Optical Fiber MEMS Pressure Sensor

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Abstract: This paper describes the fabrication and working of an optically interrogated microelectromechanical system (MEMS) pressure sensor. The entire MEMS structure is fabricated directly on an optical fiber. The working principle of optical fiber pressure sensor is based on Fabry–Pérot interferometer, by a new micromachining process. The study of pressure sensor fabricated on an optical fiber shows an approximately linear response to static pressure (0–80 psi). This sensor is used in wide applications where small size is advantageous, such as medical and aerospace industries.

Keywords: Fabry–Pérot interferometer, MEMS, Optical Fiber, Pressure Sensing.

I. INTRODUCTION

Pressure sensors are devices which are used for pressure measurement of gases or liquids, which have several applications from automotive and aerospace to healthcare industry. An optical fiber has a diameter slightly thicker than that of a human hair (250 µm) and is a flexible, transparent fiber made by drawing glass (silica) or plastic[1]. Optical fibers are used most often to transmit light between the two ends of the fiber and find wide usage in fiber-optic communications, where they permit transmission over longer distances and at higher bandwidth (data rates) than electrical cables. Fibers are used instead of metal wires because signals travel along them with less loss. Another advantage over metal wires is that fibers are immune to electromagnetic induction, a problem from which metal wires suffer excessively. In this paper, the fabrication and working of a pressure sensor on the tip of a fiber optic cable is studied.

Micro-electromechanical systems (MEMS) are micrometer scale devices that integrate electrical and mechanical elements. The main advantage of using MEMS is that they are economical and are very precise in sensing pressure. These are fabricated using methods like those used to construct integrated circuits. Size makes it possible to integrate it into wide range of systems. Feature sizes may be made with size of the order of the wavelength of light, thus making them attractive for many optical applications, hence the reason for studying of fabrication and working of Optical Fiber MEMS Pressure Sensor.

Whereas current miniature fiber-optic sensors usually involve several different materials in fabrication, the proposed sensor is made of commercial silica fibers only, resulting in an all fused-silica structure with excellent mechanical properties[2]. It eliminates the problem of thermal expansion mismatch between different materials, extending the sensor's high-temperature capability to the limit determined only by silica itself. Therefore, this miniature sensor has great potential to operate reliably at elevated temperatures (up to 530^{o}C). It may find applications where high temperature and/or small size are important.

This paper further describes about the Fabry-Perot Interferometer, design and fabrication of the sensor, its working principle, analysis, application along with its future scope.

II. FABRY-PEROT INTERFEROMETER

The sensor works on the principle of Fabry–Pérot interferometer. A Fabry–Pérot interferometer (FPI) is typically made of transparent plate with two reflecting surfaces (called as flats)[13]. The reflective surfaces in

Fabry–Pérot interferometer are facing each other and the flats are made in a wedge shape to prevent the rear surfaces from producing interference fringes. An inverted image of the source is produced on focusing lens after the pair of flats if the flats were not present; all light emitted from a point on the source is focused to a single point in the systems image plane. The wedge angel is highly exaggerated in this illustration; only a fraction of degree is necessary to avoid ghost fringes. Low-finesse verses high-finesse images correspond to mirror reflectivities of 4% (Bare glass) and 95%[14].

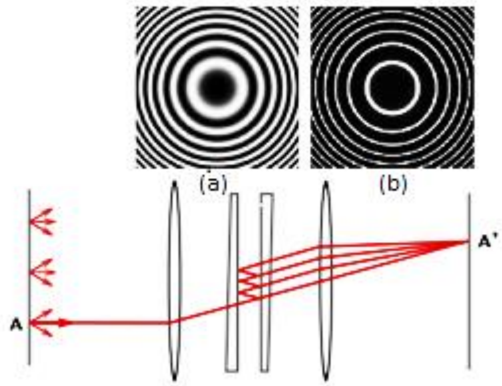


Fig.1 Fabry-Perot Interferometer, using a pair of partially reflective slightly wedged optical flats[3]

