International Journal of Engineering and Technical Research (IJETR)
ISSN: 2321-0869 (O) 2454-4698 (P), Volume-3, Issue-10, October 2015

A Comparison between Fiber Optic Based Pressure, Strain and Temperature Sensors

Muhammad Sajid Iqbal, Dr. Khurram Karim Qureshi

Abstract— **A comparison between different types of fiber optic based pressure, strain and temperature sensors is presented in this paper. The paper is divided into three major sections and pressure, strain and temperature sensors are discussed in sections II, III and IV respectively. Each section contains three different methods for measuring pressure, temperature or strain and then a comparison table is also included in every section describing different parameters of particular type of sensors and their applications. At the end of each section some recommendations and suggestions are made based on the comparison data.**

Index Terms — **Fiber Optic Sensors, Strain Sensors, Temperature Sensors, Pressure Sensors.**

I. INTRODUCTION

Sensors are the components that we use to measure other physical quantities like pressure, distance, strain, temperature, acceleration etc. In order to minimize the human interaction and errors due to human negligence, industries are going towards automation. And sensors are key components to achieve this task. Initially electrical components were used to develop sensors but over the last few decades fiber optic sensors are drawing much interest of automation engineers and researchers due to plenty of advantages. And now fiber optic sensors are widely used to measure different physical quantities in almost every field. In this paper only fiber optic based pressure, strain and temperature sensors along with their applications are discussed.

II. PRESSURE SENSORS

Optical fiber based pressure sensors are very commonly used in different industries. There are several techniques to build optical pressure sensors. For example optical pressure sensor can be designed by using Fiber Brag Grating, Using the interference of different modes inside the fiber, using super-structure fiber grating, using birefringent optical fibers and many other techniques. But in this section only three techniques are discussed. These are pressure sensor using fiber brag grating (FBG) [1], super-structure fiber grating (SFG) [2] and all-fused silica based optical pressure sensor respectively [3].

A. FBG Based Pressure Sensor

Fiber brag gratings are important component of any communication system. But now a day's FBGs are widely used for sensing purposes as well. A FBG based optical pressure sensor is discussed here.

Initially optical pressure sensors were made using bare FBG. And it was observed that the sensitivity of bare FBG pressure sensor is very poor (3.04pm/MPa) as shown in [4].

With the passage of time many techniques were proposed to improve the sensitivity like embedding FBG in polymer, soldering metal-coated FBGs on a free elastic cylinder, attaching the FBG fiber to a diaphragm and many more. These techniques helped to improve sensitivity but the structure of sensor became too complex and cost of sensor also increased. In [1] a new technique based on bourdon tube is proposed. The structure of the sensor is shown in figure 1. A circular C-type bourdon tube is used as a spring element. Two fiber brag gratings are fixed with an epoxy adhesive on the inner and outer side of the tube. In this way the pressure can be measured indirectly by measuring the strain.

As mentioned earlier that the sensitivity of FBG is very low. So the pressure can be measured indirectly by measuring the strain. Strain can be measured by calculating the change in the wavelength. As it is shown in [1] that the strain is related to wavelength shift and then after doing some mathematics it can be shown that difference between the wavelength shifts of two FBGs is directly proportional to change in temperature.

The simulations are carried out by using ANSYS and finite element analysis is made. The parameters of bourdon tube like curvature radius (R), semi-major axis (a), semi-minor axis (b) and wall thickness (h) are set accordingly and results are obtained. Then these results are compared with the experimental results. The experiment is carried out by using a piston gauge, FBG interrogator, personal computer and the FBG sensor. The pressure varied with the resolution of 0.1MPa and change in wavelength is monitored. And it is found that the FBG pressure sensor has a sensitivity of 1.414 pm / kPa in a range from 0 to 1 MPa. The fitting correlation coefficient is found to be 99.949%.

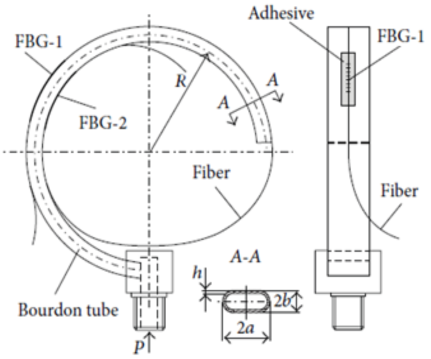


Fig.1. Structure of fiber brag grating based pressure sensor [1]

B. SFG Based Pressure Sensor

Muhammad Sajid Iqbal, Electrical Engineering Department, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia, Mobile: +92 334 7424334, +92 213 111 128 128 Extension: 289

Dr. Khurram Karim Qureshi, Electrical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran (KFUPM), Saudi Arabia

Fiber brag grating can be formed by varying the refractive index of the optical fiber. There are different structures of FBG based on the refractive index variation. A super structure FBG is a grating in which groups of sub-gratings are separated by dead zones. The lengths of sub-gratings and dead zones can be different from each other [5]. The SFG is used in designing of tunable filters but it is shown that it can also be used to increase the sensitivity of a pressure sensor [2].

