Ultrasensitive liquid level sensor based on slice-shaped composite long period fiber grating

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In this paper, a novel liquid level sensor with ultra-high sensitivity is proposed. The proposed sensor is configured by a slice-shaped composite long period fiber grating (SSC-LPFG). The SSC-LPFG is prepared by polishing two opposite sides of a composite multimode-single-mode-multimode fiber structure using a CO₂ laser. The method improves the sensitivity of the sensor to external environment. Based on the simulation calculation, a liquid level sensor with a length of 3 mm is designed. The experimental transmission spectrum agrees well with the simulation result. The experimental results show that the sensitivity reaches 7080 pm/mm in the liquid level range of 0–1400 μm in water. The temperature sensitivity is 24.52 pm/°C in the range of 20°C–90°C. Due to the ultra-high sensitivity, good linearity, and compact structure, the SSC-LPFG has potential application in the field of high-precision liquid level measurement.

Keywords: liquid level sensor; composite long period fiber grating; ultra-high sensitivity.

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1. Introduction

Optical fiber sensors have the advantages of strong resistance to electromagnetic interference, high sensitivity, no operating current, and ability to work in complex environments^[1]. Therefore, they are widely used in temperature^[2], refractive index (RI)^[3], bending^[4], strain^[5,6], liquid level^[7], and other measurements^[8], especially in chemistry and biotechnology applications^[9]. Among them, liquid level is an important parameter in chemical industry production, fuel storage, water level monitoring, medical testing, dose control, and biochemical progress fields. In some specific environments, for example, aircraft fuel level monitoring in the aviation field^[10], the quantitative measurement of water infiltration in the underwater launch chamber^[11], and the liquid probe in the medical field^[12], high-precision and small-range liquid level sensors are needed, so it is of great significance to carry out research on small-range liquid level sensors. In environments that require ultra-high liquid level sensitivity like medical testing, the common capacitance, resistance, magnetostriction, and ultrasonic sensors have various defects and cannot meet the requirements of liquid level measurement^[13]. In recent years,

various optical fiber liquid level sensors were proposed, such as fiber Bragg gratings (FBGs)^[14,15], long period fiber gratings (LPFGs)^[16,17], Michelson interferometers (MIs)^[18], and Mach-Zehnder interferometers (MZIs)^[19,20]. Especially, the sensor based on a multimode fiber (MMF) structure has attracted more and more attention because of its advantages such as simple structure, low cost, and convenient manufacture. Because more modes and fields leak into its surroundings providing stronger light-matter interaction, the sensor will be more susceptible to the influence of external environment changes. Thus, the sensor based on a multimode structure has shown great potential in the measurement of liquid levels.

In the research of high-sensitivity liquid level measurement, some people proposed the MMF cascading hollow-core fiber (HCF) and FBG (SMF-MMF-HCF-SMF/FBG) with an aligned spliced structure^[21], surrounding RI (SRI)-based etched chirped FBG structure^[22], and MMF-HCF-FBG structure^[23]. MMF has many modes and strong RI modulation ability, which can effectively shorten the grating length. In the process of SMF and MMF coupling, higher-order modes can be excited to improve sensor performance. We use polishing to enhance

the evanescent field on the surface of the optical fiber, making the sensor more sensitive to the external environment. Compared with these structures, in this paper, we propose an ultra-high-sensitivity sensor for liquid level measurement. The sensor has high liquid level sensing sensitivity and low temperature crosstalk. The proposed sensor is configured by a slice-shaped composite LPFG (SSC-LPFG), in which the liquid level sensitivity reaches 7080 pm/mm. The temperature sensitivity is 24.52 pm/°C. Compared with the MZI sensors, the SSC-LPFG achieves higher sensing characteristics without increasing the complexity of preparation. Its level sensitivity is much higher than that of most known level sensors in the measurement range of 1.4 mm. Meanwhile, we simulate the energy transfer diagram and the transmission spectrum, and the simulation results are consistent with the experimental results. Due to the advantages of ultra-high sensitivity, compact structure, and good stability, it has potential application in the detection of liquid levels of medical, industrial, and other fields.

