Polydimethylsiloxane fabricated Optical Fiber Sensor capable of measuring both large axial and shear strain

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Abstract. In harsh environments, structures often undergo large strain where few traditional fiber optic sensors could survive. A Polydimethylsiloxane(PDMS) fabricated large axial/shearing strain sensor is proposed. The sensor is fabricated by directly coupling a conventional signal mode fiber into half cured PDMS material. Photo detector was utilized to investigate the transmission characteristic of 1310nm infrared laser relating with the applied axial/shearing strain. The results show that the proposed sensor survived an axial strain of $7.79\times10^{6}\mu\varepsilon$; a shear of $6.49\times10^{4}\mu\varepsilon$ with a good linearity and repetition. This indicates that the proposed sensor can potentially be used as strain sensing elements in Structure Health Monitoring systems under earthquake or explosion
Keywords: Structure health monitoring, polydimethylsiloxane, strain sensor, optical fiber

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1 Introduction

Fiber optic sensor (FOS) has received much attention in the field of Structure Health Monitoring (SHM) due to its advantages of low weight, small size, high sensitivity multiplexing ability, free of electromagnetic interference and long durability[1]. Based on the transduction mechanism which includes intensity, phase, interferometry, scattering, polarization, modal content and so on, a variety of strain sensors have been realized[1-3]. As strain is of primary concern in the SHM systems, FOS strain sensor not only indicates the strain statues of key structures but also provide information to strain modal analysis[4], structure damage detection/assessment[5], etc. In addition, strain sensing is the core of many other types of meter such as weight scale meter, acceleration meter and so on. Many SHM systems in China employed large quantities of strain sensors[6-9]. In harsh environments, structures often undergo large strains leading to progressive collapses[10]. Limited by the mechanical properties of glass, the bare FOS strain sensor can only stand an axial strain of $3000\mu\varepsilon$ and extremely fragile under shear strain[1], which cannot satisfy the need of strain monitoring of structures under extreme environment excitation such as earthquake, explosion, tsunami, etc.

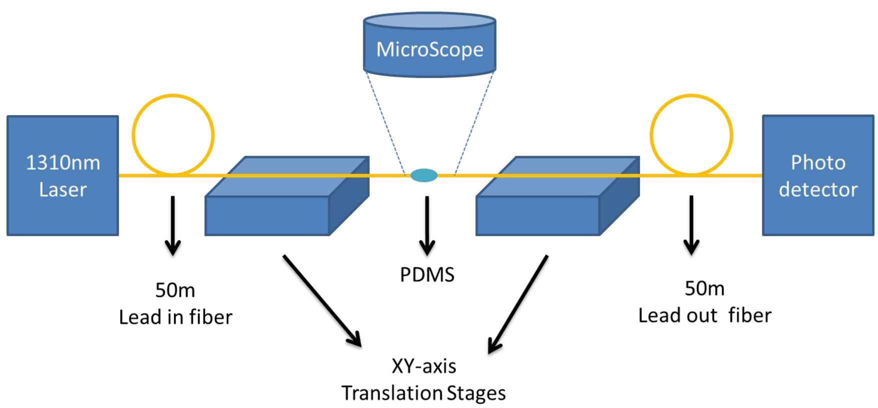
One common way to toughen fiber optic sensor is relaying on proper packages. For example, Zhi Zhou, et al brought forward a novel crack sensor (also named as large strain sensor) by using a spring to share most part of strain which can experience a strain up to $100,000\mu\varepsilon$ [11]. Genda Chen, et al proposed CO_2 laser induced LPFG sensor and by utilizing packaging to transfer strain[12]. Ying Huang, et al proposed a three-layer packaged structure extrinsic Fabry–Perot interferometer-based strain sensor which can measure a strain up to $120000\mu\varepsilon(12\%)$ [13]. However, although the packaged sensor has the potential to measure a larger axial strain, the packaged sensor no longer possess the advantages of the bare FOS strain sensor mentioned earlier, meanwhile the complex fabrication process and uncertainty of strain transfer mechanism of the packaged sensor brings more limitations.