The SFG based sensor is designed to measure the pressure and temperature simultaneously. The structure is shown in figure 2. The sensor consists of a polymer half filled cylinder and an SFG. The SFG is encapsulated inside the cylinder and glued to a circular plate placed in the middle of cylinder. Two openings are placed to cross the fiber and one round hole is on the wall of cylinder to sense pressure. In this way the polymer will be pressurized along one direction and sensitivity will increase.

As mentioned earlier that SFG consists of periods of gratings, so an SFG couples the forward and reverse propagating LP_{01} modes at different wavelengths and forms the loss dips. SFG also couples the forward propagating core and cladding LP_{01} modes like a Long Period Fiber Grating (LPG) [6]. So SFG can be considered as the combination of FBG and LPG. And its wavelength shift can be related to temperature change as shown in [2]. For pressure measurements the deformation of polymer inside the cylinder is considered and its relation is made with the applied strain and then pressure is calculated by using the relationship between the polymer deformation length and strain [2].

To perform the experiment the sensor is kept inside a pressure chamber and to measure the pressure the temperature is kept constant, and pressure changed from 0 to 0.16 MPa with a resolution of 0.02 MPs. And it is observed that the sensor has a pressure sensitivity of 0.03 pm / MPa. This is much higher than the sensitivity of bare FBG. Then pressure is kept constant inside the chamber and change in wavelength by varying the temperature is measured. And it is found that the sensor is capable of measuring the temperature from 20 ^{o}C to 80 ^{o}C without disturbing the pressure reading. The sensitivity of temperature sensor is found to be 0.023 nm / ^{o}C. It is also found that fitting linear correlation coefficient is 0.972 and ± 9% error is present between measured and simulated results.

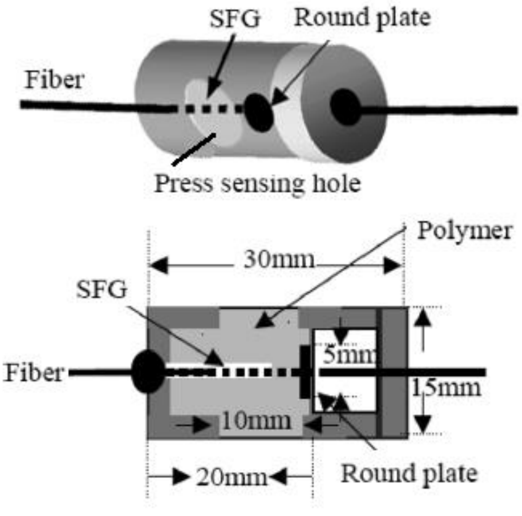


Fig.2. Proposed structure of SFG based pressure sensor [2]

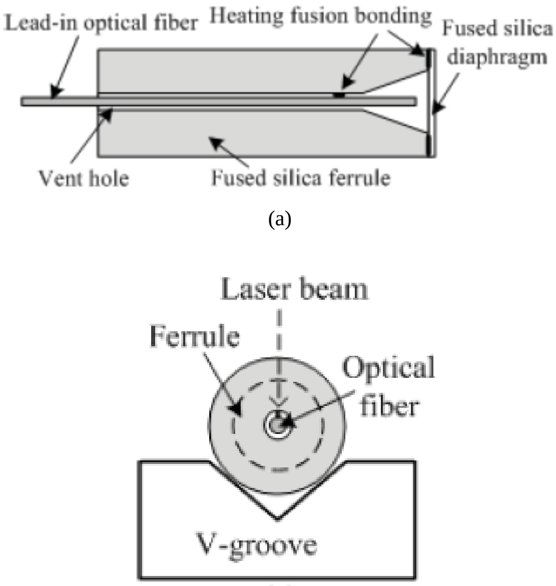
C. All-Fused-Silica Extrinsic Fabry–Pérot Optical Fiber Interferometer Based Pressure Sensor

A lot of work has been done in improving the sensitivity of optical pressure sensors. And it is shown that a diaphragm based configuration is more suitable to measure pressure with high sensitivity [7]. Lot of diaphragm based structures has been reported in the literature like silica elements combined with silicon carbide, sensor fabricated on the tip of hollow fiber by using dipped polymer membrane, a photo-resist ferrule and many more. These structures have a large temperature dependence and complex structure. So an all fused extrinsic fabry perot fiber interferometer based pressure sensor is proposed to reduce the temperature dependence and to increase the sensitivity.

Structure of the sensor is shown in the figure 3. It consists of a cup with horn shape and through hole fused silica ferrule. Ultra thin layer of fused silica is welded directly to the end face of cup. CO_2 laser is used for this purpose because the direct laser heating is not suitable for very small size sensors. At the bonding joint a hole for passing the air is also kept to avoid thermal coefficient expansion mismatch. Due to this vent hole, sensor can also work in high temperature environments.

Light from a computer controlled source is launched towards sensor's head through a fiber. And the interfering light is also routed back to the same optical fiber. So there will be a phase shift between input and reflected light. The phase shift is dependent on the cavity length [8]. When the pressure is applied to the sensor's head, it results in changing the length of cavity, and hence the applied pressure can be measured by examining the change in cavity length. Cross co-relation signal propagation method is used for this purpose.

