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. Fiber optic sensors have advanced to an extent that they can be readily made use of in many applications. The different types of fiber optic sensors, components used in optical fiber sensing, sensor design and analysis, distributed\ multiplexed sensor schemes and the role of integrated optics are highlighted.

1. INTRODUCTION

With the advent of lasers and semiconductor optoelectronics, a great revolution in modern optics took place. Rapid developments in fiber 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 realm of 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 fiber 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 developments 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 fiber optic sensors and photonic communication and control schemes. In smart structure applications, composite materials, fiber optic sensing and telemetry systems, piezoelectric actuators and microprocessor based control schemes seem to offer the best advantages as of now.

2. FIBER OPTIC SENSORS

The technology and applications of optical fibers have progressed very rapidly in recent years. Optical fiber, 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 fiber 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 fiber is already modulated, while in sensing, the fiber 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 fiber 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 fiber 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 fibers can withstand high temperature and other harsh environments. In telemetry and remote sensing applications it is possible to use a segment of the fiber as a sensor gauge while a long length of the same or another fiber 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 fiber elements thus enabling the realization of an all-fiber 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 fiber optic sensors. These can be classified as follows.

A) Based on the modulation and demodulation process a sensor can be called as an 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 interferometeric 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) Fiber 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 is another classification scheme. In the former, sensing takes place in a region outside of the fiber and the fiber essentially serves as a conduit for the to-and-fro transmission of light to the sensing region efficiently and in a desired form. On the other hand, in an intrinsic sensor one or more of the physical properties of the fiber undergo a change as mentioned in A) above.

3. BASIC COMPONENTS

A fiber optic sensor in general will consist of a source of light, a length of sensing (and transmission) fiber, a photodetector, demodulator, processing and display optics and the required electronics.

3.1 **Optical fibers:**

These are thin, long cylindrical structures which support light propagation through total internal reflection. An optical fiber consists of an inner core and an outer cladding typically made of silica glass, although, other materials like plastics are some times used. Three types of fibers are in common use in FOS. The multimode (MM) fiber consists of a core region whose diameter (~50 m 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 fibers have a step index profile and a core size of about 1mm. The microbend type or the evanescent type intensity sensors use MM fibers. MM fiber 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) fiber 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, l is the wavelength, *a* is the core radius, and n_1 and n_2 are the core and cladding refractive indices, respectively. When V < 2.405 single mode condition is ensured. SM fiber is an essential requirement for interferometric sensors. Due to the small core size (~4 m *m*) alignment becomes a critical factor.

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

4. 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 fiber. For this class of sensors a normalized modulation index (m) can be defined as

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

where, D 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 (measurand).

The sensor response expressed as a differential voltage per unit change in measurand 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.

The minimum measurable quantity in the shot noise limit is given by where e = electronic charge and B=detection bandwidth.

4.2 Microbend Sensor

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

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

Fig.1 Microbend sensor

It is designed using multimode fiber of a few meters in length which is placed between two rigid plates having an optimum corrugation profile such that the fiber 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 fiber. 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 fiber core. The use of microbend sensors in some smart structure applications is explained in a later section.

4.3 Interferometric sensors

An interferometric sensor is based on the detection of changes in the phase of light emerging out of a single mode fiber. In the case of a fiber the phase change in general is given by,

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

where the three phase terms on the RHS are due to the length, the index and the guide geometry variations, respectively. 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 fibers, 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 fiber optic sensors are by far the most commonly used sensors since they offer the best performance. They have found application as acoustic (e.g. hydrophones), rotation (eg., gyroscope), strain, temperature, chemical , biological and a host of other types of sensors.

