International Journal of Applied Engineering Research
ISSN 0973-4562 Volume 10, Number 7 (2015) pp. 17891-17908

http://www.ripublication.com

Optical Pressure Sensor: A Review

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Abstract

In industrial environments a traditional pressure sensor has very limited usage, especially in a system with electromagnetic interference. Using optics in these situations eliminates all external influences. Optical means of measurement have many advantages such as higher sensitivity, resistance to electromagnetic and radio frequency interference, compact size, increased accuracy etc. It also provides the flexibility of data transmission and acquisition for longer distance without losses. This paper discusses different technologies and sensing principle being used for pressure measurement using optical properties such as Mach–Zehnder interferometer, Fabry-Perot interferometer, MEMS, Diaphragm and Optical fiber. The comparative analysis of various methods in terms of sensitivity, accuracy, range, wavelength, resolution etc. is presented in this paper.

Keywords: Pressure, Sensor, Mach–Zehnder interferometer, Fabry-Perot interferometer, Diaphragm, MEMS, Optical fiber, Weak lensing effect.

Introduction

Pressure is one of the most important process parameter which is required to be measured, indicated, transmitted or controlled in many applications such as automotive, petrochemicals, oil and gas, consumer electronics, medical, utilities, process industries etc. It is defined as force per unit area, where force applied is perpendicular to the direction of the surface on which it acts. In most pressure transducers, the pressure is sensed by measuring the deflection or movement of some pressure sensing element. The deflection can be measured using a number of techniques such as strain gauge / resistive, piezoresistive, electromagnetic, piezoelectric, optical, capacitive etc. Diaphragm is most widely used pressure sensor. The designs of the diaphragm can lead to errors, such as hysteresis, temperature effects and corrosion. Capacitive transducers are generally applicable to low pressure ranges with high resolution, good stability and low hysteresis; but they are highly temperature dependent. Most electromechanical type sensors have the ability to perform well in most conditions; however, many of these sensors using silicon semiconductor technology fail above 250 ºC. [28]

Technologies using Optical fiber play major role not only in the field of communication but also in the design and development of different types of sensors. Fiber optic sensing is facilitated by its salient features like high sensitivity and fast response in sensing different chemical and physical variables, which make it prominent among other sensing methods. The measurement and monitoring of various physical and chemical parameters can be achieved utilising optical fiber sensing devices in which the measureand follows one of the principal parameters that describe a light beam. These principal parameters include intensity of light, phase and wavelength. Optical techniques have the potential to provide measurements where electrical techniques fail to deliver.

Fiber optic based sensing system has advantages of immunity to electromagnetic interference (EMI) and radio frequency interference (RFI), compact size and light weight. Lower levels of loss offered by optical fibers to the signal travelling through it, makes it useful in remote sensing applications. Other advantages of optical sensing system like chemical inertness, safe to use in explosive environments and potentially resistant nature to nuclear or ionizing radiations make it highly efficient sensor. Since optical fiber sensors offer electrical isolation so they can be used for detection of high voltage and current [1].

Existing Technology

There are many types of pressure measurement devices based on various principles. They can be either direct-reading gauges, where working elements are directly influenced by pressure, or indirect-reading gauges, where actually some other pressure dependant parameters are measured. Some of the gauge types are listed below.

1. Hydrostatic gauges – which are based on comparison between the pressure and hydrostatic force of a column of fluid. It includes piston type and liquid in column type gauges.
2. Elastic gauges – based on metallic element which flexes under pressure. The examples are bourdon gauge (flattened tube gauge), diaphragm gauge and bellows gauge.
3. Electronic pressure sensors – it generates an electronic signal as a function of the pressure imposed such as strain gauge.

In this paper the review of optical pressure sensors based on different technologies and sensing principle such as Mach–Zehnder (MZ) interferometer based, Fabry-Perot (FP) interferometer based, MEMS, Diaphragm based, Optical fiber based etc. are discussed [2]. Interferometer is an instrument design to exploit the interference of light and fringe patterns that result from the optical path difference. Interferometers are extended to acoustic and radio waves as well. The basic principle of MZ interferometer and FP interferometers are discussed below.

Mach–Zehnder (MZ) interferometer: The Mach–Zehnder interferometer is a device for demonstrating interference by division of amplitude. A light beam is first split into two parts by a beam splitter and then recombined by another beam splitter. Depending on the relative phase acquired by the beam along the two paths the second beam splitter will reflect the beam with efficiency between 0 and 100%. In figure 1, the light of an incoming plane wave is again divided by a beam splitter into two waves. Then the transmitted plane wave is reflected at the upper mirror and passes the second beam splitter or is reflected at it. The plane wave which is reflected at the first beam splitter is reflected at the lower mirror and can pass an optional transmissive object to be tested. At the second beam splitter this wave can be transmitted or reflected. So, the Mach–Zehnder interferometer has two exits which can both be used. The exit with equal number of reflections and passages of object and reference wave at beam splitters is called symmetric exit. [29]

