Front. Optoelectron. China 2009, 2(4): 362–367
DOI 10.1007/s12200-009-0057-1

REVIEW ARTICLE

Recent development and applications of polymer optical fiber sensors for strain measurement

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Abstract This paper presents the characteristics and advantages of polymer optical fiber (POF) sensors compared with common silica optical fiber (SOF) sensors. The development and application of POF sensors for strain measurement are introduced in detail. Because of the recent developments in POF technology, the future of POF sensors is considered optimistic.

Keywords polymer optical fiber (POF), sensor, strain, characterization

1 Introduction

Over the past twenty years, fiber-optic sensors (FOSs) have found widespread usage in structural health monitoring due to their light weight, small size, and immunity to electro-magnetic interference. These sensors can be either surface mounted or embedded in large civil structures and composite materials to assess their reliability. FOSs in general measure a variety of parameters including strain, pressure and temperature which in particular are important for civil applications. They can be implemented into a continuous data acquisition system in order to monitor strains before a malfunction occurs in the structure [1]. Ideally, the surface mounted or embedded strain sensors should have a lower stiffness and higher strain fracture toughness than the host materials. However, common FOSs are fabricated from silica optical fibers (SOFs). They have large stiffness and can only sustain a maximum strain of 2% unless special preparation procedures are followed.

In recent years, polymer optical fiber (POF) sensors have attracted much interest as a sensing device. POFs have an inherently large strain range, which provides a potential maximum strain range of 6%–12%. POFs are more flexible than SOFs and possess a high fracture toughness that makes them ideal for large strain applications. The Young's modulus of typical POFs is much less than that of SOFs. It also makes them more advantageous for sensing applications [2,3]. SOFs are brittle in nature which makes them more susceptible to impact and abrasion damage. A polymer coating is required to protect the surface from scratches, cracks and possible fracture. POFs do not require such a jacket due to their high fracture toughness. They have a better resistance to impacts and vibration than SOFs [4].

The advantages of POF sensors are mostly those of SOF sensors. Additionally, POF may offer other significant advantages, such as large core size, large numerical aperture, flexibility, easy non-skilled handling and ruggedness, safe disposability and lower cost. The disadvantages of POF are its high attenuation limiting the operational range to a few tens of meters, and the lower glass transition temperature (T_g) beyond which POF cannot be used. But at the same time, the low T_g of POF is also considered an attractive feature when doping the core with various organic dyes.

POFs represent their viscoelastic property, which makes their mechanical property complicated. As a result, their applications for strain measurement are different from SOFs. Yang et al. [5] reported that POFs were more suitable for measurements of temperature, humidity, pressure, wind speed, load and crack levels in civil structures rather than rapid loading-unloading strain applications because the residual strain need time to erase.

2 Character and development of POF

Some of the most common optical polymers are poly methyl methacrylate (PMMA), polystyrene (PS), perfluorinated (PF) polymer, polycarbonate (PC), etc. Table 1

Received March 24, 2009; accepted June 30, 2009

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Table 1 POFs material properties

material properties	characteristics	PMMA	PS	PC
optical	spectral passing band/nm	390–1600	400–1600	360–1600
	refractive index at 587 nm and 20°C	1.4918	1.5905	1.5855
	abbé value	57.2	30.7	30
	transmittance/%	92	88	90
	haze/%	1.3	1.5	1.7
physical	specific gravity/($g \cdot m^{-3}$)	1.18	1.06	1.25
	max service temperature/°C	80	90	120
	linear expansion coefficient/K^{-1}	6.8×10^{-5}	8.0×10^{-5}	6.6×10^{-5}
	abrasion resistance (1–10)	10	4	2
environmental	sensitivity to humidity	high	low	low
	water absorption (weight%) at 23°C	0.60	0.10	0.15
manufacturability	process ability	excellent	good	poor
	birefringence	low	high	high

shows their main properties including characteristics of optical, physical, environmental and manufacturability. Most conventional POFs are made from low-loss PMMA. The PMMA-based POF typically has attenuation ranging from 80 to 120 dB/km in its transmission window around 650 nm. These figures are significantly higher than that of SOF. In particular, the temperature range of operation of POF is important for industrial environments. Conventional PMMA-based POFs are typically fine up to 85°C. However, the long term performance remains an issue.