The experiment is carried out to calculate the pressure of a fluid inside the capillary tube. To launch the light sm125 interrogator is used and it is found that this sensor can measure the pressure from 0 to 3 MPa with a sensitivity of 5.18nm/kPa. Measurements are almost independent of temperature in the range from 29 ^{o}C to 78 ^{o}C. The sensor has the resolution of 38 Pa. Resolution and sensitivity is much higher than other pressure sensor available in literature.



(a)

(b)

Fig.3. (a) Structure of EFPI sensor (b) Fused silica ferrule holder [3]

Table I is showing the comparison between the three types of pressure sensors that were discussed before. The FBG based sensor is limited for low temperature applications like pipeline leakage detection, but its good resolution and linear fitting correlation coefficient make is applicable for real time pressure monitoring. On the other hand SFG based sensor has wide operating temperature range which makes it suitable for little higher temperature applications like liquid level detection and pressure monitoring in boilers. EFPI based pressure sensor has a very wide pressure range among these sensors. And can be operated at high temperatures as well, with a good sensitivity it is suitable for environmental monitoring and harsh environment pressure measurements. It is clear from table I that EFPI based pressure sensor is best among them. It has more pressure range, higher sensitivity and good temperature range. One more advantage of EFPI based sensor is that its sensitivity and range can be changed by varying the radial distance to the diaphragm center and the thickness of diaphragm. But the SFG based sensor can measure the temperature and pressure simultaneously.

III. STRAIN SENSORS

There are lots of fiber optic based strain sensors available in the literature. In this section only three types of strain sensors are discussed. These are strain sensor with elliptical hollow core photonic band-gap fiber (PBGF) [9], Photonic Crystal Fiber (PCF) based strain sensor [10] and twin core PCF based [11].

A. Elliptical Hollow Core PBGF Based Sensor

In normal optical fibers light travels inside the core due to difference of refractive index between core and cladding. A special type of fiber in which light propagates based on the photonic band-gap effect is called photonic bad-gap fiber (PBGF). The birefringence phenomena of PBGFs can be used to measure strains. It is also shown that the birefringence can be increased by making the core of PBGF in elliptical shape [9]. So an elliptical core PBGF is fabricated and its birefringence is measured experimentally by using Sagnac interferometer method and a strain sensor is formed.

EC-PBGF is drawn with the diameter of 125 μm. The core is of elliptical shape and with major axis of 11.56 μm and minor axis of 10.44 μm. The core is hollow and a photonic structure is placed outside the core with a hole to hole distance (pitch) of approximately 4μm. Total 8 rows are surrounding the hollow elliptical core as shown in figure 4. At a fix operating frequency the group birefringence and wavelength spacing are inversely proportional over the fixed fiber length.

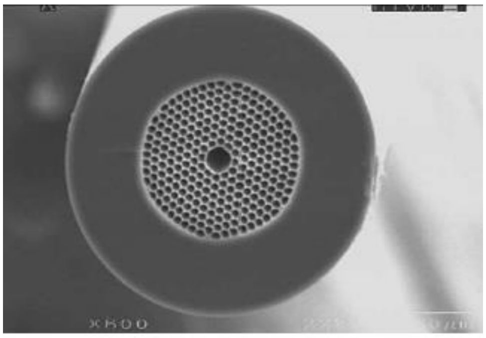


Fig.4. Fabricated elliptical core photonic band-gap Fiber [9]

The sensitivity of an EC-PBGF can be related to the phase shift between two polarization modes and the length of fiber. To measure the strain, the fiber is stretched from one end while keeping fixed from other end. The experimental results have shown that the sensor has a sensitivity of -0.81pm / με. It can measure the strain values from 0 to 1000 με. The linear fitting correlation coefficient is found to be equal to 0.9985. Sensor shows a linear response in the temperature range from 20 ^{o}C to 93 ^{o}C. According to author of this paper, this was the first ever experimental demonstration of elliptical core PBGF by using Sagnac Interferometer.

B. Photonic Crystal Fiber Based Strain Sensor

Optical fiber in which light propagates due to the properties of photonic crystals is called photonic crystal fiber (PCF). The main advantage of PCF is that it can confine the light inside the hollow core. PCF has large applications in the field of optical communication, fiber laser fabrication and highly sensitive optical sensors. Here it is shown that PCF can be used as a strain sensor. Some PCF based optical sensors are also proposed earlier [12, 13]. But they are using polarization maintaining fibers. And any sensor using PCF and with low birefringence was not present. So the authors of [10] proposed a PCF based strain sensor with low birefringence realized by Sagnac loop.

The sensor is formed by using 40cm long PCF. The core is kept hollow while drawing the fiber. There are seven rows of holes surrounding the core. The mode filed diameter of the fiber is set to be about 2.4 μm and pitch of holes is kept around 4 μm.

