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Liquid Level Sensor Based on CMFTIR Effect in Polymer Optical Fiber

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Abstract: The macro-bending induced optical fiber cladding modes frustrated total internal reflection effect is used to realize the liquid level probe with a simple structure of single macro-bend polymer optical fiber loop. The test results show that the extinction ratio reaches 1.06 dB. "First bath" phenomenon is not obvious (about 0.8%). The robustness of the sensor is better, and the ability of anti-pollution is stronger compared with the conventional sensors. The process of making this sensing probe is extremely easy, and the cost is very low.

Keywords: Water leakage measurement; polymer optical fiber; frustrated total internal reflection

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1. Introduction

The techniques of liquid level measurement are widely required in the fields of oil and chemical engineering. At present, there are varieties of designs including the simple dipstick and kinds of liquid level sensors with complex structures such as capacitive type [1, 2], acoustic wave [3–5], and optical fiber based on different principles. But there are still prominent contradictions between the existing level measurement technologies and the market demands. Firstly, the demand for the level sensor is huge in the petrochemical field, but expensive and complex designs are difficult to be widely applied. Secondly, the complex measurement environments, such as flammable liquids, present a huge challenge on the safety and adaptability of existing level sensors. Due to non-electrical measurements and immunity to electromagnetic interference, optical fiber liquid level sensors are suited to liquid level measurement in complex environments. Among them, pressure-sensitive sensors and refractive index-sensitive sensors are representative. With regard to pressure-sensitive types, there are fiber Bragg grating sensors [6–8], Fabry-Perot sensors [9–11], and so on. The production process of these sensors is difficult and expensive. And complex and expensive instruments, such as high-resolution spectrometer and tunable laser source, are also required for detecting the wavelength shift. So these sensors can hardly be applied and popularized in cost-sensitive areas. The refractive index-sensitive sensors mainly include long-period fiber grating (LPFG) sensors [12–14] and fiber frustrated total internal reflection (FTIR) sensors. The LPFG sensors are similar to the

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pressure-sensitive types in complexity and cost. The FTIR sensors just need to detect the light power changes, so the cost is quite low. And this advantage makes it possible that FTIR sensors play an important role in petroleum and chemical fields.

Currently, there are mainly two ways to produce FTIR sensors with fibers. Bottacini *et al.* [15] polished fiber end to form a 90° angle as the reflective surface on which the FTIR effect occurred. Using this method, 1.09-dB extinction ratio was achieved. But this method is difficult to process and make the fiber tip more slender, fragile, and susceptible to contamination. Golnabi *et al.* [16] using a prism as the reflective surface achieved an extinction ratio of 0.03 dB. Due to the sensor probe is large, the liquid level measurement accuracy of the sensor is affected. And the extinction ratio is relatively low, so erroneous judgment easily appears at noisy environments. Hou *et al.* [17] using plastic optical fibers with the twisted macro-bend coupling structure inspired cladding modes which had cladding modes frustrated total internal reflection (CMFTIR) effect and realized a liquid level probe with an extinction ratio of 4.18 dB. On one hand, because the coupling ratio is low and the sensing signal of sensor is weak, the signal will attenuate continuously in the long-distance propagation and hardly be detected in this situation. On the other hand, the gaps in the twisted structure result in more remaining liquids and evidently generate the "first bath" phenomenon (nearly 30% output difference).

In this paper, the CMFTIR effect is used to realize the liquid level probe with an extremely simple structure of single macro-bend polymer optical fiber loop (Fig. 1). By using this method, the process of making sensing probe is very easy, and the cost is very low. But the sensor may exhibit similar or even better performance than the existing sensors. The test results show that the extinction ratio reaches 1.06 dB. The robustness is better, and the ability of anti-pollution is stronger compared with the conventional sensors. The sensing signal power is four orders higher than that of twisted macro-bend coupling structure (TMBCS), and the "first bath" phenomenon is not obvious (about 0.8%). It is foreseeable that the level probe has excellent competitive advantages in the future market.

2. Experiment and results

It can be seen in Fig. 1 that a commercial polymer optical fiber (POF) fiber (SK-40, Mitsubishi) is bended to form a small loop with the 2.5-mm macro-bend radius and is encapsulated with the silica gel in a rubber shield which is low-cost. Except for the bended head of fiber, all the naked parts are set into a black thermal casing to shield visible light interference. One end of the fiber is connected to a 660-nm light-emitting diode (LED) light source (Thorlabs, M660F1), while the other end connects the optical power meter (Thorlabs, PM100USB).

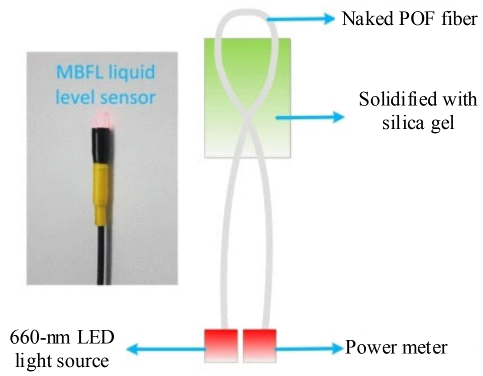

Fig. 1 Macro-bend optical fiber loop (MBFL) liquid level sensor.