DuPont was the first company to produce POFs in the 1960s. In the 1970s mainly DuPont and Mitsubishi worked on the production of POFs. Work was mainly focused on the field of data communication with the aim of lowering the losses of POFs. Attenuation decreased dramatically in current commercial POFs with improving production methods. A great breakthrough had been made in improving the optical property of polymer fiber materials in the early 1990s. Researchers at Asahi Glass Company and Keio University in Japan developed excellent fluorinated polymer materials for making very low loss POFs. The fluorinated polymer had excellent chemical, thermal, electrical and surface properties. New POFs based on these perfluorinated materials had been made and attenuation achieved around 15 dB/km at 1000–1300 nm [6].

Optical source is an important component in POF systems. Low cost optical source develops quickly for POF telecom and data transmission. Red light emitting diodes (LEDs) emitting at 650 nm are typically used in PMMA-based POF systems. They can be used with POF connections to create very low cost optical interconnects. However, the transmission distance is limited due to the absorption of the POF and the decrease in output power of the LED over the operating temperature range. Other less powerful, recently developed green LEDs emitting at 520 nm are especially suitable for telecoms and sensing applications. The wavelength of the green LEDs at 520 nm coincide with a relatively broad absorption minimum of POF. Wipiejewski et al. [7] developed a green LED for POF low speed applications. The green LED exhibited only a small decrease of output power at high temperature because of the high bandgap offsets of the InGaN material. An experiment was set up to compare the decrease of optical power versus temperature at the end of a 40-m-long POF between the green LED and the red LED. The power drop for the green LED transmission system was only 1.3 dB compared to 4.4 dB for the red LED case. The 1.3 dB power drop was mainly due to the decreased output power of the LED itself. The POF link contributed only 0.1 dB to the additional transmission loss.

The reliability of the network of POF is a critical issue for telecom and sensing applications. Novel POF is required for long-term applications with high stability in a harsh environment. Sato et al. [8] developed a PMMA-dopant graded-index (GI) POF with high stability in the attenuation at high temperatures. Experiments verified that the POF represented sufficiently high stability through the aging at 70°C for 500 h.

3 Polymer optical fiber strain sensors

The optical parameters, such as intensity, phase, and wavelength, are influenced by loading strain. The strain sensors could be classified as intensity-based fiber optical sensors, fiber Bragg grating (FBG) sensors, and interferometeric FOSs, etc.

Kuang et al. [1] investigated an intensity-based POF sensor for curvature and strain measurements. Rectangular and H-section samples were subjected to three-point bending flexural tests in this study. POF sensors were surface mounted on the portion of the sensitized region oriented away from the host specimen. The light intensity was monitored during loading. This simple and robust sensor exhibited a high signal-to-noise ratio and excellent repeatability, rendering the system cost effective for operation in harsh environments. In addition, this inexpensive system offered signal linearity and signal stability comparable to that of FBG sensors and other more sophisticated optical fiber sensor systems. Results of quasi-static tests revealed a highly linear response to axial strain up to 1.2% and bending strain up to 0.7%. The results also highlighted the possibility of using the sensor for monitoring strain on either the tensile or compressive side/region of a beam subjected to flexural loading. It was a cost-effective method compared to other more sophisticated health monitoring systems currently employed in civil engineering structures.

Later, Kuang et al. [9] did some more work on intensity-based POF sensors for different structure matrix materials. They proved that POF sensors were compatible with not only concrete samples but also composite materials. These sensors were also able to detect crack propagation in concrete beams and sustain large deflections that would not be obtainable by SOFs.

Kuang et al. [10] investigated a surface-mounted, extrinsic POF sensor used to monitor static, dynamic and impulse-type loading conditions. The sensor, which resembled an extrinsic Fabry-Perot sensor, consisted of two cleaved step-index multi-mode POFs enclosed in a specially designed housing comprising two polytetrafluoroethylene (PTFE) sleeves and a PTFE outer tube. Scheme of the sensor was shown in Fig. 1. The intensity of light changed as the longitudinal separation of the fibers was altered.

Takeda et al. [11] investigated embedded multi-mode POFs and silica FBG in quasi-isotropic composite laminates to detect and monitor transverse cracks. POF sensors were considered due to lower cost and larger core compared to SOFs, also because the POF was easier to embed into fiber reinforced polymer (FRP) because its thermal expansion coefficient was almost the same as that of the matrix. The experiments incorporated an ESCA CK10 POF produced by Mitsubishi Rayon Co., Ltd. The loss in optical power was monitored due to local deformation in the fiber as a result of transverse cracking. Results showed that there was a linear loss in light as strain was applied until cracks appeared.