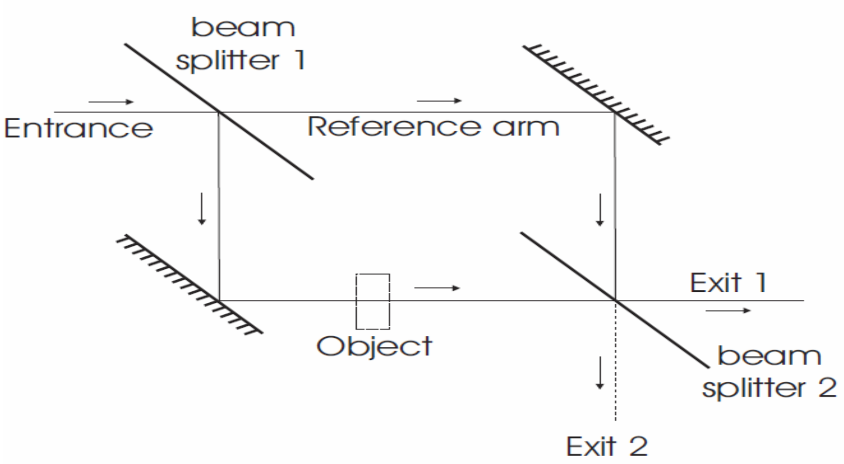

Figure 1: Basic Principle of A Mach–Zehnder Interferometer

Fabry-Perot interferometer: A Fabry–Perot interferometer (Fig. 2) is used to measure the spectral composition of light sources with narrow adjacent spectral lines. The light source is assumed to be extended. The lens L1 collimates the light and then it enters a so called Fabry–Perot etalon. The Fabry–Perot etalon consists of two plane glass plates and the inner surface of both of the plates are coated with a thin silver layer. These coated surfaces are exactly parallel, whereas the non-coated surfaces of the glass plates have a small tilt angle relative to the other surfaces in order to suppress reflections from these surfaces which would disturb the multiple interference patterns of the coated surfaces. So, the coated surfaces of the Fabry–Perot etalon form a plane - parallel plate with air inside. Since the surfaces are coated they have a quite high reflectivity R and their distance h is the thickness of the 'air' plate. The considerations of the last sections about multiple beam interferences can be easily transformed to this 'air' plate using $n = 1$ and $\phi' = \phi$, where ϕ is the angle of the collimated beam relative to the optical axis. Behind the Fabry–Perot etalon the lens L2 focuses the collimated light beam to the observation plane. [29]

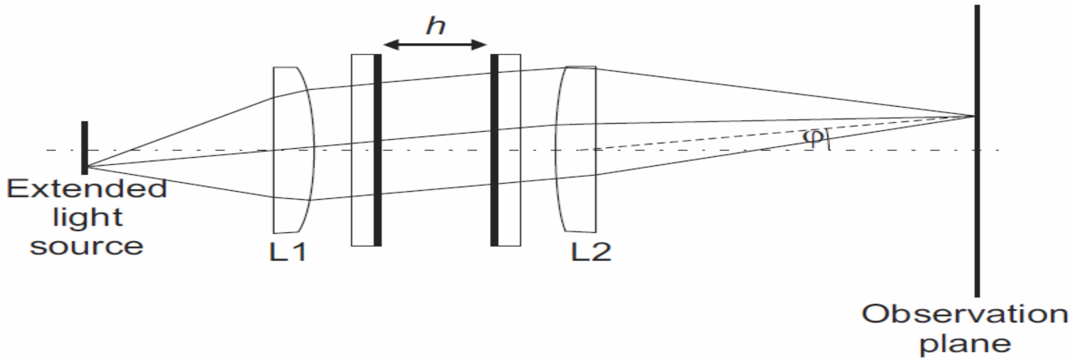

Figure 2: Scheme of A Fabry–Perot Interferometer

Technology Based on Optical Properties

This review paper discusses the optical pressure sensors based on different technologies and sensing principle such as Mach–Zehnder (MZ) interferometer based, Fabry-Perot (FP) interferometer based, MEMS, Diaphragm based, Optical fiber based. Optical interferometers have made feasible a variety of precision measurements using the interference phenomena produced by light waves. Interferometric measurements require an optical arrangement in which two or more beams, derived from the same source but traveling along separate paths, are made to interfere. Interferometers can be classified as two beam interferometers or multiple beam interferometers according to the number of interfering beams; they can also be grouped according to the methods used to obtain these beams. The most commonly used form of beam splitter is a partially reflecting metal or dielectric film on a transparent substrate; other devices that can be used are polarizing prisms and diffraction gratings. The best known two-beam type interferometers are the Fizeau, the Michelson, the Mach-Zehnder, and the Sagnac interferometers; the best known multiple-beam type interferometer is the Fabry-Perot interferometer.

Mach–Zehnder interferometer Based

Integrated optical sensors, especially those based on the interferometer principal, allow the detection of physical parameters in harsh and electromagnetically active environments with high accuracy and safety. The advantage of silicon based technology is that optical and electronic circuits as well as micromechanics can be integrated on the same substrate.

Wagner et. al. [3] has designed an optical pressure sensor based on MZ interferometer principle. The pressure sensor is integrated with hydrogenated amorphous silicon (a–Si:H) PIN photodiode. They have fabricated and utilized different materials on a silicon substrate to make an optical rib-waveguide which is used in place of the setup which consists of mirrors, lens and beam splitters. The system is based on a silicon substrate with oxide and oxinitride layers for the waveguide and a narrow rib on the top cladding layer to act as lateral confinement for the optical mode. The waveguide design consists of three layers on top of a silicon substrate. Bottom layer is a 2.5 µm thick thermal oxide layer and top layer is 0.5 µm thick PECVD oxides with a refractive index of 1.465 and 1.484 respectively. Bottom layer is also called as optical isolation layer. The MZ-interferometer has a total length of about 4 cm with a separation of the reference and the measuring arms of 5mm. In order to avoid the optical beam in the far-field resulting from the destructive interference pattern at other junction to enter the detector, the output arm is slightly bent.

The advantage of integrated MZ interferometer with a lateral a-Si:H PIN photodiode is that macroscopic components such as partially reflecting mirrors, couplers, filters, lenses etc., can be designed using rib waveguides, gratings and steps in the upper cladding layer. Author have found more oscillations in TM mode as compared to the TE mode.

K. Fischer et. al. [4] have designed an integrated optical pressure sensor based on the principal of interferometer, which detects the interference between the two paths. Pressure to be measured is applied on the force plate attached to the quadratic membrane. When pressure is applied to the membrane, the refractive index of waveguide layer changes in proportion to the change in optical pathlength of the interferometer arm. The phase difference induced by the pressure between the paths produces a change in the resulting interferogram at the output. The output of the interferometer is detected by an integrated photodiode. They have coupled the cross-sectional plane of the waveguide via a lens for simplicity.