The phase change of light propagating through a fiber of length *l* and propagation constant b = *ko n*, is given by

$$\phi = \beta l = k_o n l$$

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

$$\Delta\phi = \beta\Delta l + l\Delta\beta = \beta\Delta l + l[k_o \Delta n + \frac{\delta\beta}{\delta a}\Delta a]$$

where n = refractive index, and a = radius of the fiber. The change in b , due to radius variations is very small and can be neglected. The change in refractive index can be obtained from the the index variation due to photoelastic effect as,

$$\Delta\left(\frac{1}{n^2}\right)_{ij} = \sum_{i,j} P_{ijhl} \varepsilon_{hl}$$

where p_{ijhl} is the photoelastic tensor and e_{hl} is the strain. In the case of an optical fiber made of isotropic glass there are only two independent photoelastic constants p_{11} and p_{12}.

$$\varepsilon_z = \frac{\Delta l}{l} \text{ and } \varepsilon_x = \varepsilon_y = \frac{\Delta r}{r} = \varepsilon_r$$

Let

$$\frac{\Delta\phi}{\phi} = \varepsilon_z - \frac{n^2}{2}[(p_{11} + p_{12})\varepsilon_r + p_{12}\varepsilon_z]$$

Combining the above,

The above analysis can be generalized and extended to obtain the induced phase changes in an optical fiber due to pressure, temperature or strain variations. The normalized phase changes are as given below.

In an optical interferometer the reference and phase modulated light are combined and detected using a photodetector. One obtains an interference equation which has a sinusoidal dependence. A fixed phase bias of p /2 is introduced in the reference arm with the help of a piezoelectric modulator so that the output variation is linear. The current output from the detector is given by,

$$\frac{\Delta\phi}{L} = \frac{2\pi}{\lambda_0}\left[\left(n + \frac{\lambda_0 a}{2\pi}\frac{\partial\beta}{\partial a}\right)\alpha + \frac{\partial n}{\partial T}\right]\Delta T$$

The photon noise current associated with this detection is

$$\frac{\Delta\phi}{L} = \frac{2\pi n}{\lambda_0}\left[1 - \frac{n^2}{2}\left\{p_{12} - \mu(p_{11} - p_{12})\right\} - \frac{\lambda_0 \mu}{2\pi n}\frac{\partial\beta}{\partial a}\right]S$$

$$\frac{\partial\beta}{\partial a}$$

Signal to noise ratio,

The minimum detectable pressure is found by setting SNR = 1. Hence *Pmin* is obtained as

$$i_s = I_o\frac{qe}{h\nu}\Delta\phi = \left(\frac{I_o qe}{h\nu}\right)\left(\frac{d\phi}{dP}\right)(\Delta P)$$

where *h* = Plank's constant, *n* = optical frequency, B = detection bandwidth and *q* = quantum efficiency.

The limiting sensitivities (ie., minimum detectable change in pressure etc.) thus depends on the desired SNR. If we assume that a phase change of one microradian is the detection limit due to quantum noise limit then the detection thresholds (per unit length of fiber) for pressure, temperature and strain are approximately , 10-7 bar, 10-8 degree C and 10-7 strain, respectively. These numbers indicate that the fiber optic interferometric sensors are very sensitive and therefore these need careful packaging and handling if they are to be exploited in practical applications.

4.4 Mach- Zehnder interferometric sensor

A fiber optic Mach-Zehnder interferometric sensor consists of two 3-dB couplers (beam divider/ combiner) and two lengths of fiber, one serving as a sensing arm and the other as a reference arm as shown in Fig.2. For purposes of applying a fixed phase bias a piezo modulator is some times included in the reference arm. Perturbations due strain or temperature changes induce a phase shift and is detected as an intesity variation by the photo detector.

$$i_N^2 = 2e\left(\frac{I_o qe}{h\nu}\right)B$$

Fig.2 Mach-Zehnder interferometer

4.5 Sagnac interferometer (fiber optic gyroscope)

While mechanical gyros work on the principle of Newton's laws of motion, it is a different phenomenon in the case of an optical gyro. Here interferometry plays a major role in the form of Sagnac effect. Essentially, the Sagnac principle is a phase modulation technique and can be explained as follows:

Two counter propagating beams, (one clockwise, CW, and another counterclockwise, CCW) arising from the same source, propagate inside an interferometer along the same closed path. At the output of the interferometer the CW and CCW beams interfere to produce a fringe pattern which shifts if a rotation rate is applied along an axis perpendicular to the plane of the path of the beam. Thus, the CW and CCW beams experience a relative phase difference which is proportional to the rotation rate. Consider a hypothetical interferometer, with a circular path of radius R as shown in fig. 3.