Wong et al. [12] reported an optical fiber sensor system for long-term environmental monitoring that exploited light intensity modulation. The POF strain sensors appeared to be well-behaved in that it showed little data scatter and was able to monitor strains up to 1.4% without failure. They demonstrated that the POF sensors were suitable for cheap, on-line continuous environmental monitoring.

Nakamura et al. [13,14] utilized 1 mm diameter POFs from Mitsubishi Rayon Co., Ltd., Eska Premier GH-4001-P, in optical time-domain reflectometry (OTDR) experiments. The system was capable for testing POF up to about 120 m in length with the use of a photon counting detector. For a small strain, the POF OTDR sensor worked without the memory effect. However, the OTDR responses remained even after the external force was removed due to the plastic deformation of the POF if the applied strain was large enough.

In general, intensity measurements may encounter unwanted intensity losses from bending of the fiber, connector issues, or a variable power source. Additionally, their sensitivity to applied strain is low. Intensity-based FOSs offer an alternative for incorporation into operational engineering structures in price-sensitive industries. Therefore, FBG sensors and interferometeric FOSs have a wider application in high precision sensing. However, the sensing systems are more complicated than intensity-based FOSs. They are comparatively expensive and not very mechanically robust.

Xiong et al. [15] reported that Bragg grating was incorporated into POF. Figure 2 shows the experimental setup for writing Bragg grating in POF. The polymer optical fiber Bragg grating (POFBG) had a length of 1 cm with a reflectivity of 80% and a linewidth of about 0.5 nm. The wavelength tunability of the grating was larger than silica optical fiber Bragg grating (SOFBG) due to the low Young's modulus of POF. When the fiber was released it completely returned back to its original state if it did not exceed its elastic limit. The yield strain was determined to be 6.1% with a potential recoverable strain up to 13%.

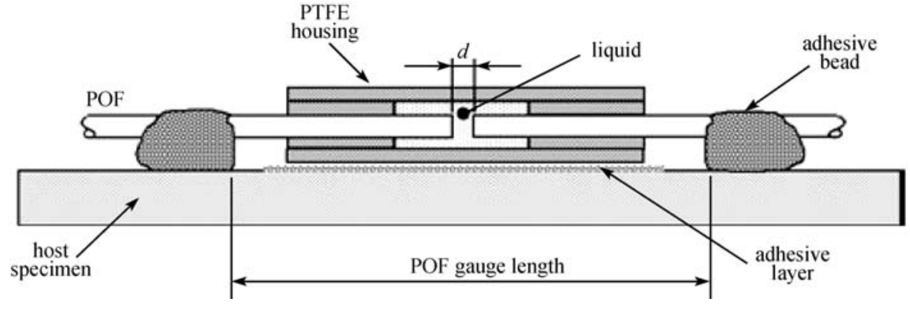

Fig. 1 Scheme of extrinsic POF sensor

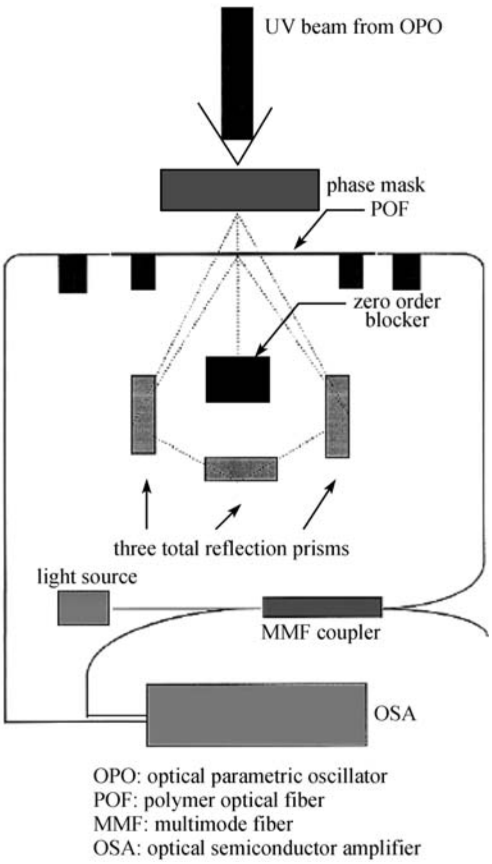

Fig. 2 Experimental setup for writing FBG

According to the author, the variation of the resultant yield strain and the predicted value could be due to the processing procedure, drawing temperature and speed. The POFBG could be applied for mechanical and temperature sensing.