The interferometer is designed as a single mode striploaded waveguide of a SiO_2-SiON-SiO_2 layer system. The refractive indices of the buffer and upper layer are chosen as 1.46 and of the waveguide layer as 1.50. Thin SiO_2 and SiON layers are used for the optical waveguides, which are deposited on a silicon substrate by thermal oxidation and an LPCVD and PECVD process, respectively. The portion of O_2 in the mixture allows adjustments to the refractive index of the deposited layer very accurately.

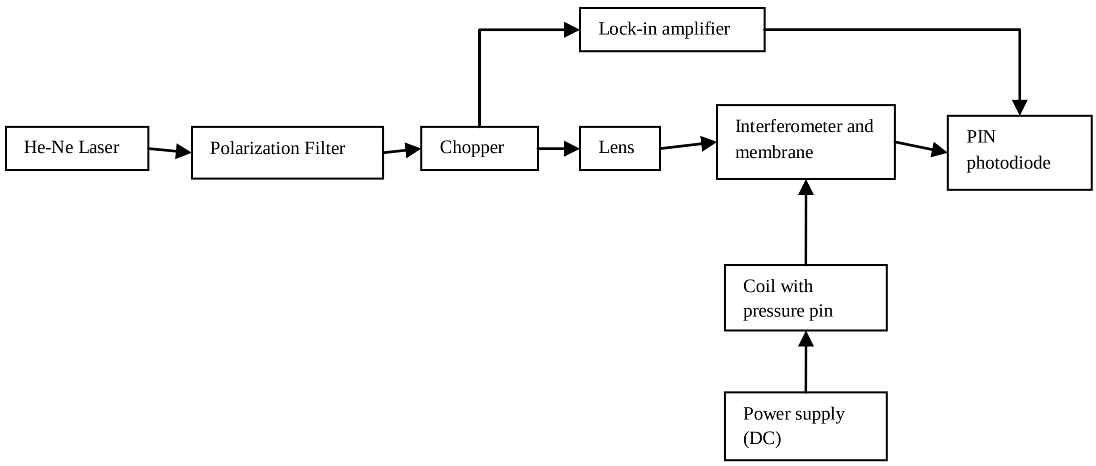

Figure 3: Measurement Set-Up For Pressure Sensor

The optical frequencies are dominated by the polarizability of the electrons. The dielectric constant depends on the polarizability of the material, which is a function of frequency. The principal refractive indices and the stresses in the elastic range of the material can be expressed by the Neumann-Maxwell stress-equation (1):

$$n_i = n + C_1\sigma_1 + C_2(\sigma_j + \sigma_k) \quad (1)$$

Where n_1 is principal refractive indices, σ_1 is principal stresses, C_1, C_2 are elastooptical coefficients and n is refractive index of unloaded material. The critical stress required for cracking in silicon is 500 MPa but less than half of maximum stress in the membrane of this sensor is calculated as 220 MPa.

At low pressures the data is not sinusoidal, which is caused by difficulties in controlling small forces with the pressure pin in the measurement setup. At high pressures the periodicity is stretched and the fringe of the intensity is decreased. In this range, the silicon membrane leaves the elastic range, and the coupling to the circuit is more difficult due to a slight lifting of the sample in the setup, which changes the coupling of the laser to the waveguide. TM-polarized light in the sensor gives the higher sensitivity but also exhibits very high losses. Symmetry and the high thermal conductivity of silicon, compensates any temperature gradient in the structure, which makes the interferometer output insensitive to any change in temperature.

Nabeel A Riza [5] and team have developed a wireless optical sensor based on silicon carbide (SiC) weak-lensing effect which enables remote sensing and measurement. It has many advantages like accuracy, safety, repeatability for harsh environments.

The measurement set up shown in figure 4 targets a single crystal SiC chip with an optical beam. The chip is used as an optical window within a pressure capsule. If the differential pressure of the capsule is increased, the focal length of the mirror formed by silicon carbide chip changes to make it a weak convex mirror. The laser beam passes through a beam splitter (BS) and then to a high pressure capsule. The SiC chip is fitted to the capsule which reflects the optical beam coming from laser through beam splitter are captured by an optical image detector (OID). Due to weak lensing effect the SiC based high pressure capsule can be used in remote pressure measurement.

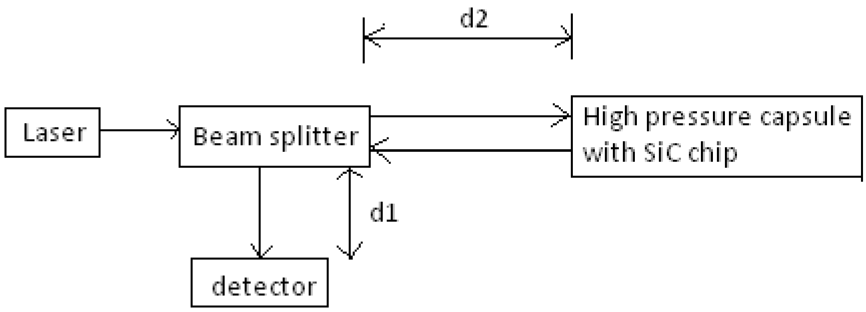

Figure 4: Block Diagram of Weak-Lensing Effect Based Sensor

The capsule pressure can be monitored and measured by magnification of reflected light from the chip. Equation 2 gives the relation between pressure and magnification factor. The magnification factor is defined as the ratio between D(P) and D_0 which represents beam diameter and initial beam diameter respectively. d_1 is the distance between beam splitter and pressure capsule and d_2 is the distance between beam splitter and optical detector.

$$M(P) = \frac{D(P)}{D_0} = 1 + \frac{(d_1+d_2)}{f(P)} \quad (2)$$

The experiment was performed for a remote distance of 2.5 m at room temperature for 0 to 600 psi (0–41 atm) differential pressures using a 633-nm wavelength laser beam.