$$\mathrm{SNR} = \frac{i_s^2}{i_N^2}$$

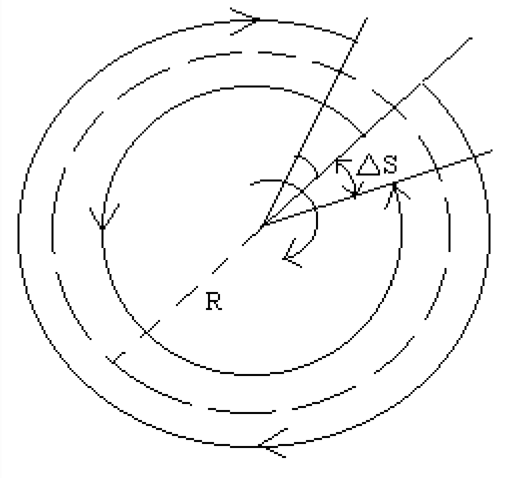
Fig 3. Sagnac Interferometer principle.

$$P_{\min} = \left(\frac{2h\nu B}{I_o q}\right)^{1/2} \left(\frac{d\phi}{dP}\right)^{-1}$$

When the interferometer is stationary, the CW and CCW propagating beams recombine after a time period given by,

where *R* is the radius of the closed path and *c* is the velocity of light. But, if the interferometer is set into rotation with an angular velocity, W rad/sec about an axis passing through the centre and normal to the plane of the interferometer, the beams re-encounter the beam splitter at different times.

The CW propagating beam traverses a path length slightly greater (by D s) than 2p *R* to complete one round trip. The CCW propagating beam traverses a path length slightly lesser than 2p *R* in one round trip. If the time taken for CW and CCW trips are designated as *T*+ and *T*-, then,



The difference yields

$$T = \frac{2\pi R}{c}$$

With the consideration that, *c2* > > (*RW*)2,

$$\Delta T = (T_{+} - T_{-}) = \frac{4\pi R^2 \Omega}{c^2 - (R\Omega)^2}$$

The round trip optical path difference is given by

$$\Delta T = \frac{4\pi R^2 \Omega}{c^2}$$

and the phase difference is given by

$$\Delta L = \frac{4\pi R^2 \Omega}{c}$$

or more generally

$$\Delta \phi = \frac{8\pi^2 R^2 \Omega}{c\lambda}$$

where *A* = area of the enclosed loop.

If the closed path consists of many turns of fiber, D f is given by, where N = number of turns of fiber, each of radius R, and L = total length of the fiber.

Sagnac effect can also be arrived at by using the frequency shift approach, particularly in case of resonating gyros. The CW and CCW ring laser modes have different frequencies due to difference in effective round trip optical path lengths caused by cavity rotation.

Oscillations having wavelengths which fulfill the resonance condition

$$\Delta\phi = \frac{4\pi LR\Omega}{c\lambda} = \frac{8\pi^2 R^2 N\Omega}{c\lambda}$$

can be sustained in the cavity. As a general case, the Sagnac frequency shift is given by,

$$\Delta f = \frac{4A\Omega}{P\lambda}$$

where A= the area enclosed and P = perimeter of the light path.

If we take l = 0.85 *mm*, L = 200 m and D = 3 cm, we find that the Sagnac phase shift is p radians for a rotation rate of 1200o/s. To detect earth's rotation rate (15o/hour) we need therefore a detection capability of about 10 microradian phase shift. The constant phase shift introduced in a fiber of 200 m is of the order of 1010 rad. Thus the CW and CCW beams between which a small Sagnac phase shift due to rotation is to be sensed must traverse identical paths to an accuracy of about 1 in 1015 so that the reciprocity condition (i.e., no phase shift in the absence of rotation) is fulfilled. As in any interferometer, the detection limit of gyro is set by photon shot noise. If a 10 mW optical power is received at the detector, a noise equivalent phase shift of about 10-7 rad/ Ö Hz can be sensed or an equivalent rotation rate of about 1o/hr/Ö Hz can be detected.

A minimum configuration fiber optic gyro which ensures perfect reciprocity is shown in fig.4.