Recently, the most popular material for making optical waveguides- polydimethylsiloxane (PDMS) was introduced[14, 15]. It is highly light-transparent, chemically inert, thermally stable, permeable to gases, isotropic and homogeneous, simple to handle. These properties make PDMS the ideal material to fabricate Fiber Optic Sensors.

The paper presents a way to measure both large axial and shear strain using PDMS as the waveguide and sensing part. This paper proposed a simple way to prepare the sensor by directly coupling a conventional single mode fiber into PDMS material. The relationship between axial/shearing strain and transmission characteristic of 1310nm infrared laser was investigated. Results showed that the proposed sensor can undergo a strain up to $7.79\times10^{6}\mu\varepsilon$ axial strain and $6.49\times10^{4}\mu\varepsilon$ shearing strain. The proposed large axial/shearing strain sensor offers the advantages of easy fabrication, simplicity of signal processing and cost effective and opens a new area for large Axial and shearing strain measurement in SHM.

2 Experimental setup

The experimental setup is shown in Fig.1 which consists of a 1310nm laser source(Model CY-300, -7dBm output optical power), photo detector(Model CY-860, InGaAs, dynamic range -70dBm-6dBm), XY-axis translation stage(Model LGY60-L, displacement range +- 6.5mm, minimum displacement 0.01mm), micro-scope(Model auchans, magnification ratio 20x-800x), 50m lead in and lead out optic fiber. The preparation of the sensor included four steps which were preparation of PDMS material, cut and align the optical fiber, fabrication of sensor and curing of PDMS material. Later, the transmission properties of the sensor were analyzed as a function of its axial/shear strain.



(a)

(b)

Fig. 1 (a) Schematic view of fabrication process (b) Lab view of experimentation

The PDMS material used was Dow Corning Sylgard 184-1. It is colorless and has a tensile strength of 6.7MPa. Refractive index of the material at 1321nm is 1.4028. Those features indicate the material is optimal to be used as sensitive elements of the sensor. The product is served as two-part liquid component kits, component A is the base material and component B is the curing material. When component A and component B were thoroughly mixed at the ratio of 10 to 1, the mixture cures to a flexible elastomer. The curing process was gradual which was 48 hours at the temperature of $25°C$. However, the curing process can be accelerated by heating. The curing time at $100°C$ was reduced to 35 minutes. In the experiment, when the material was half cured at the temperature of $20°C$ for 8 hours, the material's viscidity increased and presented as a transforming stage from fluid to solid indicating it is ready to be connected to the optical fiber.

Before connecting the PDMS material with the optical fiber, the optical fiber needs to be aligned axially. This procedure was realized by connect the left side of the optical fiber to a 1310nm Laser source, and the right side of the optical fiber to a photo detector which was shown in Fig.1. By gradually adjust the translation stage and visually examine the micro scope image, the optical fibers were aligned roughly. Precisely alignment was achieved by adjusting the translation stage again to get the maximum power at the photo detector. Finally, axially move the translation stage to reserve a gap for the PDMS material to be applied. The aligned optical fiber is shown in Fig.2(a).

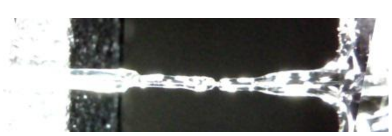
The sensor was then fabricated by using needle tubing filled with half cured PDMS material. At first the needle tubing was adhered at the left end, after that gradually drag the needle tubing to reach the right end. Then the needle tubing was removed at last leaving a PDMS drop on the left end, shown in Fig.2(b). The final step was to remove the drop and adjust the translation stage axially to get expected gauge length and the maximum transmission optic power.