Zhang et. al. [6] has simulated an optical pressure sensor based on curvature deformation of silicon carbide (SiC). It is very useful for pressure measurement with high temperature applications. The simulation of maximum pressure was done based on the mathematical relation of thickness – radius ratio of diaphragm and its material properties is given in equation (3), Where P_{max}, E, t, μ and R represents maximum pressure, elastic modulus, thikness of diaphragm, poisson's ratio and radius of diaphragm respectively.

$$P_{max} = \frac{16\, Et^4}{9\,(1-\mu^2)R^4} \quad (3)$$

This type of sensor can be used for aerospace sensing applications where pressure is measured at elevated temperature. The simulation result shows that the sensor displayed higher accuracy, linearity and sensitivity.

Hallynck [7] et. al. has fabricated an optical pressure sensor on silicon-on-insulator. It is based on ring resonator and Mach-Zender interferometers. Differential pressure applied to the membrane is expressed in terms of the change in phase shift which can be represented by equation (4), where λ is wavelength of incident light and $n_{eff}(l)$ is local refractive index.

$$\Delta\emptyset = \frac{2\pi}{\lambda}\int n_{eff}(l)dl \quad (4)$$

Table 1 shows the comparative analysis of Mach-Zehnder interferometer based optical pressure sensor for different wavelength, pressure range and methods/software used.

Table 1:

Sl. No.	Reference	Principle	Wavelength	Pressure	Software	Remarks (through)
1	Wagner et al. [3]	Mach-Zehnder interferometer	633 nm	Not mentioned	ANSYS	Experiment
2	Fischer et al. [4]	Mach-Zehnder interferometer	632.8 nm	Upto 200 MPa	FEM simulation	Theoretical analysis & Experiment
3	Riza et al. [5]	Weak lensing effect	633 nm	0 – 600 psi	Not mentioned	Experiment

4	Zhang et al. [6]	Reflective optical sensing method	Not mentioned	Not mentioned	MATLAB	Simulation
5	Hallynck et al. [7]	Mach-Zehnder interferometer & Ring resonator	Not mentioned	0 – 80 kPa	ANSYS	Experiment

Fabry-Perot Interferometer Based

Among the commercially available optical fiber sensors, the Fabry-Perot sensing technology is the most versatile and relatively less costly. Fabry Perot sensors can measure different physical parameters such as strain, temperature, pressure, displacement, or refractive index. The Fabry-Perot interferometer is a very simple device that is based on the interference of multiple beams. It consists of two partially transmitting mirrors that form a reflective cavity. Incident light enters the Fabry-Perot cavity and experiences multiple reflections between the mirrors so that the light can produce multiple interferences.

Mengchao [8] and team has designed optical pressure sensor based on Fabry-Perot interferometer. Diaphragm is used as pressure sensing element which is based on elastic deformation principle. The relation between the deflection (d) of round diaphragm with the pressure applied (P) can be expressed as equation (5). Where μ is possion's ratio, E is young's modulus, t is thickness, R is effective radius of diaphragm and r is any radial position leaving central position.

$$d = \frac{3(1-\mu^2)P}{16Et^3}(R_0^2 - r^2)^2 \quad (5)$$

It is found that by changing the thickness of diaphragm the sensitivity can be improved. There is a linear relation between the deflections of the diaphragm with the applied pressure. The sensitivity of this sensor is 1052 nm/MPa.

Dai et. al. [9] has proposed a polymer structure based pressure sensor. The sensor is based on Fabry-Perot interferometer principle which consists of two highly reflecting mirrors connected parallel to each other. Unknown pressure can be measured by detecting the shift of the reflected or transmitted beam due to change in the gap length. The authors have calculated the sensitivity of the sensor using formula (6), where Δd is small angle approximation and P is applied pressure.

$$S = \frac{\Delta d}{P} \quad (6)$$

It is found that the sensitivity is directly proportional to radius, and inversely proportional to the thickness of diaphragm.

Hyungdae et al. [11] have designed a dual-cavity Fabry-Perot pressure sensor which consists of a spliced segment of single mode fiber, a UV molded cavity structure and a diaphragm composite with polymer or metal, which is sensitive to pressure as well as temperature change. It has built-in measurement and compensation capability for temperature as well. A large cavity diameter is needed to achieve high sensitivity for pressure measurement but the cavity diameter size is limited and dependent on the single mode optical fiber diameter. The metal/polymer diaphragm has relatively low stiffness, which makes the sensor highly sensitive. This method offers high resolution, low noise and lesser calculation time.

Table 2 shows the comparative analysis of Fabry-Perot interferometer based optical pressure sensor with pressure range and sensitivity.

Table 2:

Sl. No.	Reference	Principle	Pressure	Pressure sensitivity	Remarks (through)
1	Mengchaoet al. [8]	Fabry-Perot interferometer	0 – 40 MPa	1052 nm/MPa	Experiment
2	Dai et al. [9]	Fabry-Perot interferometer	0 – 0.1 MPa	7.6983 μm/MPa	Experiment
3	Hyungdaeet al. [11]	Fabry-Perot interferometer	6.89 to 27.58 kPa	0.0122 μm/kPa	Experiment

MEMS Based

During recent years, micro electromechanical system (MEMS) has gained significant importance in micro sensors and micro actuators. The sensor based on any physical principle such as piezoresistive, capacitive, piezoelectric, magnetic, electrostatic, optical etc. can be implemented using MEMS.

Wang [10] and team have proposed silicon-on-insulator (SOI) wafer as elastic Diaphragm. The diaphragm forms part of an optical cavity of Fabry-Perot arrangement where mirrors are used as diaphragm itself, and the reflection at the end face of the optical fiber used to address the cavity. The deformation of the diaphragm thus modulates the optical path difference in the cavity between the fiber and the diaphragm. The cavity is sealed, and contains air at ambient atmospheric pressure. The change in pressure can be expressed as equation (7)

$$I = I_0 + I_0 V cos(KP - \varphi_0) \quad (7)$$

Where I is reflected intensity, I_o is the mean signal, V is the visibility of the interferometer, K is a phase constant and φ is the optical phase and P is differential pressure applied.