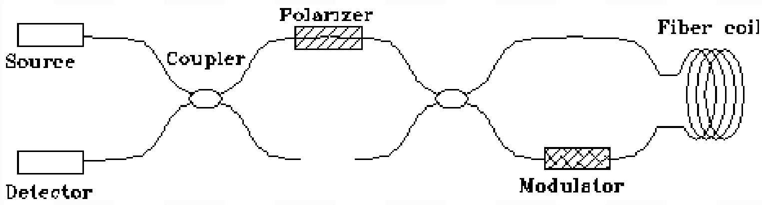


Fig 4. Minimum configuration fiber optic gyro.

4.6 Fiber Optic Polarimeter

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

The birefringence property arising from optical anisotropy is used in the study of photoelastic behaviour . The anisotropy may be due to naturally occuring crystalline properties or due to stress induced birefringence. It is the latter that is used in a photoelastic fiber optic strain gauge. In a simple setup two lead fibers 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

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

where I_0 is the total light intensity and q 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 a given by

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

where l 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 fa= (l \C) is known as material fringe value. When the polarisers are oriented 45^0 w.r.t. principal stress directions equations (28) and (29) simplify to

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

with a = (2p /fa) s d where the applied load is assumed to produce a uniaxial stress . By taking the derivative of the above equation we obtain

This has a maximum sensitivity when a =p / 2 (quadrature condition) . Under this condition (D I / I 0) / D Î = p E d/fa , where E is the elastic modulus and Î is the strain in the direction of applied load . The photo-detector output which is expressed in terms of voltage sensitivity can be written as

It may be noted that in this case the fiber only serves as a light conduit and the set up described above is basically same as the conventional bulk optic polariscope .

5. DISTRIBUTED SENSORS

In some applications there may be a need for multisensor systems. Such a system can be realized in a number of ways. One way is to arrange a set of discrete (point) sensors in a network or array configuration, with individual sensor outputs multiplexed using time division multiplexing (TDM) or frequency division multiplexing (FDM) or such other scheme. Alternatively, it is more interesting to exploit the inherent ability of the fiber sensors to create unique forms of distributed sensing. For example, optical time domain reflectometry (OTDR) and distributed Bragg grating sensors are two such schemes in common use (fig.5). In smart structure design and application these sensors play an important role.

There are number of methods for producing intra core gratings in a single mode fiber as used in distributed Bragg grating sensors. These include side writing techniques such as exposure to UV laser radiation from an Excimer laser . Such exposures could be in the form of two beam interference (holography) or exposure to a face mask or point by point exposure . These methods are time consuming and suitable for single element strain sensors . In the case of distributed strain sensors on-line fabrication of arrays of FBG is desirable . A scheme utilizing a polarised Ti sapphire laser for this purpose has been reported.

