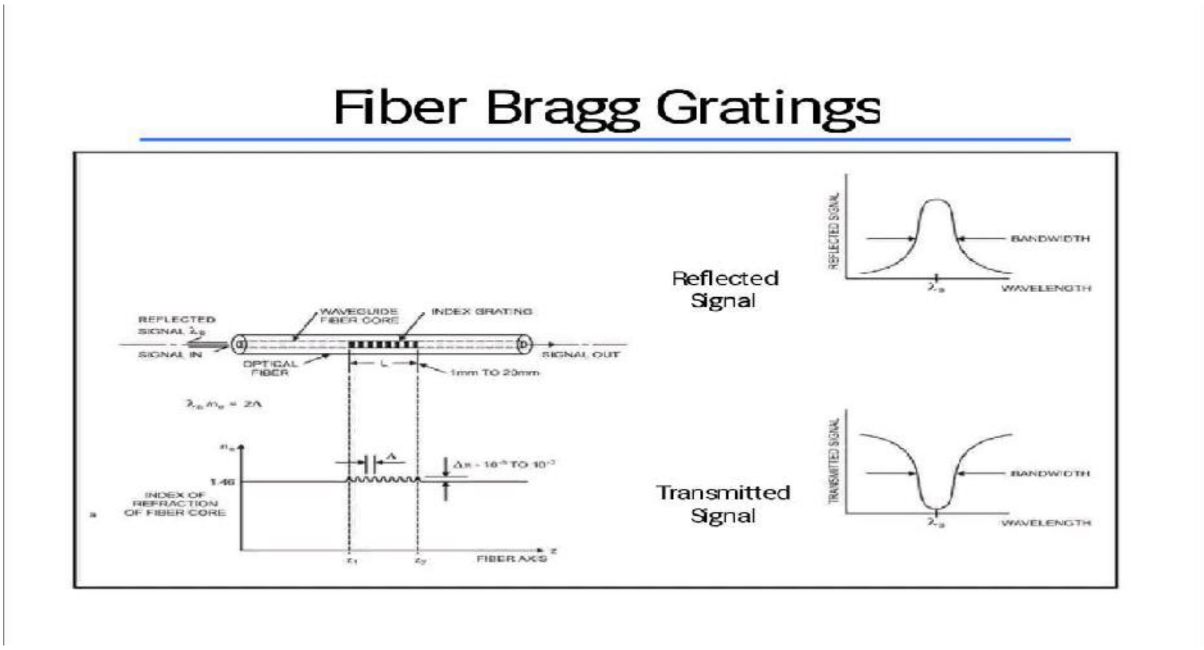


Fig: Bragg grating sensor

The above figure shows the operation of Bragg grating sensor. These are the most widely used sensors. They are formed by constructing periodic changes in refractive index of the core of a single mode fiber. In the above figure light from a broadband source (LED) is taken whose wavelength approximately close to the Bragg wavelength .The light propagates through the grating and some part of the signal is being reflected at the Bragg wavelength. The complimentary part of the process shows a small portion of signal removed from the total transmitted signal.

FREQUENCY MODULATED FIBER OPTIC SENSORS: There are very few frequency modulated fiber optic sensors. This is because of the frequency modulation of light occurs under a limited range of physical conditions .It is most importantly based on Doppler Effect. There are few other circumstances under which frequency of light is modulated. These included luminescence and Raman scattering. Vibration sensors are the optically self – resonant micro beam oscillators that are driven and sensed by a single multimode optical fiber .The fabrication of these sensors into acceleration sensitive microstructures, made the frequency of oscillator modulated by the vibration of the micro structure. By treating them as F M sources, they work as a combine temperature and vibration sensors with the average carrier frequency. This carrier frequency depends on the temperatures and F M demodulated signal provides the vibration spectra. By designing acceleration sensitive micro structure, low noise laser source and detection electronics properly, such devices provide high performance as both temperature sensors and vibration sensors. **POLARISATION MODULATED SENSORS** Polarisation modulated sensors are the most complicated and delicate instrument. It uses Faraday Effect to measure magnetic fields by measuring polarisation rotation .Special fibers and other components have been devised with specific polarisation features for e.g. Single mode fiber with special polarisation characteristics offers the possibility of producing a variety of sensors. The polarisation maintaining fiber is highly birefringent fiber, where the birefringence is the result of anisotropic thermal stress between the core and the stress producing sectors in the fiber. In a similar manner, in single polarisation fiber, one polarisation state suffers a high attenuation (50dB/Km) while others suffers a low attenuation (5dB/km). Single polarisation fiber can be used as intrinsic sensors as the birefringence change with both longitudinal strain and temperature. A Varity of physical phenomena influence the state of polarisation of light and hence introduce birefringence .The state of polarisation can also be affected by the presence of electric or magnetic field and a variety of sensors can be realised using the Faraday magneto-optic effect, the Pockels effect, the Photo elastic effect, or the optical activity of solutions. During the last few years, evolution has been made towards the enclosing of light path in optical interferometers (Michelson, Mach–Zehnder, Sagnac) so to act as compact stable elements that use phase rather than amplitude as the sensing parameter.