Experiment for strain measurement is carried out by using setup shown in figure 5. The light is launched in fiber from a wideband source, which is then coupled by a 3dB coupler. Light will travel inside the sagnac loop and will meet at the coupler again. The light beam travelling in the opposite direction will produce a phase shift due to birefringence. These light beams will interfere and produce the maxima and minima. The phase difference between two lights is dependent upon the birefringence and the length of PCF. To measure the strain another PCF of fixed length (140mm) is placed inside the loop. When strain is applied to that element, the length of the PCF changes and hence the phase shift observes a change. The change in phase difference can be related to the change in length (ΔL) and birefringence (B) keeping operating wavelength and length of PCF constant [10]. And hence the quantity ΔL/L (strain) can be calculated.

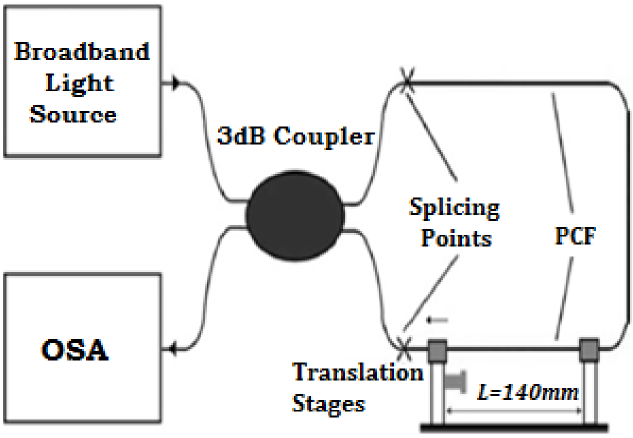


Fig.5. Strain measurement setup by using low birefringence PCF [10]

TABLE I
COMPARISON BETWEEN FBG, SFG AND EFPI PRESSURE SENSORS

Sensor Type	Sensor Range *MPa*	Sensitivity *pm/MPa*	Operating Temp- Range *°C*	Linear Fitting Correlation coefficient	Applications
FBG Based [1]	0-1	1414	25-30	99.949%	Pipeline leakage detection, Real time pressure measurements for oil industry
SFG Based [2]	0-0.16	30	20-80	97.277%	Underwater depth measurements, liquid level detection in industries, pressure measurements for medium temperature range boilers
EFPI Based [3]	0-3	5180	29-78	99.879%	Fluid level and pressure measurements, environmental monitoring, harsh environment measurements

The results have shown that this sensor can measure the strain values from 0-2520με with a sensitivity of -0.41pm / με. The linear fitting cross correlation coefficient is found to be 0.9982. The sensor can operate in the temperature range from 25 ^{o}C to 75 ^{o}C. Due to larger temperature dependence this type of sensor cannot be used for variable temperature applications. It can be used in applications like structural health and traffic flow monitoring.

C. Twin Core PCF Based Strain Sensor

Photonic crystal fiber can be designed in many ways like photonic band-gap fiber, holey fiber and twin core (TC) fiber. TC-PCF consists of two solids. Their cores are separated by a centered air hole. TC-PCF is widely used in optical communication due to its applications in designing of multiplexer and de-multiplexer. It can also be used for compensating the intermodal dispersion. Aside from its applications in optical communication, TC-PCF can also be used to fabricate fiber optic based sensors. Here a strain sensor is discussed by using TC-PCF and in line fiber mach zehnder interferometer.

TC-PCF is fabricated by using stack and draw method. There are two cores each having a diameter of 2.5μm. The diameter of fiber itself is about 125μm. Air holes of 1.1μm diameter are surrounding the two cores in a hexagonal fashion. The hole to hole distance in this structure is 1.85μm. The complete structure is shown in figure 6.

Experiment is carried out by configuring an in-line mach zehnder with the help of splicing a 30 cm long TC-PCF and single mode fiber SMF-28. Light from a broadband source is launched in both cores of TC-PCF. Light beam couples at the initial splice point and re-coupled at the other splicing point. In this way interference occurs due to phase shift between these two light beams. To measure the strain, another 10 cm long TC-PCF inserted and kept fixed from one end as shown in figure 7. Strain is applied by stretching the free end of fiber. Then the strain is measured by observing the wavelength shift.

The results have shown that the proposed sensor can measure the strain in a range between 0-4000με, which is much higher than the other PCF based strain sensors. The sensitivity is also much higher and is equal to -0.31 pm / με. The linear fitting coefficient is 0.998. The sensor is also tested from a temperature range of 25^{o}C to 136 ^{o}C and a linear relationship is found between wavelength shift and temperature. Temperature sensitivity of sensor is 6.68 pm / ^{o}C, which is pretty good.