Liu et al. [16] reported that they used POFBG and long period fiber grating as a strain sensor. The sensor head was formed by a POFBG and the long period fiber grating was used for strain related wavelength shift demodulation. This strain senor could be used for large strain measurement up to tens of thousands of micro-strains.

Peng et al. [17] reported their experimental work on polymer optical fiber sensing. They used two POFBGs to separate the strain component and temperature component. The Bragg wavelength shift was more than 70 nm and the tensile strain was nearly about 5%.

Chu et al. [18] wrote a grating into PMMA-based POF in their laboratory. The grating was used for strain measurement and had a wide tuning range, the Bragg wavelength shift could be up to 20 nm by loading the grating to 1.3% strain. On releasing the strain, the wavelength returned to its original value with no hysteresis. Another experiment was carried out by stretching the grating until it broke. The resulting wavelength shift was 73 nm.

Liu et al. [19] used POFBG for the strain sensing characterization of static tensile strain. Experimental results indicated that the strain sensitivity of POFBG was higher than that of SOFBG. Experimental results also demonstrated the large strain sensing range with good reproducibility, reversibility and repeatability. The maximum tensile strain was 3.61% and the corresponding Bragg wavelength was 1589.1 nm in the experiment. There were no obvious changes in the reflection level and spectrum shape when the tensile strain was less than 2.22%. When the strain was greater than 2.22%, the reflection level became smaller and the linewidth of the spectrum also became wider.

Harbach [20] investigated the possibility of writing FBG in POFs and used them as sensor units for strain measurement. The POFBGs were characterized using optical low coherence reflectometer (OLCR). The FBGs writing using femtosecond laser irradiation had reflectivities up to 1.2×10^{-4}, but they were not stable. The POFBGs were used for strain measurement with the temperature and humidity influence considered. The experiment showed that the strain sensitivity of POFBG was to be $1.4\ \mathrm{nm}/\mu\varepsilon$, which is higher than SOFBG.

Huang et al. [21] presented a novel technique to fabricate hybrid silica/polymer optical fiber sensors for large strain measurement. The hybrid silica/polymer strain gauges were tested using a micro-tester. The relationship between the transmitted power and the strain remained fairly linear for strain up to 5%.

Silva-López et al. [2,3] reported the first interferometric measurements with single-mode POFs. The strain measurement experimental setup is shown in Fig. 3. POFs were used from Paradigm Optics, Inc. The cladding was commercial acrylic with an index of refraction of 1.4905 whereas the core was PMMA with an index of refraction of 1.4923. The fiber was glued into a silica capillary tube and then polished on both ends to permit free space coupling. The phase shift as a function of displacement was measured using a Mach-Zehnder interferometer with a He-Ne laser. By counting the number of

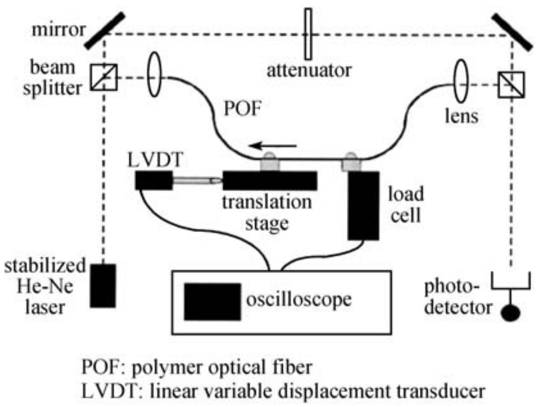

Fig. 3 Schematic drawing of Mach-Zehnder interferometer measurement experiment

fringes it was possible to measure the phase change per unit length elongation of the fiber. The average value obtained was measured to be $(131 \pm 3) \times 10^5$ rad/m.

References [22–24] used phase measurement techniques for strain measurement by POF strain sensor. The test system was realized with a 1-m-long PMMA-based POF with 1 mm diameter. The fiber was stretched at different steps using different modulation frequencies. Two fiber loops of 1 m length each were surface mounted on a wooden board with 10 mm thickness in another test. The board was fixed on one side and bent on the opposite side by 10 mm. A movement downwards caused a stretching of the fiber loop on the upper side and a compression at the lower side. The sine signals had been detected after passing the two different fiber loops by two identical receivers. The receiver output signals were the inputs for the phase comparator. Phase difference was calculated from the output voltage. The reference fiber was used for temperature compensation.