The set-up is based on a double laser beam interference principle which consists of a laser source, optical splitter and lens, single-mode optical fiber, pressure tube, photomultiplier tube (PMT), power supply, signal amplifier, analogue to digital converter (ADC) and a computer for processing the data.

It is observed that resolution will be poor if thick diaphragm is used. If the radius is too small the sensor response will be nonlinear. It has also been found that the pressure sensitivity is not dependent on cavity length.

Pattnaik [12] et al. has proposed MEMS based pressure and vibration sensors with integrated optical ring resonators. According to elasto-optic effect, the refractive index changes due to stress in the waveguide located over the diaphragm which results in the phase shift of the light propagating through it. The output is given in terms of phase shift because resonant wavelength shift of the ring resonator is located over the diaphragm. Phase shift in the waveguide is more due to cumulative photo-elsatic effect. The phase shift (ΔΦ) along the edge of the diaphragm is given by equation (8), where λ is wavelength, n is refractive index, a is the area and h is the thickness of the diaphragm and P is applied differential pressure.

$$\Delta\emptyset(P) = \frac{2\pi}{\lambda}\left(\frac{n}{n_{eff}}\right)C\left(\frac{3a^2}{4h^2}\right)(2\pi a)P \quad (8)$$

Optical MEMS pressure sensors can be used in various applications such as blood pressure monitoring, precession instrumentation, aerospace propulsion application and other harsh environments.

Wang [13] and team have described the signal interrogation technology to design MEMS optical pressure sensor. The sensor has various advantages such as high sensitivity, can be operated in high temperature for longer period of time, mechanically flexible and rugged, suitable for use in wet environments and has light weight. A single wavelength interrogation was selected for operating wavelength to ensure a nominal quadrature operating point. The pressure sensor film was fabricated on silicon substrate. Figure 5 shows the block diagram of measurement set up. The optical beam reflected from the EFPI sensor head travels back in the same fiber and is directed to the spectrometer from the other port of the coupler. Then, the measured spectrum is transferred to the computer for processing of data.

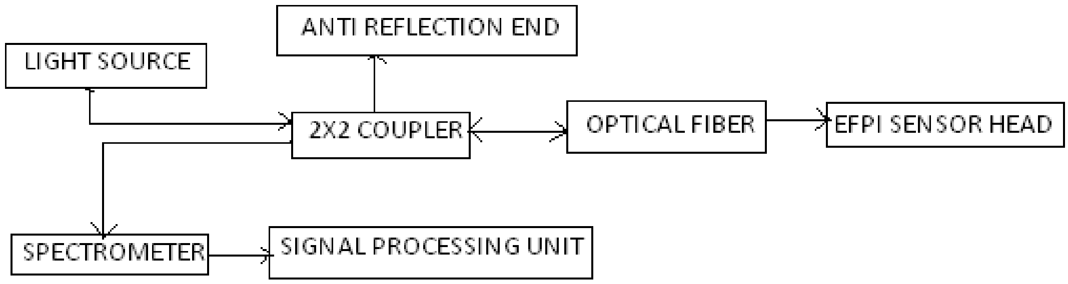

Figure 5: Block Diagram of MEMS Based Sensor

It was found that the senor is not influenced from the light source, and thus it eliminates two sources of errors from the final result of the measurement.

Dessalegn [14] et al. have used serially coupled double ring resonator (DRR) in a microcantilever for pressure sensing application. When pressure is applied, the beam bends, which involve mechanical deformation of the ring resonator that induces a stress. Due to stress on ring resonator the refractive index changes in the waveguide which leads to change in the output spectrum shift. As a result, the sensitivity as high as 3.4149 pm/kPa was achieved for measurement within the range of (0-30.469) MPa.

Diaphragm Based:

Diaphragm based fiber optic pressure sensors have been shown to possess advantages of high sensitivity, wide bandwidth, high operation temperature, immunity to EMI, Light weight and long life.

Toshima [15] and team have proposed diaphragm optical fiber with the sleeve for fiber insertion. The diaphragm is connected with the sleeve which is attached with half mirror and reflection mirror. The diaphragm attached to reflection mirror gets deflected when experienced with external pressure. When the deflection is smaller than the diameter, the Fabry-Perot interferometer is constituted between two mirrors. Since the deflection is changed by the applied pressure, so the pressure measurement is done by the light intensity of the interferometer. The block diagram of the pressure sensor is shown in figure 6.

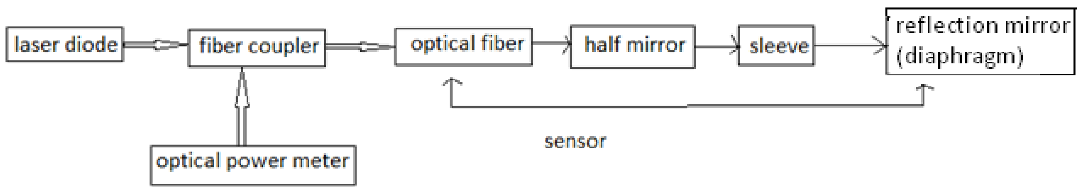

Figure 6: Block Diagram Of Diaphragm Based Sensor

The diaphragm with the sleeve is suitable for high reliable bonding due to its large bonding area between the sleeve and the optical fiber.

Khosravi [16] and team have designed a multilayer diaphragm for pressure measurement. It can be used for both optical sensing and common sensing of pressure. The multilayer diaphragm was deposited on SiO_2/Si/SiO_2 wafer. Solid 45 element type and Solid 46 element type were used to model Substrate layers and elastic layers of Si and SiO_2 respectively. A linear relation was found between the thickness of SiO_2 layer and sensitivity.

Optical Fiber Based

Pressure measurements are required in various industrial applications, including extremely harsh environments such as turbine engines, power plants and material processing systems. Conventional sensors are often difficult to apply due to the high temperatures, highly corrosive agents or electromagnetic interference (EMI) noise that may be present in those environments. Fiber optic pressure sensors have been developed for years and proved themselves successfully in such harsh environments. Fiber optic sensors can be used to measure pressure and possess a number of inherent advantages including immunity to electromagnetic interference, wide range of potential measurands, high resolution, remote sensing capability, high reliability and do not pose a spark source hazard for flammable environment applications. A variety of fiber optic pressure sensors (FOPS) have been developed and proven themselves in various applications.