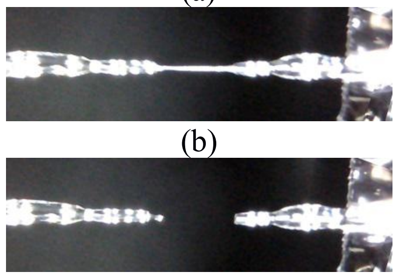
The material was cured again at the temperature of $20°C$ for 40 hours. During the curing process the PDMS material had a gradual increase in viscosity followed by gelation and conversion to a solid elastomer. The transmission optical power which was initially -10dBm dropped to -23.87dBm. This process can be accelerated by increasing the curing temperature. The prepared sensor is shown in Fig.2(c).

After the sensor was prepared, applied strain were given by adjusting the translation stage. The transmission properties of the sensor were analyzed as a function of its axial/shear strain.

2.1 Axial strain measurement

Axial strain was applied on the sensor by adjusting left translation stage at a step of 0.01mm. Meanwhile, the transmission power was measured using a photo detector. Shown in Fig.3(a), the initial gauge length of the sensor is 0.077mm which was measured by the micro-scope precisely.





(a)

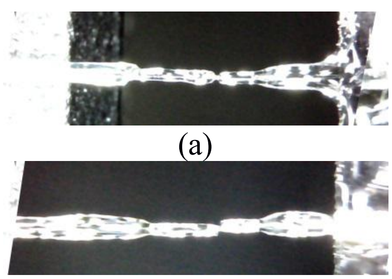
(b)

(c)

Fig. 2 (a) Sensor which zero axial strain was applied (b) Sensor which maximum strain was applied (c) Sensor which was failed due to large axial strain.

2.2 Shear strain measurement

Shown in Fig.5(a), the initial gauge length of the sensor is 0.077mm which was measured by the micro-scope precisely. Quite like the axial strain, shear strain was applied on the sensor in the same way by adjusting the translation stage transversely at a step of 0.01mm. Meanwhile, the transmission power was measured using a photo detector.



(a)

(b)

Fig. 3 (a) Sensor which zero shear strain was applied (b) Sensor which maximum shear strain was applied

2 Results & discussion

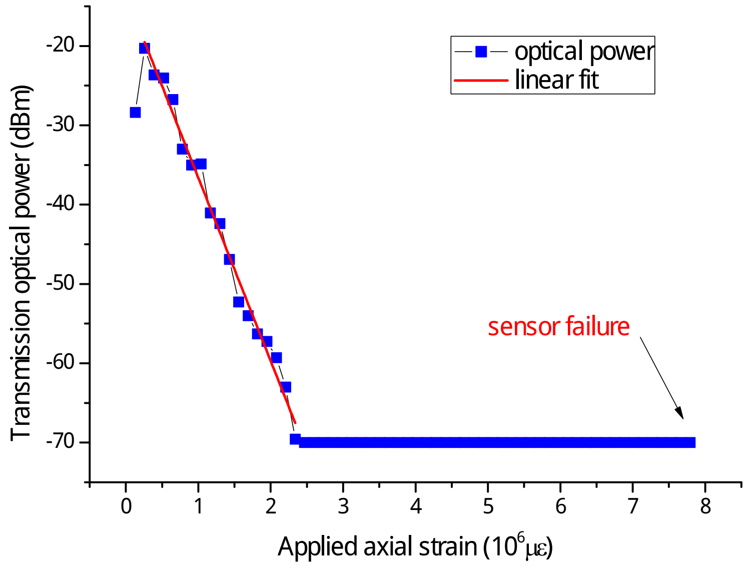


Fig. 4 Transmission optical power vs. applied axial strain

Transmission optical power vs. applied axial strain was plotted in Fig.4. Like most of the intensity based sensor, there was a stabilization stage. After the strain was initially applied on the sensor, the transmission optical power increased and then decreased, which was shown in Fig.4. When the sensor was stabilized, it worked in a linear manner. The fitted curve has a slope of -23.1dBm/ ε and a intercept of -13.5dBm. The Adj.R-sqare was 0.988 indicating the sensor showed good linearity. When there was a strain of $2.33\times10^6 \mu\varepsilon$, the transmission power was exceeded the minimum measuring range of the photo detector. However, the sensor still robust enough to withstand a larger strain Finally, the sensor survives a deformation of more than 700%, shown in Fig.3(b). The maximum strain experienced before the sensor failure was $7.79\times10^6 \mu\varepsilon$ which corresponds to a deformation of 779%.