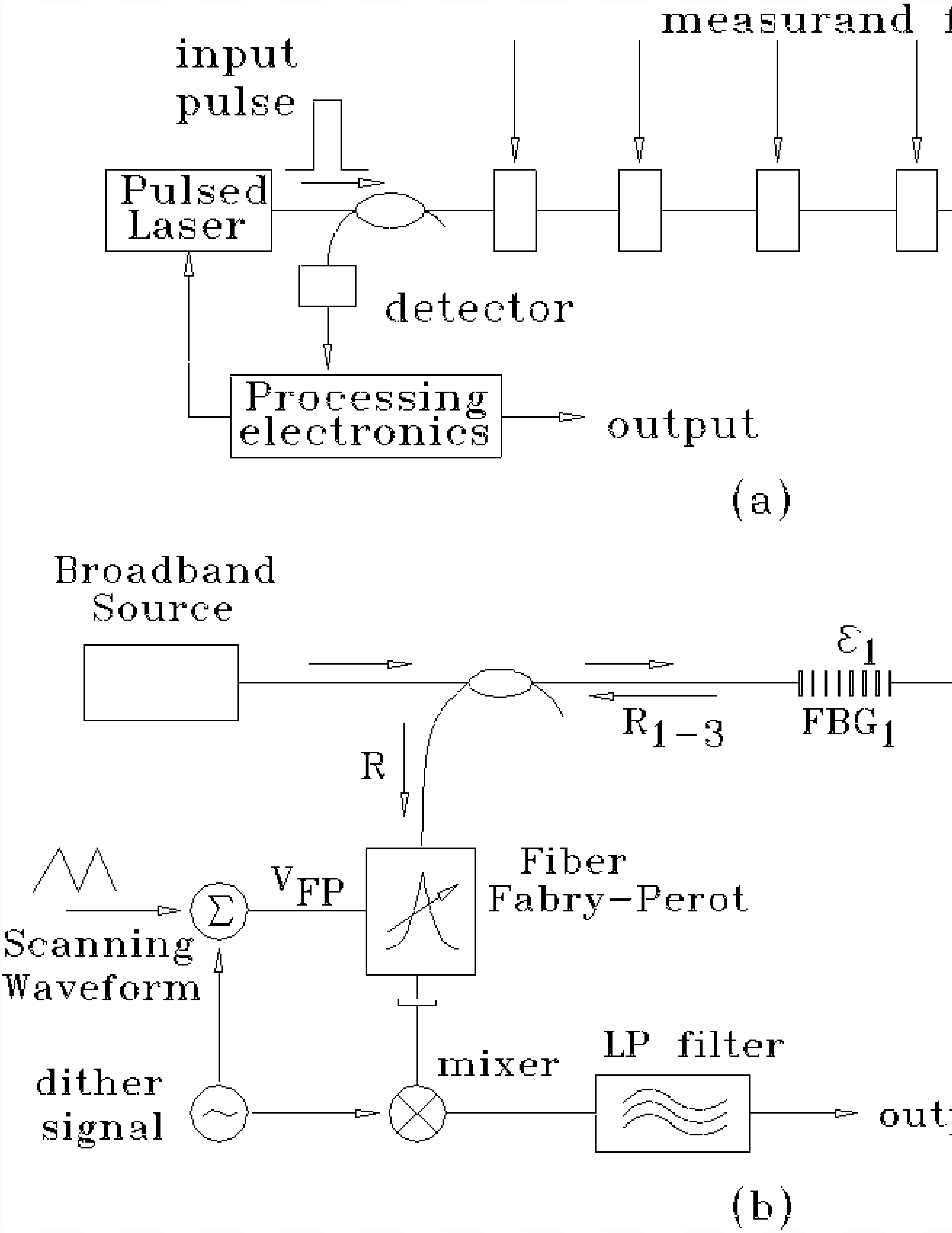


Fig 5. Multiplexed sensor arrays using (a) OTDR and (b) WDM / Bragg grating principles.

6. ROLE OF INTEGRATED OPTICS

In optical fiber sensing, in some configurations such as interferometric sensors or gyroscope there is requirement of several (functional) optical components such as modulator, coupler, polarizer etc., for effective signal handling and analysis. Such components can be realized in bulk-optic, integrated-optic or all-fiber-optic form. Integrated optics (IO) combines thin-film and micro fabrication techniques to make optical wave guides and devices in planar form and offers the advantages of compactness, power efficiency and multi-function in single chip capabilities. For example, the couplers, polarizer and phase modulator required in the case of a fiber-optic gyroscope can easily be realized as a single chip on lithium niobate as shown in fig.6. The device consists of a branching waveguide as a coupler and a pair of electrodes on one of the straight arms. Application of a small voltage can bring about a phase modulation via the electrooptic effect. When a process known as proton exchange is used the waveguide thus made supports one polarisation only. The whole chip can be made on a wafer of a few mm in size. Similarly various types of modulators useful in Mach-Zehnder type sensors can also be made in IO form. When IO devices are made on semiconducting substrates like GaAs or InP, complete integration of both optical and electronic components is feasible.