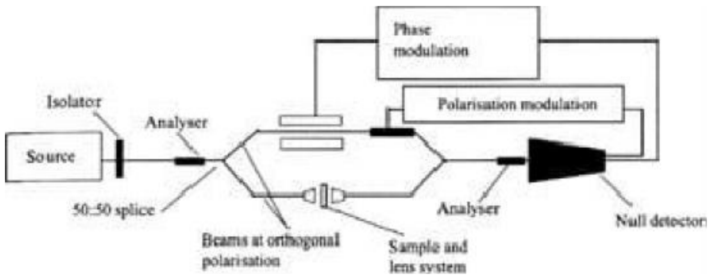


Fig: A Mach-Zehnder polarising interferometer

CHEMICAL SENSORS: Chemical sensors in used for pH measurement, gas analysis, spectroscopic studies etc. The field of application of fiber sensors in analytical chemistry greatly increased when other kind of optical spectroscopy were coupled with the fiber optic technique .As a result, sensing is no longer restricted to measure parameters that changes the transmission of a fiber, but can be extended to numerous Organic , Inorganic, clinical and Biomedical analytes which have an intrinsic colour or fluorescence for which indicators are known or which give rise to any kind of measurable change in optical system. These are referred to as extrinsic fiber sensors. Both intrinsic and extrinsic FOCS are typically used for in situ measurements. A chemical sensor is devices that can be used to measure the concentration or activity of a chemical species in a sample .It operate by transporting light by wavelength or intensity to provide information about analytes in the environment surrounding the sensors. The most commonly found fiber optic chemical sensors are- 1) Distal type probe in which the indicator is immobilised at the tip of bifurcated fiber optic bundle or single optical fiber. 2) Evanescent field type

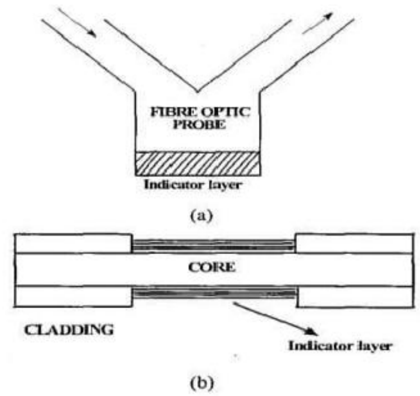


Fig: Two common fiber optic chemical sensors designs (a) Distal type probes (b) Evanescent wave type

BIOSENSORS: Biosensors are used in bio-medical application like measurement of blood flow, glucose content etc. Broad research and development activities are progressing in the area of fiber optics biosensors (FOBS). Fiber optic biosensor are divided into two – the first sensor which is based on bio catalyzed reaction and the other which is based on selecting binding reaction. The term biosensors are occasionally applied to all kind of sensors suitable for sensing biological system, for example to biomedical pH and oxygen obtrudes.

STRUCTURE OF BIOSENSOR: Bio reorganization Elements- Bio molecule (enzyme, micro-organisms, stand of DNA) produced by interaction of an analyte with an interface
•Interface – Surface of transducer immobilized bio elements.
•Transducing Elements — Electrochemical, acoustic, piezo-electrical and optical etc.

BIOSENSOR= Bio recognation molecule /Bioreceptor +Transducer

RECEPTORS: The bio receptors are given below

- Enzyme
- Tissues
- Antibody
- Cofactors
- Membranes
- DNA
- Organelles
- Peptide
- Cells
- Micro organisms

TRANSDUCERS: Transducers are of two types

1) Chemical
2) Physical

• Transformation • Electrochemical
• Coupling • Amperometric
• Potentiometric
• Conductiometric
• Piezo-electric
• Colormetric
• Acoustic
• Optical