Illumination is provided by a diffused source which is set at the focal plane of a collimating lens. A focusing lens after the pair of flats would produce an inverted image of the source if the flats were not present; all light emitted from a point on the source is focused to a single point in the system's image plane. In the figure given (Fig.1), only one ray emitted from point A on the source is traced. As the ray passes through the paired flats, it is multiply reflected to produce multiple transmitted rays which are collected by the focusing lens and brought to point A' on the screen. There is an appearance of concentric rings of the interference pattern. The sharpness of the rings depends on the reflectivity of the flats. If the reflectivity is high, resulting in a high Q factor, monochromatic light produces a set of narrow bright rings against a dark background. A Fabry–Pérot interferometer with high Q is said to have high finesse[4].

An optical fiber consists of a thin, low-loss glass wire with a center or core region having a slightly higher refractive index than its surrounding region or cladding. Light enters the core region by total internal reflection (TIR) at the core-cladding interface.

III. DESIGN AND FABRICATION

The new process for micromachining which is used on a flat fiber end face that includes photolithographic patterning, wet etching of a cavity, and anodic bonding of a silicon diaphragm[18].

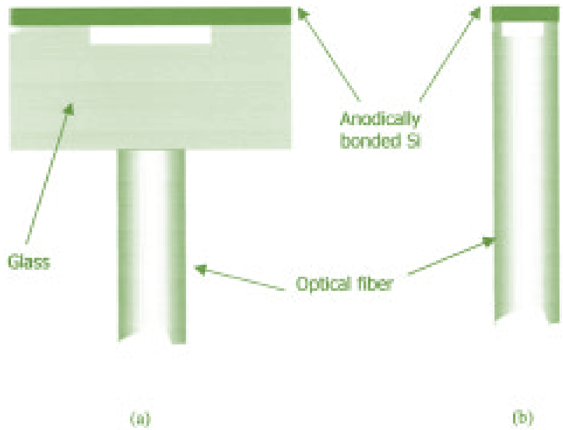


Fig.2 Illustration of two configurations of fiber optically interrogated MEMS pressure sensors based on Fabry–Pérot interferometry.

Fig.2 (a) Shows the usual configuration, which consists of a glass plate with a shallow cylindrical cavity etched into one surface with the cavity covered by a thin silicon diaphragm that has been anodically bonded to the patterned glass wafer, Fig.(b) Shows the configuration where the cavity is formed on the end of the optical fiber and a silicon diaphragm is bonded anodically. The configuration of the Fabry–Pérot interferometric optical fiber pressure sensor reported here is shown in Fig. 1(b)[16]. The silicon diaphragm and the cavity–fiber interface act as reflectors forming a Fabry–Pérot interferometer. Pressure inside causes the diaphragm to move, which causes change in the Fabry–Pérot reflectivity, and allowing measurement of pressure.

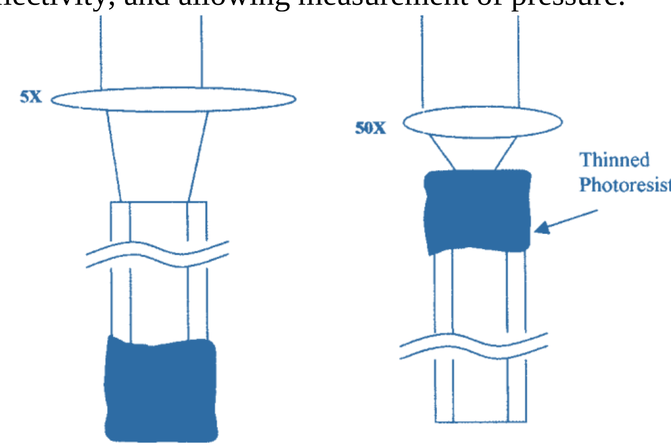


Fig.3 Schematics of two photoresist exposure techniques.