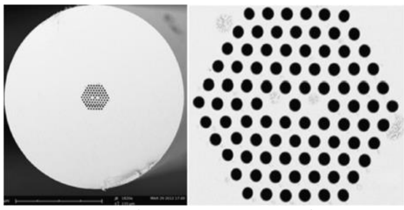


Fig.6. TC-PCF fiber and structure of holes [11]

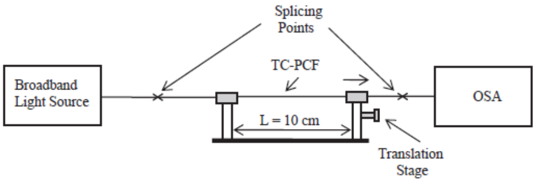


Fig.7. Experimental setup for strain measurement using TC-PCF [11]

Table II is showing the comparison between three types of strain sensors which are discussed in this section. For PBFG sensor it is not an easy job to build elliptical cores, so the fabrication of this type of sensor will be complicated. This sensor has a lower range because it is using the high birefringence phenomena. When the value of applied strain is increased from a certain value the wavelength shift will overlap with each other. In order to increase the range of this sensor, low birefringence must be used and it will cause to sensitivity to reduce further. So there will be a compromise between sensitivity and range, if someone wants to use PBFG based strain sensor. Due to its wide temperature range, PBGF based sensor can be used in electromagnetic and high voltage environments. It is also suitable for manufacturing load cells and monitoring the pavement due to a moving load. PCF based strain sensor has a wide range but it also has large temperature dependence. That mean the error due to temperature variations will be large. So it can be used in situations where temperature remains constant like monitoring the health of piles and bridges structure, traffic flow monitoring at highways, crack and damage detection in water storage tanks and pipelines. It is clear from the table that twin core photonic crystal (TC-PCF) fiber based strain sensor has wide range, large sensitivity and low temperature sensitivity (the error due to change in temperature is much lower than the other two). Due to its smaller size it can be used for life sciences related applications. It is also low cost and easy to fabricate. So TC-PCF based strain sensor must be preferred over other two for structural health monitoring or material damage detection. Some other applications of TC-PCF based strain sensor include the river levee collapse detection and damage detection and estimation for hulls.

TABLE II
COMPARISON BETWEEN PBGF, PCF AND TC-PCF BASED STRAIN SENSORS

Sensor Type	Sensor Range με	Sensitivity *pm/με*	Temp-Range *°C*	Temp-Sensitivity *pm/°C*	Linear Fitting Correlation coefficient	Applications
PBFG Based [9]	0-1000	-0.81	20-93	3.97	99.85%	Strain measurement in Electromagnetic and high voltage environments, moving load pavement monitoring, load cell manufacturing
PCF Based [10]	0-2520	-0.41	25-75	-80	99.82%	Piles and bridges structure monitoring, traffic flow monitoring at highways, crack and damage detection in water storage tanks and pipelines
TC-PCF Based [11]	0-4000	-0.31	25-136	6.68	99.80%	Material’s damage detection, health monitoring of structures (dams, bridges etc), river levee monitoring, damage detection for hulls

IV. TEMPERATURE SENSORS

Optical fiber based temperature sensors has drawn the interest of researchers due to their lot of advantages over conventional temperature measuring device. The main advantages of optical temperature sensors are high sensitivity, wide temperature range, high resolution and low cost. There are several ways of fabricating temperature sensors. In this section three types of temperature sensors are discussed. These are temperature sensor based on core diameter mismatch (CDMM) [14], multimode interference (MMI) based temperature sensor [15] and photonic crystal fiber (PCF) tip sensor [16].

A. CDMM Based Temperature Sensor

As described in section I that temperature sensors can be fabricated by using fiber brag gratings. But these sorts of sensors have a very small range of temperature. Because in high temperature conditions the grating will erase and sensor become extremely inaccurate. Special types of gratings can be formed by using intense UV exposure but it will damage the fiber itself. So some other kind of phenomena is required to cover the higher temperature ranges.

Optical sensor can be formed by using the interference of different modes inside the fiber. And the interference can be created by introducing mode field diameter (MFD) mismatch. So a temperature sensor has been proposed in [14], in which an uncoated single mode fiber is spliced with two multimode fibers creating the core diameter mismatch. The structure of sensor is shown in the figure 8. The uncoated single mode fiber has a diameter of 9µm with a fixed length. The multimode fiber has a core diameter of 50µm and each piece has a length of only 1mm.

The light is launched into 1st multi mode fiber. At splicing point the light rays is coupled to the cladding of single mode fiber due to the mode field diameter mismatch. As the difference between two core radii is very large, so higher modes will also propagate inside the cladding of single mode fiber. When these modes arrive at the second splicing point, then some of the modes propagating inside the cladding of single mode fiber are coupled with the guided modes of multimode fiber. In this way the cladding modes of uncoated single mode fiber and guided modes of multimode fiber will travel in the lead out single mode fiber and will produce interference pattern.