Wang [17] and team have utilized the photo elastic effect using a new compensation technique for pressure measurement shown in figure 7.

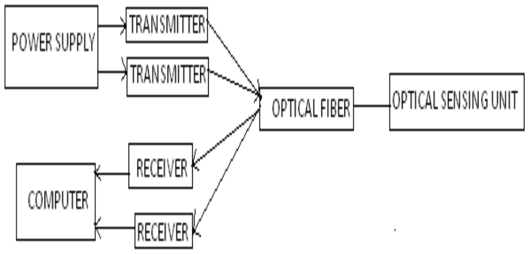

Figure 7: Block Diagram of Optical Fiber Based Sensor

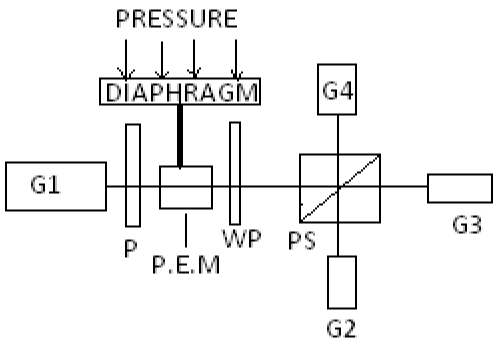

Figure 8: Block Diagram of Optical Sensing Unit

Figure 8 shows the optical sensing unit where the light from transmitter enters to optical cable with some loss to an optical sensor head. After being collimated by a GRIN lens G1, the light passes through P, PEM, and WP and is then split by the PS into refection and transmission beams. The transmission beam is injected into a lead-out fiber by a GRIN lens G3 and propagates to a photo detector alongF3. The reflected light is focused into another lead-out fiber through G4 and travels to photo detector. The light from a transmitter T2 propagates along another lead-in fiber and, after being collimated by a GRIN lens G2, directly gets split by PS into two beams, which are also focused into optical fiber by G3 and G4, respectively.

It is found that the measurement range of 0-147 KPa can be obtained with accuracies of 0.2% within the temperature range of -10°C to 42°C and a resolution of 10 Pa using the proposed method. Fiber loss compensation has been observed up to -30 dB.

Roger [18] et al. have developed a dual function sensor system for measuring pressure and temperature at the tip of a single optical fiber. It consists of a filter band-edge shift temperature sensor, a reflecting dichroic filter, and spectral modulation pressure sensor shown in figure 9.

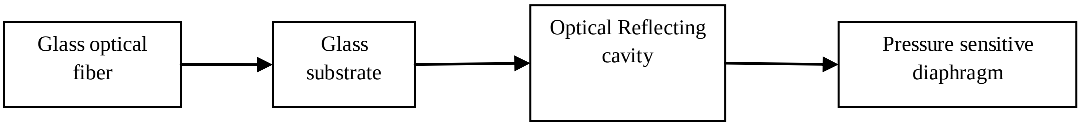

Figure 9: Block Diagram of An Optical Sensor

As pressure changes, the diaphragm deflects and so changes the cavity depth which in turn alters reflectivity of each LED wavelength. The spectrally modulated LED light is returned to the instrument, split into two wavebands by a dichroic mirror, and measured with photo detectors. The respective photocurrents form detector output is taken and expressed in terms of the dichroic ratio.

Table 3 shows the accuracy and resolution analysis of optical pressure sensor for different pressure range.

Table 3:

Sl. No.	Reference	Pressure range	Accuracy	Resolution
1	Wang [17] et al.	0 to147 KPa	0.2%	10 Pa
2	Roger [18] et al.	-50 to 300 mmHg	± 2%	1 mmHg
3	Yuerui [25] et al.	0 to $8x10^4$ Pa	Not mentioned	1 Pa

Hara [19] et al. has demonstrated an optical hydraulic pressure sensor using frequency shifted-feedback laser to sense ocean-bottom-tsunami. They have achieved –0.0234 ppb/Pa pressure sensitivity of the sensor and 28.5 ppm/ºC respectively, in hydraulic pressure and water temperature. To detect this slight strain, frequency-shifted feedback laser was used as an optical source.

Kodl [20] have described a pressure sensor which consists of one flexible optical waveguide. The optical attenuation of waveguide depends on the local pressure and utilizes the properties of evanescent field for its operation. The optical waveguide core uses light-absorptive layer in the optical cladding. The transmitter is placed on one side of the sensor with optical source, and there is a receiver on the other side with one photosensitive element. When no pressure is applied, there is a total reflection at the boundary between the core and the cladding. The optical rays do not reach the absorptive layer. Under pressure, since the optical ray is skin-deep in the optical coating, the light gets absorb in the absorptive layer, resulting in high optical attenuation.

This sensor offers high sensitivity and coupling efficiency, durability, ease of design/manufacturing etc.

Kadlec [21] et al. has designed an optical pressure sensor for explosive industrial environment. The sensor is based on the single mode reflecting principle with micrometric distance between reflective membrane and fiber ending. The applied pressure results in deflection which can be expressed in terms of modulation index

(Q) represented by equation (9). ΔI, I_0 and P represents variation of optical power, input optical power and applied pressure respectively.

$$Q = \frac{\Delta I}{I_0 P} \quad (9)$$

The greatest benefits of this pressure sensor are high accuracy of pressure measurement and galvanic isolation, which helps it to be free from external magnetic and electric interference.

Ceyssens [22] et al. Has demonstrated a low cost and highly integrated fiber optical pressure sensor system. Both sensor and readout parts are constructed using batch micromachining techniques. Fabry-Perot interference occurs in the cavity formed by the optical fiber, the air gap and the silicon. It is observed that power reflectivity changes between 0.18 and 0.45 for a membrane deflection between 0 and 425 nm. When the measurement was done with a multi mode fiber, results are inferior due to the limited coherence length of the LED light. Actual measurements show only a 1% variation in reflected power, when deflection is measured through one meter long multimode fiber.