Fig.3 (a) The first technique involves coupling of blue laser light (λ=457.9 nm) into the opposite fiber end using a low magnification microscope objective (5X) so that the focused laser beam diameter is comparable to the core diameter. Fig.3 (b) The second technique simply directs laser light onto the photoresist-coated fiber end face using a high magnification objective (50X). In this case, the fiber is positioned away from the beam focal point by an amount that corresponds to the required beam diameter. The optical fibers used for the fabrication were borosilicate multimode glass fibers (Techman International Corporation Inc.; the index of refraction of borosilicate glass is 1.5098 at 850 nm). Two fiber sizes were used with cladding diameters of 200 and 400 µm and corresponding core diameters of 190 and 360 µm, respectively. A micromachining process for use on a flat fiber end face has been developed. This includes photolithographic patterning, wet etching of a cavity, and anodic bonding of a silicon diaphragm. Fabrication begins with a section of fiber in which both fiber ends were first cleaved and then polished using 0.3-μm grit size polishing paper for surface flatness. A thin layer of thinned Shipley 1818 positive photoresist (photoresist: thinner = 2:1) was applied on one fiber end followed by soft baking for 30 min in an oven at 90 C. The cavity on the fiber end face was formed by photolithographic patterning utilizing two different exposing techniques (Fig. 3). This was followed with wet etching of the fiber core area in a buffered hydrofluoric acid solution[5].

The first technique involved coupling blue Argon laser light (λ=457.9 nm) into the opposite fiber end from the one on which fabrication would take place using a low-magnification microscope objective (5X) whereas the second technique simply directed this blue light onto the photoresist-coated fiber end face using a high magnification objective (50X). The first technique exposed the photoresist leaving a circular area of photoresist whose diameter was equal to that of core diameter of the fiber, whereas the second technique caused the photoresist to develop leaving a circular area whose diameter was equal to the beam diameter. This latter technique was found to be less accurate in forming a calculated cavity diameter since the 50 objective produces diffraction effects and spatial spreading of the beam at the perimeter of the laser beam (see Fig. 2) as one moves off-focus. The appropriate exposure power depends on the photoresist thickness and can be determined in conjunction with exposure time for a given case[17].

Anodic bonding[6] which is used commonly in MEMS for bonding glass and silicon wafers was used to bond a thin silicon diaphragm on to the fiber end. We envisioned that this bonding mechanism should work for bonding silicon to optical fibers since optical fibers are made out of glass, but our preliminary bonding experiments suggested that telecommunication fibers made out of pure silica likely contained too few alkali ions for the anodic bonding mechanism. We identified and used borosilicate glass fibers that do contain alkali ions for our experiments. Fibers with a cavity already formed at the end face were base-cleaned and then coated with silver paint (except at the end) in order to make an electrical connection. Pieces of ultra-thin silicon wafers of known thickness (4–10 μm) were utilized. The fiber end face was positioned so that its entire area is in contact with silicon that was in turn in contact with a hot plate heated to 400 C. Application of a voltage of 1000 V between the fiber and silicon for 3 min resulted in very strong bonding.

IV. WORKING

The silicon diaphragm and the cavity–fiber interface act as reflectors forming a Fabry–Pérot interferometer. The optical pressure detection scheme is based on the fact that the reflected light from the sensor is spectrally shifted. Exposing the diaphragm to the pressure p to be measured changes the gap Ls. Hence, by measuring Ls the applied pressure ‘p’ can be determined. Different pressure ranges can be accommodated by appropriately selecting thickness and diameter of the diaphragm to keep the maximum deflection of similar value and maintain a linear relation between pressure and deflection.

When a light is emitted from LED it gets reflected from the cavity-fiber interface, and rest of the light gets refracted in the cavity which finally gets reflected from the silicon diaphragm creating a shift (delay) in light[7].This delay can be calculated as: $t = 2L/c$ where t is the time delay, L is the length of the cavity and c is the speed of light[21].