2. Fabrication and Principle Analysis

The SSC-LPFG is fabricated by polishing on the composite multimode-single-mode-multimode (C-MSM) fiber structure. We use three precision displacement platforms (accuracy is 0.01 mm) to fix the fiber and a fiber cleaver to cut the fiber, using a microscope with CCD for monitoring the cutting fiber length. The specific process is as follows. Firstly, the C-MSM section is fabricated by using an optical fiber cutter (FC-6S) and a fusion optical fiber splicer (Fujikura, 86C). A conventional segment of SMF is spliced to an MMF. After that, the part of a sensing element (MMF) is cleaved, and another segment of SMF is spliced again. As the MMF length is 200 μm , the structure will be more sensitive to changes in the external environment^[24]. In order to meet the phase matching conditions and get better sensing characteristics, the specific lengths of the cutting MMF and SMF are 200 μm and 500 μm , respectively. The above splicing process is repeated five times to fabricate the C-MSM structure.

Secondly, the high-power CO₂ laser is used to polish on the C-MSM structure in the two opposite directions parallel to the fiber axis. The schematic diagram of CO₂ laser polishing is shown in Fig. 1. The plane depth is 30 μm on the first side to ensure more exposure to the evanescent field. Then, the polishing step is repeated after the sample is twisted 180°.

Fig. 1. Experimental device diagram for fabricating the SSC-LPFG.

Fig. 2. Scheme diagram of the SSC-LPFG fiber structure.

The fabrication is completed when a sufficiently deep resonant dip appears at 1492 nm. The obtained structure is slice-shaped, so we name it SSC-LPFG. Figure 2 shows the scheme diagram of the SSC-LPFG. The total length of the SSC-LPFG is 3 mm. The experimental transmission spectrum is shown as the blue line in Fig. 3(b).

We use the R-soft simulation software to simulate the energy transfer diagram and the transmission spectrum. In the R-soft simulation process, the core/cladding diameters of the MMF and SMF are 60/125 μm and 8/125 μm , respectively. The mesh size is 0.1 μm in the XY direction and 0.4 μm in the Z direction. We set the SMF cladding RI to 1.4468, the core RI to 1.4521, the MMF cladding RI to 1.4781, and the core RI to 1.4783. Figure 3(a) shows that the energy in the core is gradually coupled to the cladding as the light propagates in the structure. Figure 3(b) shows the experimental and simulated transmission spectra of the SSC-LPFG structure, and the simulation results are consistent with the experimental results.

The phase matching condition satisfies the following relationship^[25]:

$$\lambda = (n_{\text{core}}^{\text{eff}} - n_{\text{cl},k}^{\text{eff}}) \cdot \Lambda, \quad (1)$$

where λ is the wavelength, $n_{\text{core}}^{\text{eff}}$ and $n_{\text{cl},k}^{\text{eff}}$ are the effective RIs of the core mode and the k th diffraction cladding mode, and Λ is the period of the grating. The minimum transmission value and width of the resonant dips are determined by the coupling

Fig. 3. (a) Simulated energy transfer diagram. (b) Experimental and simulated transmission spectra of the SSC-LPFG structure.

Fig. 4. Liquid level measuring device.

efficiency between the core and the cladding modes and the length of the LPFG. The minimum transmission value of the resonant dips is related to the length of the LPFG as^[26]

$$T(L) = \cos^2(\kappa L), \quad (2)$$

where L is the length of the LPFG, and κ is the coupling coefficient. The RI sensitivity of the central wavelength of the resonant dips of the LPFG arises from the dependence of the cladding modes' effective RI on the RI of the surrounding material. These effects permit the use of an LPFG as an RI sensor based on changes in the wavelength or the minimum transmission value of the resonant dips in the LPFG spectrum.