Huang [23] et al. have developed a composite optical bend loss sensor for measurement 3-D forces. The sensor consists of an array of optical fibers lying in perpendicular rows and columns sandwiched between an elastomeric pads. The basic working principle of the sensor is to increase the angle of incidence of the light rays at the core/cladding interface. They have simulated optical bend loss using the beam propagation method which is based on a series of images captured by a CCD camera on the bending curvatures of optical fiber. Multimode fibers are used to both increase bend loss effects and to reduce the light coupling losses at both input and output.

Min-Cheol [24] et al. has proposed an optical pressure sensor based on vertical direction coupling with flexible polymer waveguides between guided modes. It basically senses the distribution of pressure which is useful in many applications such as robotics, touch sensitive displays etc.

When pressure is applied on upper waveguide surface, flexible polymer waveguide bends which results in coupling of light between optical signal propagating through lower and upper channel waveguides. Once the light is coupled, it cannot go back to the channels due to diffraction of light inside planner waveguide. Transmitted power depends on the gap between waveguides which is proportional to applied pressure. The sensor shows good repeatability because the flexible polymer waveguide exhibits strong restoring strength.

Yuerui [25] et al. has utilized vertical silicon nano wire array based all-optical pressure sensor. Vertical silicon nano wire arrays with photonic crystal structure, can trap or diffract some amount of light, depending on the light wavelength, nano wire diameter, and pitch spacing. When pressure is applied, membrane deforms which leads to change in the color of membrane because of the modulation of the nano wire pitch and deflection angle.

The pressure was calculated by capturing the image using a camera and the image was cross correlated with the calibration data set. Pressure sensor proposed in this paper offers high sensitivity between 0 Pa up to $8x10^4$ Pa with 1-Pa resolution.

Patridge [26] et al. has presented an optical fiber pressure sensor capable of measuring the changes in the meniscus of the liquid. It consists of a tapered single mode silica fiber which is mounted with a small curvature and positioned with the tapered region so that the fiber can be immersed in the liquid. The low angle curve formed by the fiber helps to enhance the movement of the meniscus along the fiber by creating a capillary channel between the fiber and the surface of the water.

Poeggel [27] et al. has combined a Fabry-Perot interferometer with Fiber Bragg Grating to design a pressure and temperature sensor in a single optical fiber. The Sensor consists of an optical fiber and the diaphragm. The optical fiber which transmits the light into the cavity is formed by the capillary. Between 2 and 10 μm thick diaphragm deforms when an external force is applied to it. This force is caused by the relative pressure difference between the sensor cavity and the environment. Such pressure difference leads to bending of the diaphragm, which is described by equation (10). ΔP is the relative pressure change and ΔL the resultant physical displacement of the diaphragm, where μ is Possion's ratio and E is the Young's modulus of glass. The radius and thickness of the diaphragm are represented by r and h respectively.

$$\Delta L = \frac{3}{16}\frac{(1-\mu^2)r^4}{Eh}.\Delta P \tag{10}$$

The sensor can be used in several applications such as bladder or lung pressure measurement. Because of the small diameter (max 200 μm), the measurement of pressure within blood vessels is also possible.

Conclusion

Measurement of pressure can be done by various means. This paper discusses the optical methods of measuring the pressure. Two beam and amplitude splitting of Mach Zehnder Interferometer can be used in aerodynamic research and industrial applications. It offers detection of change in parameter in harsh environments, free from electromagnetic interference, high accuracy and safe to use.

Fabry-Perot interferometer is very simple in structure but a very precise measurement tool. The interference pattern is composed of superposition of the multiple beams of transmitted and reflected light.The effective gap between the surfaces can be adjusted by changing the pressure of a gas, or by means of piezoelectric actuators. Its applications include precision wavelength measurements, hyperfine spectral structures, measuring refractive indices of gasses, calibration of the standard meter in terms of wavelength. Fabry-Perot technology provides a great flexibility in terms of pressure ranges, high sensitivity and small size that make them suitable for most applications at an affordable price. In order to achieve the high accuracy and resolution capability of fiber optic sensors, the fiber tip must be within the coherence length of the source to observe the optical interference.

Fiber optic sensors are immune to electromagnetic interference, and do not conduct electricity so they can be used in places where there is high voltage electricity or flammable material. Fiber optic sensors can be designed to withstand high temperatures as well.

References

[1] Wojtek J. Bock, "High-pressure Polarimetric Sensor Using Birefringent Optical Fibers", IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL 39, NO I, 2333-237, FEBRUARY 1990.

[2] Jose Luis Santos, FaramarzFarahi, "Handbook of Optical Sensors", CRC Press.

[3] C. Wagner, J. Frankenberger, and Peter P. Deimel, "Optical Pressure Sensor Based on a Mach- Zehnder Interferometer Integrated with a Lateral a-Si:H p-i-n Photodiode", IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. *5*, NO. 10, 1257-1259, OCTOBER 1993.

[4] K. Fischer, J. Muller, R. Hoffmann, F. Wasse, and D. Salle, "Elastooptical Properties of SiON Layers in an Integrated Optical Interferometer Used as a Pressure Sensor", JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 12, NO. 1, 163-169, JANUARY 1994.

[5] Nabeel A. Riza, FarzanGhauri, and Frank Perez, "Silicon Carbide-Based Remote Wireless Optical Pressure Sensor", IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 19, NO. 7, 504-506, APRIL 1, 2007.

[6] Dongzhi Zhang, Guoqing Hu, GengxinZeng, "Modeling and Simulation of High Temperature Optical fiberSiC-based Pressure Sensor", Proceedings of the IEEE International Conference on Mechatronics and Automation August 9 - 12, Changchun, China, 2009.

[7] E. Hallynck, P. Bienstman, "Integrated Optical Pressure Sensors in Silicon-on-Insulator", IEEE Photonics Journal, Volume 4, Number 2, 443-450, April 2012.