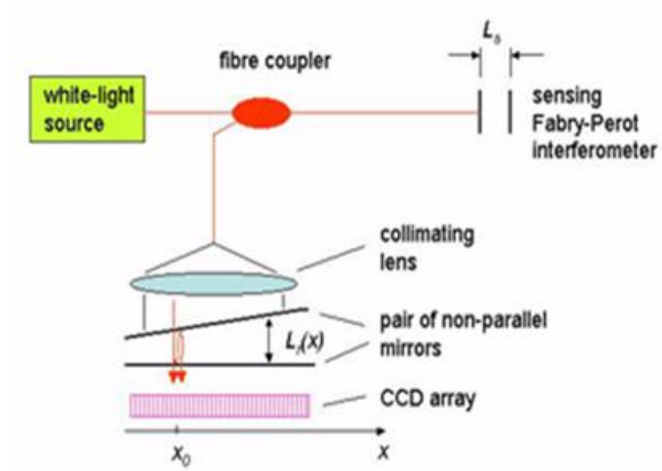


Fig.4 Setup of fiber optic pressure sensor including the light source, fiber coupler, collimating lens and wedge mirrors.

A large number of short pulses are generated as a form of light. These pulses are emitted in a random fashion with no fixed phase relation between them. As a result, they do not interact or interfere with each other and for the following it is sufficient to consider a single pulse only. Interference, which is a signal containing information about Ls, takes place only if the two pulses generated from the same original pulse can be brought back to overlap again. This is achieved by employing a second (or readout) interferometer[8].

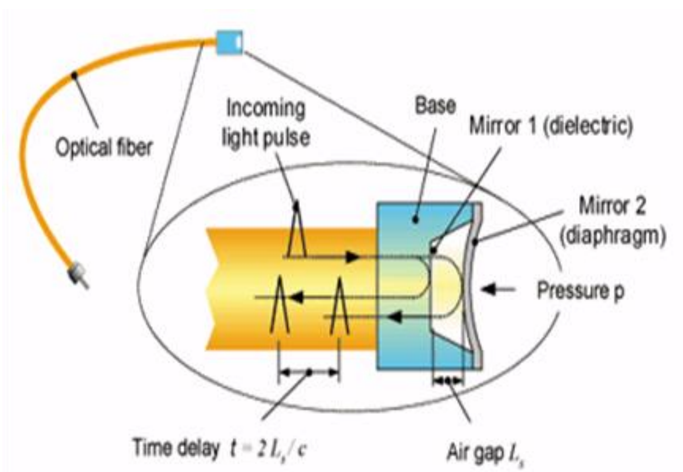


Fig.5 Schematic of pressure transducer based on Fabry-Perot cavity

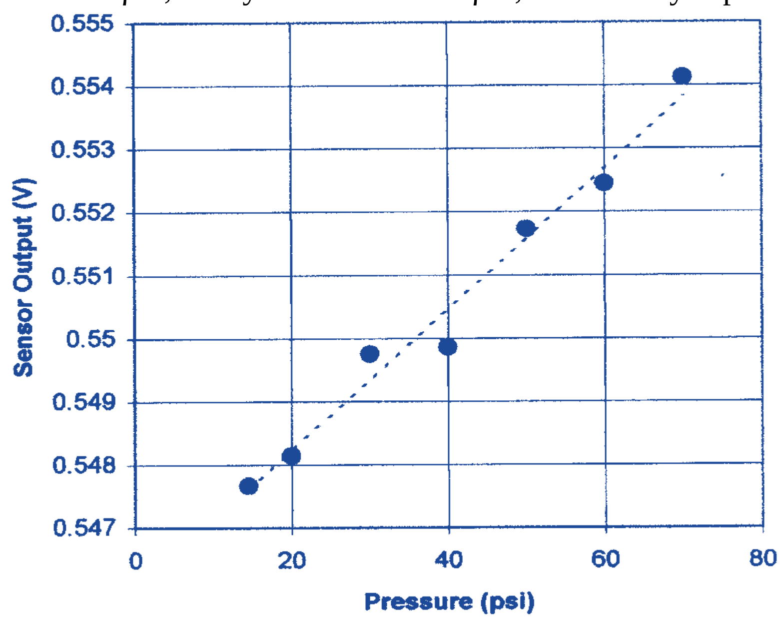
The reflected light was collected back through the same fiber. Now, the reflected light and delayed reflected light have a phase difference which creates an interference pattern. These reflected lights are then refracted through the fiber coupler onto a collimating lens. From the collimating lens, the rays become parallel to each other. After that a wedge (which is made of two non-parallel mirrors at a certain angle) is placed in order to achieve an interference on a CCD array mounted behind the wedge. For measuring the pressure applied we use the Fabry-Perot interference phenomenon in which the air gap Lr(x) depends on the position x along the wedge and a maximum interference signal is generated at the position x0 where Lr(x0) is exactly matched to the gap