The RI sensitivity is used to measure the concentration of some substances^[27], so we use it to measure the liquid level. When the SSC-LPFG is partially immersed within the liquid, it can be considered to be two separate LPFGs. As shown in Fig. 4, where L_1 is the LPFG length surrounded by liquid, $L - L_1$ is the LPFG length surrounded by air, and L is the length of the overall LPFG. For each cladding mode, the transmission spectrum will contain two resonant dips, as shown in Fig. 5. One is centered

Fig. 5. Liquid level measurement begins and ends with wavelength drift.

at the coupling wavelength of the result where the minimum transmission value and width of the resonant dips will depend on the liquid level. By using Eq. (2), for an LPFG of length L , it can be shown that the dependence of the minimum values of resonant dips A and B, on the length of the LPFG immersed in the liquid L_1 , is given by

$$T_A(L_1, L) \propto \cos^2\left[\frac{\pi}{2}\left(\frac{L - L_1}{L}\right)\right], \quad (3)$$

$$T_B(L_1, L) \propto \cos^2\left[\frac{\pi}{2}\left(\frac{L_1}{L}\right)\right], \quad (4)$$

where T_A and T_B are the minimum transmission values of resonant dips A and B, respectively. Equations (3) and (4) are valid in the range of $0 < L_1 < L$. From Eqs. (3) and (4), if $L_1 = 0$, T_A reaches the minimum, T_B reaches the maximum, and the superimposed resonant dip consisting of resonant dips A and B coincides with resonant dip A. As the liquid level increases, T_A monotonously increases, T_B monotonously decreases, and the superimposed resonant dip gradually shifts from the wavelength of resonant dip A to that of resonant dip B. If $L_1 = L$, T_A reaches maximum, T_B reaches minimum, and the superimposed resonant dip coincides with resonant dip B. Both T_A and T_B are monotonic functions, so the changes of T_A and T_B are always opposite, and the shift of the superimposed resonant dip is unidirectional. Thus, the proposed sensor can measure the liquid level change.

3. Experimental Results and Discussion

The experimental device of the SSC-LPFG for liquid level measurement is shown in Fig. 4. The spiral micrometer pushes the connecting rod down and into the water. The moving distance of the spiral micrometer rod is the same as that of the sensor in the liquid. Figure 6 shows that the levels change from 0 μm to 1400 μm , and the wavelength shift is recorded at the same time

Fig. 6. SSC-LPFG liquid level sensing performance at different liquid levels.

every 200 μm . As the liquid level increases, the wavelength of the resonant dip will have a red shift from 1494.6 nm to 1504.2 nm. The sensitivity of the water level measurement is 7080 pm/mm, which is described by linear fitting with a correlation coefficient (R^2) of 0.99033.

To compare the liquid level performance of different polishing depth sensors, we made three sensors with polishing depths of 15 μm , 20 μm , and 25 μm on the second side and compared their liquid level sensing performance. Figures 7(a) and 7(b), respectively, show the resonant dip with three different polishing depths and liquid level sensing performance of sensors. The R^2 of the sensor with a polishing depth of 15 μm is 0.93966, which has low linearity and cannot accurately measure the liquid level. The sensor with polishing depth of 20 μm has a liquid level sensitivity of 2930 pm/mm and R^2 of 0.87226. The SSC-LPFG in this paper has a level sensitivity of 7080 pm/mm and R^2 of 0.99033. The experimental results show that the proposed SSC-LPFG has the best sensing performance.

The liquid level performance of SSC-LPFG is repeatedly measured two times to verify stability. The liquid level sensing

Fig. 7. (a) Resonant dip of sensors with different polishing depths. (b) Dip wavelength shift versus liquid level [different depth of polishing].