[8] Mengchao Li, Qiaoyun Wang, "Miniature High Sensitivity Diaphragm-based Optical FiberFabry-Perot Pressure Sensor", IEEE International Conference on Electronics, Communications and Control (ICECC), 328-330, 2011.

[9] Lihua Dai, Ming Wang, DongyanCai, HuaRong, Jiali Zhu, Sheng Jia, and Jingjing You, "Optical FiberFabry–Perot Pressure Sensor Based on a Polymer Structure", IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 25, NO. 24, 2505-2508, DECEMBER 15, 2013.

[10] Guanglong Wang, YitonFu, M E Welland, H. P. Hodson, Jusheng Ma, "Study On a Novel Optical Fiber Pressure Sensor", Fifth International Conference on Electronic Packaging Technology (ICEPT) Proceedings, 195-200, 2003.

[11] HyungdaeBae, David Yun, Haijun Liu, Douglas A. Olson, and Miao Yu, "Hybrid Miniature Fabry–Perot Sensor with Dual Optical Cavities for Simultaneous Pressure and Temperature Measurements", JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 32, NO. 8, 1585-1593, APRIL 15, 2014.

[12] Prasant Kumar Pattnaik, Bh. Vijayaaditya, T. Srinivas and A. Selvarajan, "Optical MEMS pressure sensor using ring resonator on a circular

diaphragm", IEEE Proceedings of International Conference on MEMS, NANO and Smart Systems (ICMENS'05), 2005.

[13] Wang Cong-fei, Wang Guang-long, Chen Jian-hui, Dun Yi, "The Signal Interrogation Technology of MEMS Optical Fiber Pressure Sensor", Proceedings of the IEEE International Conference on Information and Automation Zhuhai/Macau, China, 1285-1288, June 22 -25, 2009.

[14] HailuDessalegn and T. Srinivas, "Optical MEMS Pressure Sensor Based on Double Ring Resonator", IEEE International Conference on Microwave and Photonics (ICMAP), 1 – 4, 2013.

[15] Katsuhisa Toshima, Tomohisa Watanabe, Yuichi Kaneko. TsunehiroMaesakoand KoroTakahashi, "Diaphragm-Type Optical Fiber Pressure Sensor with a Sleeve for Fiber Insertion", INTERNATIONAL SYMPOSIUM ON MiCROMECHATRONlCS AND HUMAN SCIENCE, 171-174, 2003.

[16] Amin Khosravi, Mahdi Khosravi, "DESIGN, MODELING AND OPTIMIZATION OF A MULTILAYER DIAPHRAGM USED IN OPTICAL PRESSURE SENSOR", IEEE International Conference on Computer Science and Automation Engineering (CSAE), 439-443, 2012.

[17] Anbo Wang, Se He, Xiaojan Fang, Xiaodan Jin, and Junxiu Lin, "Optical Fiber Pressure Sensor Based on Photo elasticity and its Application", JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 10, NO. 10, 1466-1472, OCTOBER 1992.

[18] Roger WoIthuis, Gordon Mitchell, James Hartl, and ElricSaaski, "Development of a Dual Function Sensor System for Measuring Pressure and Temperature at the Tip of a Single Optical Fiber", IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, VOL. 40, NO.3, 298-302, MARCH 1993.

[19] Takefiuni HARA, Fumihiko IMAMURA, and Hiromasa ITO, "Optical Hydraulic Pressure Sensor using Frequency Shifted-feedback Laser for Ocean-Bottom-Tsunami Sensing", The 3rd International Workshop on Scientific Use of Submarine Cables and Related Technologies, 45 – 50, 2003.

[20] G. Kodl, "A New Optical Waveguide Pressure Sensor Using Evanescent Field", 54th Conference on Electronic Components and Technology Proceedings, 1943 – 1946, 2004.

[21] J. Kadlec, R. Helan, and R. Vrba, "Pressure sensor for explosive industrial environment based on optical measurement principle", Proceedings of the International Conference on Networking, International Conference on Systems and International Conference on Mobile Communications and Learning Technologies (ICNICONSMCL'06), 2006.

[22] F. Ceyssens, M. Driesen, K. Wouters, R. Puers, "A LOW-COST AND HIGHLY INTEGRATED FIBER OPTICAL PRESSURE SENSOR SYSTEM", International Conference on Solid-State Sensors, Actuators and Microsystems, 2601 – 2604, 2007.

[23] Chu-Yu Huang, Wei-Chih Wang, Wen-Jong Wu, and William R. Ledoux, "Composite Optical Bend Loss Sensor for Pressure and Shear Measurement", IEEE SENSORS JOURNAL, VOL. 7, NO. 11, 1554-1565, NOVEMBER 2007.

[24] Min-Cheol Oh, Jun-Whee Kim, Kyung-Jo Kim, and Sang-Shin Lee, "Optical Pressure Sensors Based on Vertical Directional Coupling With Flexible Polymer Waveguides", IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 21, NO. 8, 501-503, APRIL 15, 2009.

[25] Yuerui Lu, and Amit Lal, "PHOTONIC CRYSTAL BASED ALL-OPTICAL PRESSURE SENSOR", IEEE 24th International Conference on Micro Electro Mechanical Systems (MEMS), 621 – 624, 2011.

[26] Partridge M, Jarzebinska R, Higson S P J, Davis F, James S W, Tatam R P, "Curved tapered optical fibre surface pressure sensor", IEEE Sensors, 1472 – 1475, 2011.

[27] Sven Poeggel, Gabriel Leen, Kort Bremer, Elfed Lewis, "Miniature Optical Fiber Combined Pressure- and Temperature Sensor for Medical Applications", IEEE Sensors, 1 – 4, 2012.

[28] Bela G. Liptak, Instrument Engineers Handbook,(Volume 2) Third Edition: Process Control, CRC Press, 1995.

[29] Francis A. Jenkins & Harvey E. White, Fundamentals of Optics (3rd.ed.) McGraw-Hill, 1957.