Ls of the sensing interferometer[9]. This position x0 is easily determined by a CCD array mounted behind the wedge.

V. ANALYSIS

In both cases (first and second technique as shown above), focusing of the photoresist-coated fiber was done using red light through the same objective and with the use of a video monitor. A typical exposure power in one of our experiments was 100W exposed for 60–80µs using the first technique whereas in the second technique, 400 W exposed for 30–40 s worked well[20].

Fig. 4. Plot sensor output in volts versus pressure in psi. Each pressure point is an average of 100 readings. A broad-band LED centered at 850 nm was used as the illumination source. The best fits to the data gives a sensitivity of about 0.11mV/psi with 0.01mV/psi departure from linearity[22]. The sensor parameters are as follows: diaphragm thickness is 7 µm, cavity diameter is 135 µm, and a cavity depth is 0. 640 µm.



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VI. APPLICATION AND FUTURE SCOPE

The optical fiber pressure sensor has a number of applications, where sensing of pressure is required. Some of them are: In diving, to indicate how deep you are, and another one for checking the oxygen level in your bottle; pressure monitoring in air conditioning units; a variety of blood pressure monitoring devices; a wide range of use in industrial markets (think gas pipes, etc.); engine injection systems; in some weighing devices; and tyre pressure monitoring systems in cars and trucks[11][15].

The fiber optic sensor share of this global market is small and estimated to be at around $100 million. However, the potential is tremendous and fiber-optic biomedical sensors provide capabilities and features that cannot be otherwise obtained[12]. High cost remains a barrier, however, as does the lengthy development cycles and required regulatory process. Sensor design and development is not trivial, and proper material selection, design, biocompatibility, patient safety, and other issues must be considered. Nevertheless, there are already several successful products in the market and more to come[19].

VII. CONCLUSION

Due to its multiple advantages like high precision and small size, the fiber optic pressure sensor can be used in various industries. It uses a new micromachining process for its fabrication on the tip of optical fiber and the pressure is measured using the principle of Fabry Pérot interferometer which works on the phenomenon of interference of light. The pressure is analyzed and the results are a linear response in voltage with change in pressure (in psi).

VIII. REFERENCES

[1] Yixian Ge, Kaijie Cai, Tingting Wang, Jiahong Zhang, "MEMS pressure sensor based on optical Fabry–Perot interference", Elsevier, Optik 165 (2018) 35–40

[2] M. Fátima Domingues, Camilo A. Rodriguez, Joana Martins, Cátia Tavares, Carlos Marques, Nélia Alberto, Paulo André, Paulo Antunes, "Cost-effective optical fiber pressure sensor based on intrinsic Fabry-Perotinterferometric micro-cavities", Elsevier, Optical Fiber Technology 42(2018) 56-62

[3] M. T. Wlodarczyk, "Long-Life Fibre-Optic Pressure Sensors for Control and Monitoring of Combustion Engines"

[4] Éric Pinet, "Pressure measurement with fiber-optic sensors: Commercial technologies and applications"

[5] Jonas H. Osório, Giancarlo Chesini, Valdir A. Serrão, Marcos A. R. Franco & Cristiano M.B. Cordeiro, "Simplifying the design of microstructured optical fibre pressure sensors"