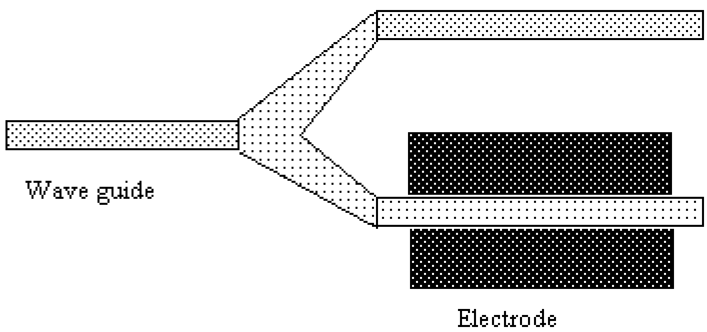


Fig.6 Integrated optic chip for gyro

Electron devices have evolved in stages from electron tubes to transistors to ICs. Currently in microelectronics very small device dimensions and very large package densities are commonly realized. A similar advance is essential in photonics if optical systems are to be competitive and compact in comparison to electronic systems. In other words miniaturized optical components integrated on a *chip* will greatly enhance the application potential of photonics. In IO it is visualized that thin films and microfabrication technologies can suitably be adopted to realize optical counterparts of integrated electronics for generation, modulation, switching, multiplexing, processing and such other optical functions in IO form.

In Integrated Optic circuits (Photonic circuits) light is confined in thin film waveguides that are deposited on the surface or buried inside a substrate. Such waveguides may be planar, channel, branching or coupled waveguides. Glasses, dielectric crystals and semiconductors can be used as substrate materials. However the type and variety of functions that can be realized in photonic circuits and systems (PCS) depend very much on whether or not the substrate is semiconducting , electrooptic, acoustooptic, nonlinear optic etc.

The advantages of IO elements over their bulk optic counterparts are: compact size, protection from thermal drift, moisture and vibration, low power requirements and low cost due to the possibility of batch fabrication. The realization of these factors led to the fabrication of several passive devices like thin film lenses, prisms, polarizers and beam splitters as well as active elements like sources and detectors in integrated optic form in the beginning. Currently more advanced and completely functional photonic circuits such as spectrum analyser, coherent receiver etc., are also being developed.

The most fundamental building block of an IO circuit is a waveguide. Other basic devices and circuits are lasers, modulators, polarizers, directional couplers etc., which are to be made on a planar substrate using standard lithographic process and thin film technology. Electron beam writing and laser beam writing are increasingly employed for device patterning purposes to achieve high resolution and long lengths.

Within the IO circuits, light propagates as guided waves in dielectric thin films. Appropriate addition of functional devices between interconnecting waveguides enables the realization of an IOC for a specific use. It is obvious that thin film techniques and semiconductor technology play a dominant role in the development of photonic circuits and systems.

The basic requirements of a thin film optical guide material are that it be transparent to the wavelength of interest and that it have a refractive index higher than that of the medium in which it is embedded. Usually, a layer of film on top of a substrate (of lower index) serves as the guide. The top of the film is generally air. Such thin film guides can easily be formed by RF sputtering, evaporation, polymerization, diffusion, epitaxy and ion implantation methods .

Epitaxial methods, well known in semiconductor device technology are used in the fabrication of sources, detectors and optoelectronic circuits on GaAs, Si and InP. Similarly the electro-optic, magneto-optic and acousto-optic phenomena and materials enable the fabrication of modulators, switches, directional couplers, etc. Table-6.1 gives some of the important materials, properties and process technologies.

There are several ways by which waveguides and devices in IO form can be realized. The type of material chosen more or less decides the process technology to be employed. In the case of glass, wet and dry ion exchange techniques are commonly used for fabricating mostly passive IO components such as splitter/combiners. Polymer waveguides on glass and other substrates, on the other hand, are formed by spin or dip coating. While this process is simple, precise thickness and uniformity control are difficult. Plasma polymerization and Langmuir Blodgett method of formation are other techniques used in the case of polymers. The most popular material for IO, LiNbO3 , can be processed either using metal in-diffusion (usually titanium) or by proton exchange in weak acids. Epitaxial methods (LPE, MBE, MOCVD) are appropriate for the growth of crystalline layers and quantum well structures in semiconductors. Amorphous layers on silicon is also useful in certain passive component development such as grating and channel waveguides in sensing and communication applications.