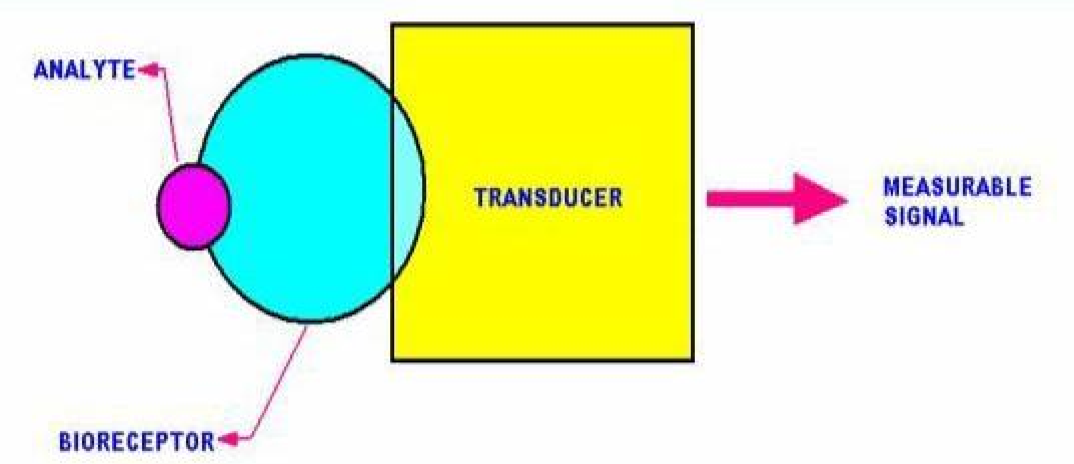


Fig: Block diagram of bio-sensor

for bio catalytic biosensors, an isolated enzyme is immobilized within the sensing region of an optical fiber .The selective bio catalytic reaction is catalyzed as the analyse approaches the immobilized enzyme and a product of this reaction is monitored through fiber optic probe.

FOBS have been developed for the detection of NH_3, C, dioxide, oxygen, hydrogen, peroxide etc.

CLASSIFICATION SCHEME FOR OPTICAL CHEMICAL SENSORS AND BIO- SENSORS **SENSOR TYPE**	**CHEMICAL SENSORS**	**BIO-SENSORS**
1st generation	Remote spectrometer for on-line monitoring of chemical species.	Remote monitoring of co-enzyme fluorescence.
2nd generation	Fiber sensors based on immobilized indicators.	Fiber sensors based on immobilized bio probes.
3rd generation	2nd generation sensor coupled to enzymatic reactions.	2nd generation sensor coupled to enzymatic reactions.

APPLICATIONS OF FIBER OPTIC SENSORS: There are various applications of fiber optic sensors, few of which are listed below-

- Application to high temperature sensing.
- Application to crack monitoring.
- Application to cable and FRP (fiber reinforced polymer) monitoring.
- Application to bridge monitoring.
- Application to moisture monitoring.
- Application to welding residual monitoring.
- Application to high current measurement.
- Application to high pressure sensing.
- Application to measuring small vibrations.
- Application in the oil and gas industry.
- Application to monitoring pipe lines.
- Application in medicine.
- Application to load monitoring of power transmission line.

CONCLUSION: On the basis of above brief description it can be concluded that fiber optic sensors can be used for accuracy of structure and determination of quantity parameters. In general fiber optic sensors shows high accuracy in average strain, stress, temperature measurement at several places. Fiber optic sensors are flexible, and small in size hence they can be installed in internal components in any device. Here an overview of fiber optic sensors and their applications has been given briefly. Few of them have been discussed in detail. On seeing above detail it can be concluded that fiber optic sensors will undoubtedly have a role to play with in structural monitoring context where much of the research and development effort have been focused.

Multiple Choice Questions:

1. Optical fiber sensors are electrically _____
   a) active
   b) passive
   c) active as well as passive
   d) cannot be determined
   Answer: b
   Explanation: Optical fiber sensors are electrically passive and consequently immune to electromagnetic disturbances. They are geometrically flexible and corrosion resistant. They can be miniaturized and are most suitable for telemetry applications.
2. Optical fibers are not immune to ________
   a) electronic disturbances
   b) magnetic disturbances
   c) ambient light interference
   d) electromagnetic disturbances
   Answer: c
   Explanation: Optical fibre sensors are non-electrical and hence are free from electrical interference usually associated with electronically based sensors. Ambient light can interfere. Consequently the sensor has to be applied in a dark environment or must be optically isolated.
3. Optical fiber sensors are not immune to electromagnetic disturbances.
   a) True
   b) False
   Answer: b
   Explanation: Optical fiber sensors are electrically passive and consequently immune to electromagnetic disturbances. They are geometrically flexible and corrosion resistant. They can be miniaturized and are most suitable for telemetry applications.