[6] Sven Poeggel , Daniele Tosi , DineshBabu Duraibabu , Gabriel Leen , Deirdre McGrath and Elfed Lewis, "Optical Fibre Pressure Sensors in Medical Applications", Sensors 2015, 15, 17115-17148; doi:10.3390/s150717115

[7] X.Y. Liu, M. O'Brien, M. Mwangi, X.J. Li, and G.M. Whitesides∗, "PAPER-BASED PIEZORESISTIVE MEMS FORCE SENSORS"

[8] Qingxu YU and Xinlei ZHOU, "Pressure Sensor Based on the Fiber-Optic Extrinsic Fabry-Perot Interferometer", Photonic Sensors (2011) Vol. 1, No. 1: 72-83

[9] Ming-Da Zhou & Chuan Yang & Zhiwen Liu & Joshua P. Cysyk & Si-Yang Zheng, "An implantable Fabry-Pérot pressure sensor fabricated on left ventricular assist device for heart failure", Biomed Microdevices (2012) 14:235–245

[10] Jiali Zhu, Ming Wang, Lu Chen, Xiaoqi Ni , Haibin Ni, "An optical fiber Fabry–Perot pressure sensor using corrugated diaphragm and angle polished fiber", Elsevier, Optical Fiber Technology 34(2017) 42-46

[11] Hin-Leung Chau and Kensall D.Wise, "An Ultraminiature Solid-state Pressure Sensor for a Cardiovascular Catheter", IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 35, NO. 12. DECEMBER 1988

[12] R. A. Pinnock, "Optical pressure and temperature sensors for aerospace applications," Sensor Rev., vol. 18, no. 1, pp. 32–38, 1998.

[13] Y. Kim and D. P. Neikirk, "Micro machined Fabry–Pérot cavity pressure transducer," IEEE Photon. Technol. Lett., vol. 7, pp. 1471–1473, Dec. 1995.

[14] A. Mendez, T. F. Morse, and K. A. Ramsey, "Micromachined Fabry–Pérot interferometer with corrugated silicon diaphragm for fiberoptic sensing applications," in Proc. SPIE—Int. Soc. Optical Engineering, vol. 1793, 1993, pp. 170–182.

[15] Perot, A; Fabry, C(1899). "On the application of interference phenomenon to the solution of various problems of spectroscopy and metrology". Astrophysical Journal.9:87.

[16] Don C. Abeysinghe, Samhita Dasgupta, Joseph T. Boyd, and Howard E. Jackson, "A Novel MEMS Pressure Sensor Fabricated on an Optical Fiber" IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 13, NO. 9, SEPTEMBER 2001

[17] M.H.Beggans,D.I.Ivanov,S.G.Fu,T.G.Digges,Jr., and R.Farmer, "Optical pressure sensor head fabrication using ultra-thin silicon wafer anodic bonding," in Proc. SPIE—Int. Soc. Optical Engineering., vol. 3680, 1999, no. II, pp. 773–782.

[18] M. D. Giovanni, Flat and Corrugated Diaphragm Design Handbook. New York: Mercel Dekker, 1992.

[19] D. Angelidis and P. Parsons, "Optical micromachined pressure sensor for aerospace applications," Opt. Eng., vol. 31, pp. 1638–1641, 1992.

[20] P. Melvås, E. Kälvesten, P. Enoksson, and G. Stemme, "A free-hanging strain-gauge for ultraminiaturized pressure sensors," Sens. Acuators A, vol. 97–98, pp. 75–82, 2002.

[21] Y. Kanda, K. Matsuda, C. Murayama, and J. Sugaya, "The mechanism of field assisted silicon-glass bonding," Sensors & Actuators, vol. A21, pp. 939–943, 1990.

[22] J. Zhou, S. Dasgupta, H. Kobayashi, J. M. Wolff, H. E. Jackson, and J. T. Boyd, "Optically interrogated MEMS pressure sensors for propulsion applications," Opt. Eng.