Table 6.1. Materials and processes for integrated optics

Substrate	Guiding layer	Fabrication process	Properties
Glass or fused	a)Various glasses	Sputtering or e-beam evaporation	Amorphous & polycrystalline

quartz	b)Ta2O5 c)Nb2O5 d)Polymers	Solution deposition	films; more lossy; not amenable to AO,EO &NLO interactions
Glass	Mixed metal oxide layers	Ion migration &ion exchange; chemical etching	Low cost & easy fabrication 3-D guides by etching
LiNbO 3 or LiTaO3	Metal oxide layers	Ti-indiffusion or Proton exchange	Low loss & excellent AO,EO and NLO properties
GaAs or InP	Ga1-xAlxAs Ga1-xInxAs1-yPy	LPE.VPE,MBE and MOCVD	Optoelectronic integration;OEIC etc
Quartz crystal	Metal oxides	Ion implantation	Leaves damage/defects

In channel optical waveguides, light is confined in the film not only across its thickness but also across its lateral direction. To realize this, the waveguide in its cross section should be surrounded in all the directions by media having lower indices of refraction. For the raised or buried type channel waveguide, transverse confinement in both the x and y directions is possible because there exists a high refractive index core region which is completely surrounded by regions of lower refractive indices. Thus, in terms of total internal reflection concept, guidance can be considered to be the result of rays which propagate within the high refractive index region, suffering total internal reflection at the boundary interfaces with the media of lower refractive indices.

A LiNbO3 phase modulator consists of a titanium diffused monomode channel waveguide and a pair of oriented electrodes (Fig.7). Through application of an electrical voltage to the electrodes, the refractive index of the waveguide and hence the phase of the optical signal passing through it can be altered.

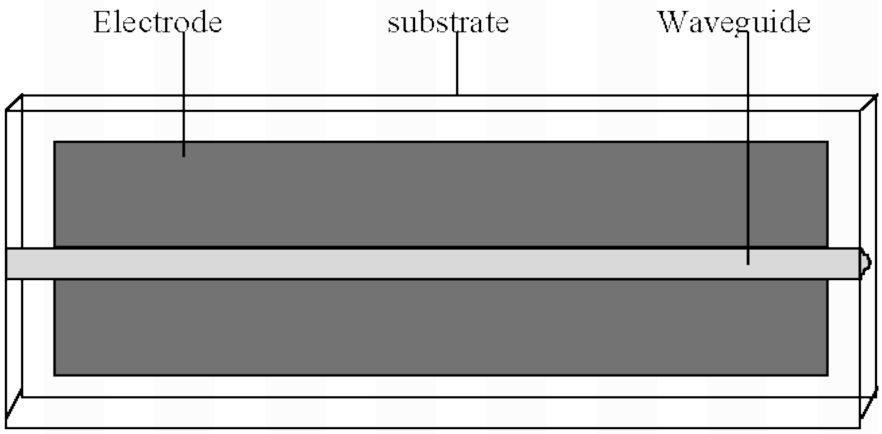


Fig.7 Lithium niobate phase modulator

In an integrated optic phase modulator, the application of a voltage causes a small change in refractive index given by,

$$\Delta n = \frac{n^3 r}{2}\left(\frac{V}{d}\right)$$

where n is the appropriate index in the absence of voltage, r is the proper electrooptic coefficient, V is the applied voltage and d is the separation between electrodes. Consequent to the change in index, a phase change given by,

$$\phi = \frac{2\pi}{\lambda}\Delta n . L$$

also occurs at the output of the waveguide, where L is the length of the electrode and l is the wavelength.

Combining the two equations and taking the modulation produced to be p , we get

$$VL = (\lambda d)/(n^3 r \Gamma)$$

where G is an overlap factor between the electric field and the optical mode field. Optimization of G forms an important aspect of modulator design.

In the case of a phase modulator many electrode geometries are possible. The lumped electrode phase modulator has been shown to give a 3 dB bandwidth

$$f_{3dB} = \frac{1}{\pi RC}$$

It is thus limited to about a GHz or so modulation bandwidth due to capacitance effects. On the other hand in the case of traveling wave electrode geometry the bandwidth is given by,

$$f_{3dB} = \frac{1.4c}{\left[\left|N_o - N_m\right|\right]L}$$

where *No* and *Nm* are the effective indices for optical and microwave (modulation) frequencies. Thus the difference in velocity between the modulating microwave signal and the optical carrier limits the bandwidth and is about 6-7 GHz in the case of LiNbO3.

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