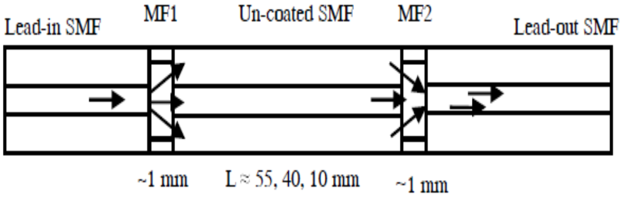


Fig.8. Structure of sensor and core diameter mismatches [14]

Equation (1) shows that the phase difference between these two modes is directly proportional to the difference of effective refractive indices of core and mth cladding mode, provided the length and operating frequency remains the same.

$$\phi^m = \frac{2\pi \Delta n_{eff}^m L}{\lambda} \quad (1)$$

Here Δn_{eff}^m denotes the effective refractive index difference. Wavelength shift is related to the effective refractive index difference and length of the single mode fiber as given in equation (2). So with temperature change, the effective refractive index difference will also change and temperature can be calculated by observing the wavelength shift.

$$\Delta\lambda \approx \frac{\lambda^2}{\Delta n_{eff}^m L} \quad (2)$$

Experiments are carried out and it is found that the sensor has a temperature sensitivity of 0.88 nm / °C and a range from 0 °C to 900 °C. The sensitivity is slightly lower than long period fiber grating based sensor, but the plus point is the range. Sensor has a linear fitting coefficient of about 0.9625 which shows a good linearity over temperature variations.

B. MMI Based Temperature Sensor

A multimode interference based optical temperature sensor is fabricated by placing a multimode fiber between two single mode fibers as shown in figure 9. The core diameter of both single mode fibers is 8µm and they have a cladding of 125µm while the multimode fiber has the 125µm core and air serves as a cladding for this part. Fiber fusion method is used to construct this structure.

Light is launched in the first single mode fiber, when it comes across the multimode fiber it experiences different core radius and hence the mismatch of mode field diameter occur and the light is diffracted and splits in several modes. These diffracted rays propagate inside the core of multimode fiber and interfere with each other. This phenomenon is called multimode interference.

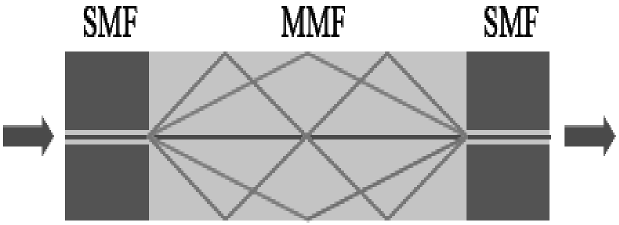


Fig.9. MMI Based Temperature Sensor's Setup [15]

The evanescent waves are formed due to total internal reflection in nearby region. The waves decays very quickly and are highly dependent on the refractive index of the material. If such a material is used whose refractive index quickly changes with the temperature variation (fluoroacrylate or Silicon elastomer), then temperature can be measured by examining the interference pattern of modes travelling in the core of multimode fiber. The change in the evanescent fields is shown in figure 10. It can be clearly seen that with the change in temperature the interference pattern of modes will change.

Experiment is carried out by using fluoroacrylate and Silicon elastomer as the claddings of multimode fiber respectively. The length of multimode fiber is kept 120mm, and it is found that when silicon elastomer is used as cladding, sensor exhibits more sensitivity as compared to fluoroacrylate. The maximum sensitivity of 1 nm/°C is achieved over a temperature range of 30 to 80 °C. It is also found that the temperature can also be measured by directly examining the change in intensity of propagation.

C. PCF Tip Temperature Sensor

Previously in this section only fiber based sensors are presented. MMI based sensor has a very short range, the CDMM based sensor shows the long range of temperature but the problem is the length of sensor. So another sensor technique having wide range and high sensitivity is presented [17]. Sensor is fabricated on the tip of photonic crystal fiber and has a very small size. It is suitable for harsh environments due to its wide range.

The sensor consists of 2D silicon Photonic Crystal (PC) attached to the facet of a normally used single mode fiber having an 8μm core and 125μm cladding. A silicon photonic crystal of dimensions 50 x 50 x 0.52 μm is attached on the tip of fiber. The structure of fiber is shown in figure 11. Firstly the chip is fabricated by using GOPHER process [18] and then it is combined on the tip of fiber by using silicon welding. The photonic crystals have the property of reflectance. The crystal structure of 2D PC changes with respect to change of temperature. So the temperature can be easily measured by monitoring the reflectance from the 2D-silicon PC.

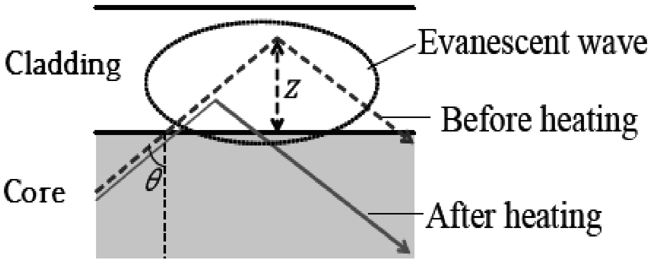


Fig.10. Evanescent wave before and after heating [15]

