Enhancement of a Continuous Liquid Level Sensor Based on a Macro-Bend Polymer Optical Fiber Coupler

Volume 10, Number 1, February 2018

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DOI: 10.1109/JPHOT.2018.2795550
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DOI:10.1109/JPHOT.2018.2795550
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Abstract: An approach to improve the side-coupling ratio of the macro-bend polymer optical fiber (POF) coupler is proposed in this paper. Two naked POFs are twisted and twined around a cylinder to achieve continuous liquid level sensing. Through filling the gap between the two twisted POFs with UV optical cement, both the sensitivity and the measurement range are increased substantially. The reversibility is also improved since the gap is eliminated, and little liquid can exist in the structure with the liquid level decreasing. The design turns out to be a good method to enhance the performance, and could also be applied in the displacement or stress sensing field.

Index Terms: Fiber optics systems, sensors, advanced optics design.

1. Introduction
Compared with their conventional electronic counterparts, optical fiber sensors exhibit particular advantages, such as immunity to electromagnetic interference, remote operation and small size, and have attracted considerable attention [1]–[10]. Traditional optical fiber sensors are based on fiber Bragg gratings (FBGs) [11]–[17], long-period fiber gratings (LPFGs) [18], Mach-Zender interferometers [19], and so on. Although these sensors are highly accurate, they are modulated by wavelength, which always involves complicated processing technology or expensive detection equipment. By contrast, a sensor using an intensity-modulated technique shows good potential to achieve a simple and cost-effective measurement system.

Currently, liquid level sensing is of great importance in a wide range of applications, such as fuel storage, flood warning, and the chemical industry [20]–[24]. Considering the cost, a variety of intensity-modulated liquid level sensor based on POF have been investigated and reported in the literature, which could achieve continuous or multipoint measurement of the liquid level [25], [26]. For example, a group of POF segments are aligned coaxially and the output power is affected by the liquid level [27]. A POF with a race-track helical structure [28] or engraved grooves [29], [30] also introduces a periodically varied loss to realize multipoint sensing. However, the resolution and the measurement range of these sensors cannot both be satisfactory. In addition, the sensing
signal may be drowned in the background noise due to the fluctuation of the light source for the intensity-based sensors. Hence, a twisted macro-bend coupling structure (TMBCS) is proposed, and the signal-to-noise ratio can be improved by measuring the side-coupling power [31]. The structure is applied not only in the continuous liquid level sensing field [32] but also in displacement [33] and relative humidity measurements [34]. However, the cost of detection is increased because the side-coupling ratio of the TMBCS is too small and the output signal is so weak.

In this letter, a new approach to improve the side-coupling ratio of the TMBCS is proposed. UV optical cement is injected in the gap between the POFs twisted in a helical structure. The fabrication process of the sensor is simple and inexpensive. When the liquid level rises, the output power of the system decreases. The sensitivity and measurement range are obviously increased over the one without cement, which lowers the demand for a power meter with a high resolution and reduces the cost. The reversibility and the temperature dependence are also investigated. The structure with cement offers advantages of high performance, low cost, great reversibility, and broad application.

2. Principle

The proposed sensing structure is illustrated in Fig. 1. The active fiber connected to the light source is tightly twisted with a passive fiber and then bent to a loop, called the TMBCS [31]. An energy coupling region is established in the curving section of the two twisted POFs. A portion of the macro-bend losses from the active fiber will be coupled to the passive fiber in what is known as the side-coupling power. It has been proven that the macro-bend losses of the POF are modulated by the curvature radius and the refractive index (RI) of the environmental medium [34]. As depicted in Fig. 1(b), R is the curvature radius, and n_1 and n_2 are the RI of the fiber and the medium in the gap. The macro-bend losses will increase when R decreases or n_2 increases, resulting in more side-coupling power. In this letter, we fill the gap between the two POFs with UV optical cement, which means n_2 changes from 1.0 (the RI of air) to 1.418 (the RI of the cement) and leads to a big improvement in the side-coupling ratio.

As the noise from the light source is mainly concentrated in the core of the active fiber, a better signal-to-noise ratio can be achieved by detecting the side-coupling power [31]. In our previous work, the liquid level sensing has been achieved by twining the twisted POFs around a polyamide cylinder [32]. The side-coupling power in the passive fiber has the same propagation behavior as the power propagating in the active fiber, which decreases as the POFs are gradually submerged in liquid. Therefore, the output power of the power meter connected to the passive fiber will decline while the liquid level rises. In contrast to the structure without the UV optical cement, the proposed structure increases the side-coupling ratio and enhances both the sensitivity and the measurement.
range. In addition, the proposed structure reduces the detection cost by raising the magnitude of the output signal.