4. In which of the following optic fiber sensor the fiber is simply used to carry light to and from an external optical device where the sensing takes place?
   a) extrinsic fiber optic sensor
   b) energized fiber optic sensor

c) all fibers are used to simply carry light to and from the external optical devices
d) intrinsic fiber optic sensor
Answer: a
Explanation: In an extrinsic fiber optic sensor fiber is simply used to carry light to and from an external optical device where the sensing takes place. In intrinsic fiber optic sensor one or more of the physical properties of the fiber undergo a change.

5. On the bases of application of optic fiber sensor, which of the following is not considered to be the classification of fiber optic sensor?
a) biomedical/photometric sensors
b) physical sensors
c) thermal sensors
d) chemical sensors
Answer: c
Explanation: The variations in the returning light are sensed using a photodetector. Such sensors monitor variations either in the amplitude or frequency of the reflected light. Two of the most important physical parameters that can be advantageously measured using fibre optics are temperature and pressure.
6. Linear encoders gives ____________ output.
a) angular
b) analog
c) digital
d) unstable
Answer: b
Explanation: Linear encoders give output in digital form. These transducers are basically encoded disks or rulers with digital pattern photographically etched on glass plate. These patterns are decoded using a light source and an array of photodetectors.
7. The type of sensor that detects the analyte species directly through their characteristic spectral properties is called
a) chemical sensor
b) thermal sensor
c) light sensor
d) Spectroscopic Sensors
Answer: d

Explanation: Spectroscopic Sensors is the one that detects the analyte species directly through their characteristic spectral properties. In these sensors, the optical fibre functions only as a light guide, conveying light from the source to the sampling area and from the sample to the detector. Here, the light interacts with the species being sensed.

8. How many coils are required to make LVDT
   a) 4
   b) 6
   c) 3
   d) 2
   Answer: c
   Explanation: Total 3 coils are required in LVDT. One centered coil which is the energizing or primary coil connected to the sine wave oscillator. The other two coils are the secondary coils so connected that their outputs are equal in magnitude but opposite in phase.
9. A chemical transduction system is interfaced to the optical fibre at its end. This type of sensor is called ?
   a) chemical sensor
   b) thermal sensor
   c) photoelectric sensor
   d) light sensor
   Answer: a
   Explanation: In the chemical sensors, a chemical transduction system is interfaced to the optical fibre at its end. In operation, interaction with analyte leads to a change in optical properties of the reagent phase, which is probed and detected through the fibre optic. The optical property measured can be absorbance, reflectance or luminescence.
10. Which of the following is a displacement transducer?
   a) thermistor
   b) lvdt
   c) strain gauge
   d) thermocouple
   Answer: b
   Explanation: LVDT is a displacement transducer. Thermocouple and thermistor are temperature transducers. Strain gauge is a pressure transducer.
11. Change in output of sensor with change in input is

(a) Slew rate
(b) Threshold
(c) Sensitivity
(d) None of the above

Answer: d

Explanation: Sensitivity is the change in output for a change in input.

12. Which of the following is correct for tactile sensors?
(a) Pressure sensitive
(b) Touch sensitive
(c) Input voltage sensitive
(d) Humidity sensitive

Answer:b

Explanation: Tactile sensors are those which sensitive to touching

13. Which of the following error is caused by reversal of measured property
(a) Noise
(b) Quantization error
(c) Hysterisis
(d) Digitization error

Answer:c

Explanation: Hysterisis error is caused by reversal of measured value

14. Which of the following is not a analog sensor
(a) Potentiometer
(b) Force sensing resistors
(c) Accelerometer
(d) None of the above

Answer:d

Explanation: All the mentioned devices are analog sensors

15. Sensitivity of a sensor can be depicted by
(a) Bode Plot
(b) Niquist Plot
(c) Pole-Zero plot
(d) None of the above

Answer: a

Explanation: Bode Plot can e used for describing sensitivity of a sensor.

16. Sensor is a type of transducer
(a) True
(b) Flase

Answer: a

Explanation: Sensor is a device which enable measurement of input value

17. Measured property have no relation with error

(a) True

(b) Flase

Answer: a

Explanation: Error of a system is independent of measured value.

18. Thermocouple generate output voltage according to

(a) Temperature

(b) Voltage

(c) Circuit parameters

(d) Humidity

Answer: a

Explanation: Thermocouple is a device which are cabable of producing output voltage according to input temperature.

19. Smallest change which a sensor can detect is

(a) Accuracy

(b) Scale

(c) Precision

(d) Resolution

Answer: d

Explanation: Resolution is the smallest change a sensor can detect.

Questions:

Q1. What is the difference between active and passive fibre optic sensor?

Q2. How do fiber optic sensors work?

Q3. What are the applications of optical fiber?

Q4. What are optical sensors used for?

Q5. How do fiber optic pressure sensors work?