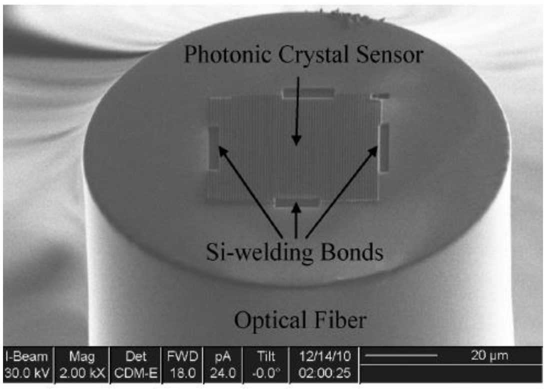


Fig.11. Silicon-Photonic Crystal on the single mode fiber [16]

Experiment is carried out by launching light from a broadband source to the sensor with the help of a 3dB coupler and fiber cable. The reflection occurs from the Si-PC and the spectrum of reflected waves is monitored with the help of an optical spectrum analyzer. The sensor itself is placed inside a furnace, in which temperature can be varied from 0 to 700 °C. The value of reflectance is measured on different temperatures. Spectral shift in the spectrum are recorded and in this way the temperature is measured.

Results have shown that the sensor has a sensitivity of 0.11 nm / °C which is higher than the bare fiber brag grating and LPG. Sensor can measure the temperature up to 700 °C. Higher value (0.99852) of linear fitting correlation coefficient is showing the excellent linearity of the sensor. The sensor is suitable for temperature measurement in high temperature environments.

Parameters of all three sensors discussed in this section are summarized in the table III. Temperature sensor based on the core diameter mismatch has a wide range, but it has a bigger size and low sensitivity. To increase the sensitivity the size of uncoated single mode fiber must be increased in order to get more number of dips per unit length. In this way the overall length of sensor will increase further. So there must be a compromise between the sensor size and sensitivity. This type of sensor is suitable for temperature monitoring in gas turbines and combustion engines, geo-thermal instrumentation and taking measurements in hazardous environments. The multi mode interference based sensor has a very small temperature range. In order to increase the temperature range, the cladding refractive index of multimode fiber must be decreased. But in this way the effective refractive index of fiber will increase, that will result a wide acceptance angle and hence the sensitivity will decrease. So here we also have a compromise between range and sensitivity. Due to small temperature range this sensor is suitable for human body temperature monitoring during MRI or monitoring the temperature of industrial conveyor belts. On the other hand Si-PCF based sensor has a wide range, good sensitivity, linear response and very small size. So Si-PCF based sensor can cover the applications of CDMM and MMI based sensors. Further applications of this sensor are in medical science, transmission line and power transformer temperature monitoring, fire detection in buildings and mines and temperature monitoring in high voltage environments. Thus we can say that Si-PCF based sensor is better than CDMM and MMI based sensors in terms of performance and applications.

TABLE III
COMPARISON BETWEEN CDMM, MMI AND Si-PC ON TIP OF SMF BASED TEMPERATURE SENSORS

Sensor Type	Sensor Range *°C*	Sensitivity *nm/°C*	Sensor Size	Linear Fitting Correlation coefficient	Applications
CDMM Based [14]	0-900	0.088	55mm	96.250%	Gas turbine and combustion engine temperature monitoring, geo-thermal instrumentation, harsh environment measurements
MMI Based [15]	30-80	0.1	140mm	98.638%	Temperature monitoring for industrial conveyor belts, body temperature monitoring during MRI, temperature monitoring in RF environment
Si-PCF Based [16]	0-700	0.11	20mm	99.825%	Medical Science, transmission line and power transformer temperature monitoring, fire detection in mines, high voltage switches and relay's temperature monitoring

V. CONCLUSION

Different types of optical fiber based pressure, temperature and strain sensors along with their practical applications are discussed in this paper. And it has been shown by comparison that extrinsic fabry perot based pressure sensor has higher pressure range and sensitivity over fiber brag grating (FBG) and super structure fiber grating (SFG) based pressure sensors. For strain sensors; twin core photonic crystal fiber based strain sensor shows better results than photonic band-gap fiber (PBGF) and photonic crystal fiber (PCF) based sensor. Similarly for temperature sensors, the sensor formed by welding a Si-Photonic Crystal on the tip of single mode fiber has high sensitivity and wide range when compared to multimode interference and core diameter mismatch based optical temperature sensors.

REFERENCES

[1] Jun Huang,Zude Zhou, Dongsheng Zhang,and Qin Wei, "A fiber bragg grating pressure sensor and its application to pipeline leakage detection," Hindawi Publishing Corporation Advances in Mechanical Engineering Volume 2013, Jun 2013.

[2] Chia-Min Lin, Yi-Chi Liu, Wen-Fung Liu, Ming-Yue Fu, Hao-Jan Sheng, Sheau-Shong Bor, and Chuen-Lin Tien, "High-sensitivity simultaneous pressure and temperature sensor using a superstructure fiber grating,"IEEE Sensors Journal, Vol. 6, No. 3, June 2006, pp. 691-696.

[3] Wenhua Wang, Qingxu Yu, Fang Li, Xinlei Zhou, and Xinsheng Jiang, "Temperature-insensitive pressure sensor based on all-fused-silica extrinsic fabry–pérot optical fiber interferometer," IEEE Sensors Journal, VOL. 12, NO. 7, JULY 2012, pp.2425-2429.