3. Sensor Fabrication and Experimental Setup

The fabrication of the sensor is simple and cost effective. First, two untreated naked POFs (Mitsubishi, Tokyo, Japan, SK40) are twisted and twined around a polyamide cylinder with a screw pitch of 20 mm. The materials of the core and the cladding are polymethyl methacrylate (PMMA, $n = 1.49$) and fluorinated polymer ($n = 1.363$), respectively. The diameter of the core is 980 µm, and the thickness of the cladding is just 10 µm. The curvature radius is 10 mm. Then, the UV optical cement (Loctite, 3311) is filled into the gap between the two POFs with a syringe needle. Finally, the structure is cured for 2 h at room temperature.

The experimental setup of the proposed liquid level sensor is shown in Fig. 2. A 660-nm fiber-coupled LED (M660F1, Thorlabs, Newston, NJ, USA) is employed as the light source with an output power of 30 mW. An optical power meter (PM100USB, Thorlabs, Newston, NJ, USA) with a resolution of 0.1 nW is used to obtain the output power of the passive fiber at different liquid levels. The insensitive regions of the POFs are covered by a black jacket to achieve visible light shielding. During the experiment, the helical structure of the two twisted POFs is fixed in a graduated container. Water ($n = 1.33$) is used as the tested liquid. When the level of the liquid changes, the corresponding output power is recorded on the power meter. A total of ten samples for each liquid level are carried out to perform a statistical analysis. All the experiments are conducted at room temperature and in the dark room.

4. Results and Discussion

The liquid level response of the proposed sensor with and without the UV optical cement is shown in Fig. 3. When the liquid level changes from 0 to 350 mm, the output power linearly decreases. The sensor with the cement has a sensitivity of 11.978 nW/mm, which is about ten times larger than that of the one with air. The reason for that is the UV optical cement increases the macro-bend losses of the active fiber, raising the side-coupling ratio. As a result, the side coupling power in the passive fiber attenuates by a larger magnitude with the level rising, which improves the magnitude of the output power and reduces the difficulty and cost of detection.

As seen in Fig. 4, the fabricated sensor not only increases the sensitivity but also expands the measurement range from 350 mm to 600 mm in comparison to the structure with air in the gap. For the air-filled sensor, the liquid surface tension can cause a little liquid to remain in the gap as the
Fig. 3. Liquid level response of the proposed sensor: (a) with the UV optical cement ($n = 1.418$); (b) with air ($n = 1.0$).

Fig. 4. Liquid level response of the proposed sensor in the ascending-descending cycle.

As temperature varies, the RI of the liquid and the numerical aperture of the POF undergo a subtle change. Since the part of the sensor submerged in the liquid is changing, the effect of the temperature is complex under different liquid levels. In the experiment, the container is placed on a heater, and the temperature increased from 20 to 60 °C in intervals of 5 °C. When the liquid level is 450 mm, the temperature dependence of the proposed sensor is observed and depicted in Fig. 5. The output power increases as the temperature rises. As the temperature has a same influence on the active fiber, a power meter can be connected to the free end of the active one to monitor the interference of temperature for compensation. In addition to the temperature, other parameters of the ambient environment or the moisture absorption property of PMMA will also affect the output power of the passive fiber, which also can compensated by the output power of the active fiber. Our follow-up work will lay emphasis on the calibration of the sensor according to the actual situation.
As mentioned previously, the proposed sensor increases the sensitivity extraordinarily without sacrificing its sensing range. In addition, the improved signal intensity decreases the cost of detection. It can be deduced that the performance of the sensor is mainly affected by the UV optical cement we choose. Hence, future research will focus on the influence of different cements.

5. Conculsion

In this letter, an approach to improve the side-coupling ratio between two macro-bend POFs is proposed. In the continuous liquid level sensing field, the TMBCS with UV optical cement not only improves the sensitivity from 1.168 to 11.978 nW/mm but also broadens the measurement range from 350 to 600 mm. The magnitude of the signal intensity increases from nanowatts to microwatts, which could lower the cost of detection. In addition, the reversibility has also been enhanced. Since the temperature has a noticeable influence on the proposed sensor, the working environment should be considered, and a compensation method should be introduced.

Acknowledgment

The authors would like to thank the anonymous reviewers for their valuable suggestions.

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