Fig. 8. Liquid level sensing performance.

performance is shown in Fig. 8. It shows that SSC-LPFG has stable performance in liquid level measurement. At the same time, we measure the temperature sensitivity of SSC-LPFG by exposing it to air. The sensor is placed into the temperature control platform, which is set to increase from 20°C to 90°C with a step of 10°C. Due to the difference of the thermal coefficients between the core mode and the cladding mode, the wavelength of the resonant dip is red shifted when the temperature increases, as shown in Fig. 9. The temperature sensitivity of the proposed SSC-LPFG is 24.52 pm/°C with a linear correlation coefficient of 0.97339. The temperature cross sensitivity of the liquid level is about 3.46 $\mu\text{m}/^\circ\text{C}$. The resolution of the liquid level measurements is 2.82 μm , and the temperature resolution is 0.82°C. It reveals that a stable operation in the proposed optical sensor can be obtained.

The experimental results are compared with other references in Table 1. It shows that most of the fiber optic sensors with high liquid level sensitivity are prepared with interferometer structures. Generally, the measurement range occupies

Fig. 9. Response of dip wavelength to temperature changing.

Table 1. Parameter Comparison of Optical Fiber Liquid Level Sensors.

Configuration	Grating Length [mm]	Level Range [mm]	Level Sensitivity [pm/mm]	Temperature Crosstalk [$\mu\text{m}/^\circ\text{C}$]
SMF-MMF-HCF-SMF/FBG with aligned spliced ^[21]	22	10	1145 (1.333 RI)	7.86
SRI-based etched chirped FBG ^[22]	7	5.6	1214	6.5
SMF-taper-TCF-taper-SMF ^[23]	16	15	1241.6	17
SMF-PCF-SMF with a bending cantilever setup ^[28]	Not reported	8	111.27 (1.333 RI)	Not reported
SMF-PMF-SMF with waist enlarged fiber tapers ^[29]	35	28	279	2.21
SMF-PMF-SMF with waist enlarged fiber tapers ^[29]	40	28	186	Not reported
SMF-MMF-TF-SMF with aligned spliced ^[30]	18	9	-175.8 (1.334 RI)	350
SMF-RCF-MMF-SMF with misaligned spliced ^[31]	300	120	6	6533
LLS based on a single LPFG ^[32]	Not reported	50	70	Not reported
This work	3	1.4	7080 (1.333 RI)	3.46

30%–70% of the sensor length. The length of the sensor is related to its sensitivity. The SSC-LPFG proposed in this paper sharply improves the sensitivity of the liquid level sensing while ensuring the mechanical performance. In addition, the SSC-LPFG structure has a low temperature response, which helps to reduce the temperature cross sensitivity in liquid level measurement. In terms of size comparison, the length range of the liquid level sensors based on gratings and interferometers is from 10 to tens of millimeters. The SSC-LPFG structure with a length of 3 mm has a strong competitive advantage in terms of integration. The liquid level sensing sensitivity of 7080 pm/mm provides a feasible solution for high-precision liquid level sensing required in medical and other fields.

4. Conclusion

In conclusion, a sensor based on SSC-LPFG for liquid level sensing is proposed. The proposed sensor is obtained by splicing MMFs with the SMF to get the C-MSM structure, and then it is polished on two opposite sides, which are parallel to the axis direction of the fiber. The sensitivity of the cladding mode to the external environment is improved by the insertion of multiple MMFs and double-sided polishing modulation by a high-power CO₂ laser. The software simulation and experimental verification are carried out. In the experiment, the wavelength changes of the resonant dip are linearly related to the liquid level, and the corresponding average sensitivity to the liquid (RI = 1.333) is 7080 pm/mm. A temperature test is performed to verify the sensor's temperature sensitivity of 24.52 pm/°C and the cross sensitivity of 3.5 $\mu\text{m}/^\circ\text{C}$. The sensor has the advantages of compact structure and ultra-high sensitivity. It is a latent candidate in the field of high-precision liquid level measurement or sensing.

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