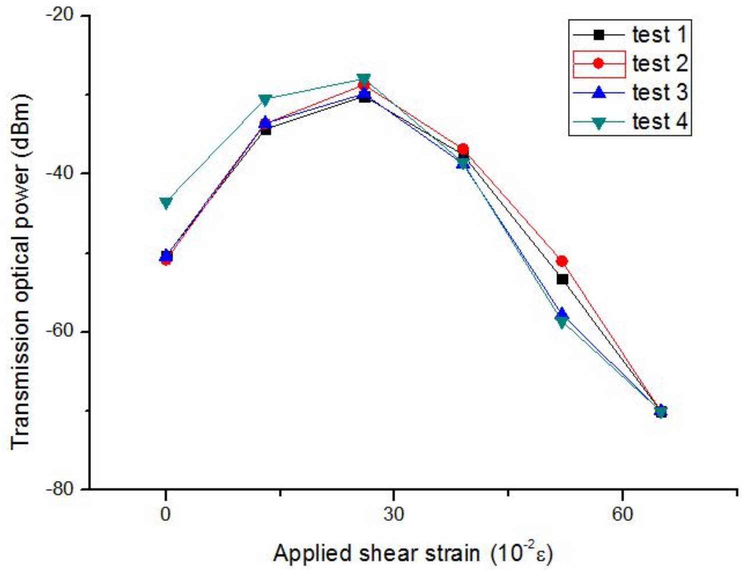


Fig. 5 Transmission optical power vs. applied shear strain

Transmission optical power vs. applied shear strain was plotted in Fig.4. A stabilization stage was again appeared. The sensor stabilized after a strain of $25.97\times10^{-2}\varepsilon$ and worked in a linear manner. The fitted curve has a slope of -105dBm/ε and an intercept of -0.309dBm. The Adj.R-sqare was 0.96 indicating the sensor showed good linearity. The experiment was stopped after the transmission power exceeded the minimum measuring range of the photo detector. The above experiment was conducted four times and the data was plotted in Fig.6. We can find that the sensor shows good repetition. The maximum shear strain tested was $6.49\times10^{4}\mu\varepsilon$ which corresponds to transverse displacement of 0.05mm.

3 Conclusion

The present paper presents a way to measure both large axial and shear strain using PDMS as the waveguide and sensing part. Both the fabrication process and testing procedure were described in detail. It has been found that the PDMS fabricated sensor is capable of measuring large axial strain of $7.79\times10^6\,\mu\varepsilon$ and large shear strain of $6.49\times10^4\,\mu\varepsilon$. After the stabilizing of the sensor, the transmission optical power vs. applied axial/shear strain has a good linearity and repetition.

This study therefore indicates that PDMS material has great potentials to be used as a sensing element for large strain measuring purposes. However, some limitations are worth noting. Although our studies reveal the fact that PDMS fabricated Fiber Optic Sensor is capable of measuring large axial/shear strain, the resolution of sensor is fairly poor. A wider dynamic range can be realized by using a photo detector with even lower threshold or a more powerful laser source. Future work should therefore include the improvements of the fabrication process and signal interrogation mechanism.

In conclusion, the proposed large axial/shearing strain FOS sensor offers the advantages of easy fabrication, simplicity of signal processing and cost effective. It can potentially be applied to sensing large axial and shear strain in SHM system under earthquake/explosion where few traditional fiber optic sensors could survive.

Acknowledgments

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