Kiesel et al. [25] developed a POF used as a high-strain sensing application such as health monitoring of a civil infrastructure subjected to earthquake loading. A separate Mach-Zehnder interferometric system was created to measure the change in phase shift of the light propagating through the fiber as well as a correlating mechanical system which applied tension to the POF. A schematic

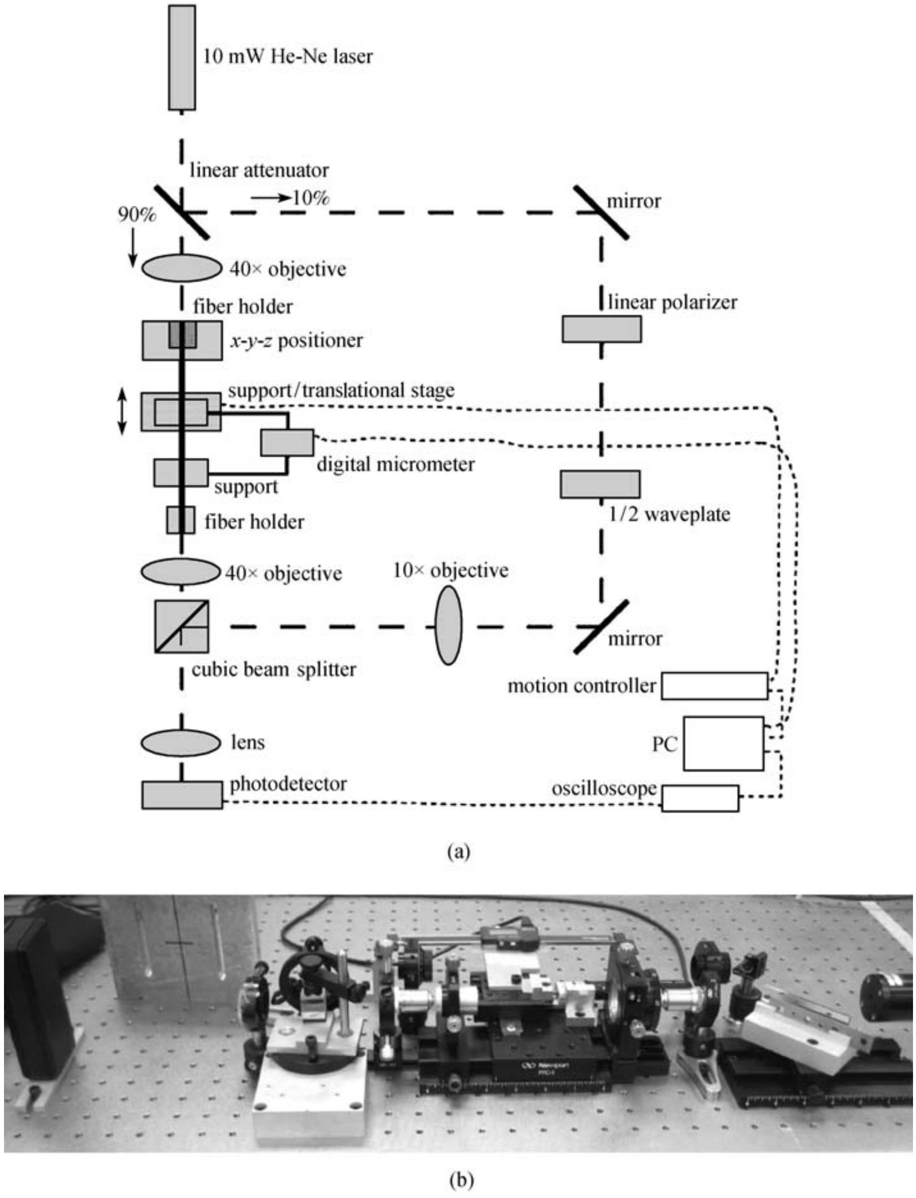

Fig. 4 Mach-Zehnder interferometer for measurement POF phase sensitivity. (a) Schematic drawing of experimental setup; (b) photograph of actual setup

drawing of the sensing system is shown in Fig. 4. The mean value of phase shift sensitivity was measured to be 139×10^7 rad/m.

4 Conclusion

It is believed that POF could be a significant advantage for sensor applications such as health monitoring of large civil structures and FRP composite materials in aerospace applications. POF sensors could be developed and utilized much more widely. One of the important reasons for this is that the POF sensor undoubtedly has lower cost for the overall sensor system. POF sensors should be considered first where the distance and temperature limitations of POF are not important. Currently, multimode POF have been used widely and single-mode POF will also be developed and applied soon. The development of POF technology gives a lot of scope for an expanding POF sensor future.

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