As shown in Fig. 2, when the fiber is bent, lights originally propagating in the fiber core become leaky rays which lose their power through the mechanism of refraction and tunneling [18]. In the model of single-mode optical fiber, the thickness of cladding is usually seen as infinite to simplify calculation. Then only one reflection on the core-cladding interface needs to be considered. It means that the escaping lights at the core-cladding interface will lose forever [19]. This approximation is invalid when the bending radius is small enough especially in highly multimode SK-40 POF fibers, because more power is transferred to the cladding and forms cladding modes which cannot be neglected. The escaping lights at the core-cladding interface actually have the chance to reflect again at the cladding-environment interface and come back to the core. Similarly with the situation of the first reflection, at the cladding-environment interface, the lights dissatisfying the condition of total internal reflection become refraction rays, which will exhaust all their power in short-distance propagation. This part of lights is radiation mode. And the lights satisfying the condition of total internal reflection become tunneling rays, which form the cladding modes with slow leakage through the mechanism of tunneling. The difference between the first tunneling rays on core-cladding interface and the second tunneling rays on cladding-environment interface is that the evanescent fields of the second tunneling rays penetrate into the environment medium, and the loss of lights is influenced by the refractive index of the medium through the mechanism of the FTIR [20–23].

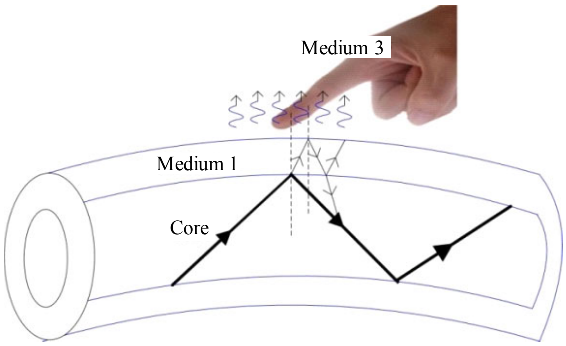

Fig. 2 Cladding mode frustrated total internal reflection in bending fiber.

Therefore, when the high refractive index medium (Medium 3) contacts with or is close to the fiber cladding (Medium 1), the FTIR effects cause partial cladding mode lights to transmit into the environment and lead to energy loss. In particular, we call this effect in fibers as CMFTIR. Specifically, when the MBFL level probe is immersed in water or touched by a finger (Fig. 2), the light loss is caused by the CMFTIR effect, and the power decline can be detected at the end of the fiber.

Under normal circumstances, the CMFTIR effect is difficult to be observed in fibers. Because the light energy in straight fibers is well confined within the core, the energy which can reach to the cladding-environment interface is almost negligible. Moreover, the quartz fiber cladding is also relatively thick and has external coating, so it prevents the energy field from contacting with the external environment. So we designedly choose POF fiber (SK-40, Mitsubishi) which has relatively thin cladding and no coating layer as the sensor material. The particular parameter of SK-40 fiber is shown in Table 1.

Table 1 Parameters of SK-40 fiber.

Core material	Core refractive index	Core diameter (μm)	Cladding diameter (μm)
Polymethyl-methacrylate-resin	1.49	980	1000

Another more important reason is that the POF fibers are flexible and can be bent to a small loop with no breakage. In the previous report [17], we used the TMBCS to acquire the dark-filed coupling signal and achieved the enhancement of the CMFTIR effect. In this paper, we find that as long as the macro-bending radius decreases to a certain extent, the CMFTIR effect can also be enhanced to a satisfactory degree.

To test the impact of bending radius of optical fiber on the enhancement of the CMFTIR effect, SK-40 optical fiber is used to produce fiber rings with different macro-bending radii. The LED light source is connected to one end of the fiber, and a power meter is connected to another end to measure the power change. The method of finger touch (Fig. 2) is used to simulate the effect of frustrated total internal reflection. The result is shown in Fig. 3.

As seen in Fig. 3, when the macro-bending radius is greater than 13 mm, there are almost no significant power changes produced by finger touch. So the CMFTIR effect is negligible under this situation. But with a gradual decrease in the bending radius, the CMFTIR effect becomes more obvious. When the bending radius reaches 2.5 mm, the power change caused by the CMFTIR effect is more than 50%. It is sufficient for the sensing applications.

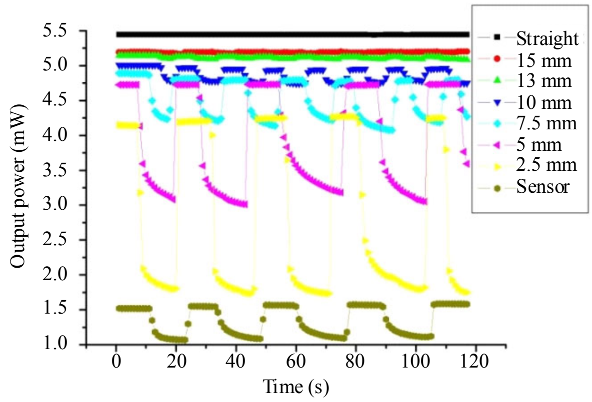

Fig. 3 Enhancement of the CMFTIR effect with different macro-bend radii.