[4] M.G. Xu, L. Reekie, Y. T. Chow, and J. P.Dakin, "Optical in-fiber grating high pressure sensor," Electronics Letters, vol. 29, no. 4, pp. 398–399, 1993.

[5] Raman Kashyap, "Fiber bragg gratings," 1st edition, Academic press 1999, pp.91-92.

[6] B.-O. Guan, H.-Y. Tam, X.-M. Tao and X.-Y. Dong, "Simultaneous strain and temperature measurement using a superstructure fiber Bragg grating," IEEE Photon. Technol. Lett., vol. 12, no. 6, Jun. 2000, pp. 675–677.

[7] J. S. Sirkis, "Optical fiber strain sensing in engineering mechanics," Topics Appl. Phys., vol. 77, 2000. pp. 233–273.

[8] Qingxu Yu and Xinlei Zhou, "Pressure sensor based on the fiber-optic extrinsic Fabry-Perot interferometer," Photonic Sensors, Volume 1, Issue 1, March 2011 pp 72-83.

[9] Gilhwan Kim, Taiyong Cho, Kyujin Hwang, Kwanil Lee, Kyung S. Lee, Young-Geun Han, and Sang Bae Lee, "Strain and temperature sensitivities of an elliptical hollow core photonic bandgap fiber based on Sagnac interferometer," Optical Society of America, Vol. 17, No. 4 / Optics Express, Feb 2009.

[10] Huaping Gong, Chi Chiu Chan, Member, Lihan Chen, and Xinyong Dong, "Strain sensor realized by using low-birefringence photonic-crystal-fiber-based sagnac loop," IEEE Photonics Technology Letters, VOL. 22, NO. 16, Aug 2010, pp. 1238-1240.

[11] Khurram Karim Qureshi, Zhengyong Liu, Hwa-Yaw Tam, M. Fahad Zia, "A strain sensor based on in-line fiber Mach–Zehnder interferometer in twin-core photonic crystal fiber," Elsevier B.V. Optics Communications, July 2013, pp.68-70.

[12] O. Frazão, J. M. Baptista, and J. L. Santos, "Temperature-independent strain sensor based on a Hi-Bi photonic crystal fiber loop mirror," IEEE Sensors J., vol. 7, no. 10, pp. 1453–1455, Oct. 2007.

[13] H. Y. Fu, H. Y. Tam, L. Shao, X. Dong, P. K. A. Wai, C. Liu, and S. K. Khijwania, "Pressure sensor realized with polarization-maintaining photonic crystal fiber-based Sagnac interferometer," Appl. Opt., vol. 47, no. 15, pp. 2835–2839, May 2008.

[14] Linh Viet Nguyen, Dusun Hwang, Sucbei Moon, Dae Seung Moon, and Youngjoo Chung, "High temperature fiber sensor with high sensitivity based on core diameter mismatch," OSA, Vol. 16, No. 15 / Optics Express, July 2008, pp.11369-11375.

[15] Y. Kushida, H. Fuk ano, and S. Taue, "High-sensitivity optical fiber temperature sensor using multimode interference," IEIEC 18th conference, 2013.

[16] Bryan Park, J. Provine, Il Woong Jung, Roger T. Howe, and Olav Solgaard, "Photonic crystal fiber tip sensor for high-temperature measurement," IEEE Sensors Journal, Vol. 11, NO. 11, Nov 2011, pp.2643-2648.

[17] W. Suh, "Photonic crystal slabs: Theory and applications," Ph.D. dissertation, Stanford Univ., Stanford, CA, 2006.

[18] I. Jung, B. Park, J. Provine, R. T. Howe, and O. Solgaard, "Monolithic Si photonic crystal slab fiber tip sensor," in Proc. IEEE/LEOS Int. Conf. Opt. MEMS and nano-photonics, Aug. 17–20, 2009, pp. 19–20.

Muhammad Sajid Iqbal received his BS degree in Telecommunication from National University of Computer and Emerging Sciences (NUCES), Pakistan in 2011, and his MS degree in Electrical Engineering from King Fahd University of Petroleum and Minerals (KFUPM), Saudi Arabia in 2015. He worked two years in NUCES-FAST as an Lab Engineer in Electrical Engineering Department and the worked for two years as Research Assistant in Electrical Engineering Department of KFUPM, Saudi Arabia, where he performed research on fiber optic based sensors, array antennas, patch antennas, circular waveguides and side-lobe level suppression in symmetric and non-symmetric array antennas. Currently he is working in Electrical Engineering Department of NUCES.

Dr. Khurram Karim Qureshi received a BSc degree with honors in Electrical Engineering from the University of Engineering and Technology, Pakistan, in 1999 and a PhD degree also in Electrical Engineering from the Hong Kong Polytechnic University in 2006. He is currently an Associate Professor with the Electrical Engineering Department of KFUPM where he is doing research on Optical performance monitoring, Optical Signal Processing, Gain clamping techniques in Optical Amplifiers, Fiber Lasers and Fiber Sensors. He is also serving as a senior member of IEEE.