In order to ensure the stability of the measurement results, the MBFL must be properly packaged. The MBFL is encapsulated in a structure shown in Fig. 1 and sealed with the silica gel. Flooding test of the packaged MBFL sensor is repeated 8 times, and the output power changes of sensor probe are observed. The measurement results are shown in Fig. 4.

We can see from Fig. 4 that when the probe is in the air (completely dry), the output power is about 1.51 mW (Line 1 in Fig. 4). When the level probe is completely immersed in water, the energy loss is generated due to the CMFTIR effect, and the output power declines down to 1.175 mW nearby (Line 3 in Fig. 4).

Usually, the extinction ratio is used to estimate the performance of liquid level sensors [15], and the extinction ratio is defined as follows:

$$E_r = -10\lg(P_{\text{liquid}} / P_{\text{air}}) \tag{1}$$

where P_{liquid} is the sensing signal output power when the sensor probe is immersed in liquid, and P_{air} is the output power in the air. It can be calculated that the extinction ratio of MBFL level probe reaches 1.06 dB. Due to the influence of the silica gel used for encapsulation, the output power of the sensor and extinction ratio decrease significantly compared with the values shown in Fig. 3 when the bending radius is 2.5 mm. So the silica gel is not an ideal choice, and there are actually spaces for further improvement, but the silica gel is cheap and already can fulfill the demands in many situations.

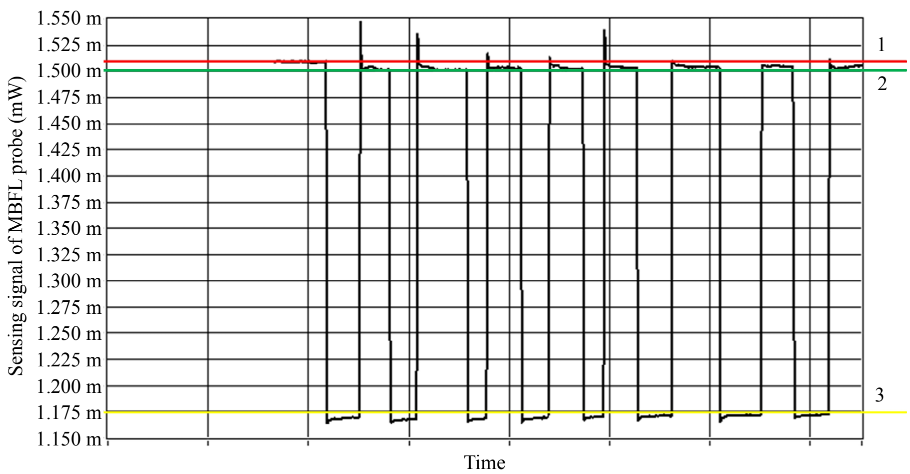

Fig. 4 Flooding test of the MBFL liquid level sensor probe.

From Fig. 4, we can also see that when the level probe is out of water and wet, the output power is about 1.50 mW (Line 2 in Fig. 4). There are some differences between the output powers of the wet state (Line 2 in Fig. 4) and dry state (Line 1 in Fig. 4). This phenomenon which is called “first bath” is due to the remaining liquids on the sensor surface after the sensor coming out of the liquids. In the previous study [17], since gaps existed between the two twisted fibers of the TMBCS structure, water droplets easily remained in the cracks, resulting in more significant “first bath” phenomenon. The output power difference of TMBCS between the dry and wet states reached 30%. In Fig. 4, it can be seen that the difference caused by the “first bath” phenomenon is about 0.8%, far less than the difference of the TMBCS probe. Compared with the MBFL level sensor, the signal power of the TMBCS probe is relatively weak (hundreds of nW). So the signal is easily to be affected by environment lights, and the signal transmission distance limited by the attenuation in optical fiber is short. It is important that the MBFL probe has higher signal output power (several mW) when the signals need to be transmitted to a long distance.

3. Conclusions

Optical fiber liquid level sensors can be divided into two classes [24]: the sensors for punctual measurement and for continuous measurement. The continuous type can accomplish real-time measurement of the continuously changing liquid level [25]. In this situation, the different liquid levels will change the submerged lengths and the outputs of the sensors, and then the level values can be calculated. The sensors for the punctual measurement are usually arranged in different places with many basic sensing probes [26]. They can also be controlled by a stepping motor system to move up and down with only one probe [27]. The sensing probe designed in this paper is used for the punctual measurement, and many probes are needed to be fixed on different positions inside a liquid reservoir or just one probe is controlled by a stepping motor system for acquiring level values. So as a basic unit, the sensing probe is only used for estimating the existence of liquids.

In summary, by utilizing the MBFL structure, we have a smaller sensor size, smaller “first bath” error, and the not bad extinction ratio (1.06 dB), and we get farther signal transmission distance and simpler production process. These make the MBFL level sensor probe have wider application scenarios and a more competitive market prospect.

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