A Refractive Index Sensitive Liquid Level Monitoring Sensor Based on Multimode Interference

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Received: 2 September 2020; Accepted: 5 October 2020; Published: 6 October 2020

Abstract: According to the beam propagation method, a fiber refractive index-sensitive multimode interference (MMI) structure fabricated by splicing a self-made silica glass rod between two single mode fibers (SMF–NCF (no core fiber)–SMF structure) is proposed for liquid level monitoring. Theoretical and experimental investigation was carried out meticulously using a 4.5 cm and a 9.5 cm long silica glass rod. It is proved that the simple and economical sensor with the shorter length has high sensitivity, satisfactory repeatability, and favorable stability. The sensitivity climbs with the increase in refractive index of the measured liquid, which is 204 pm/mm for pure water, 265.8 pm/mm for 10% glycerin solution, and 352.5 pm/mm for 25% glycerin solution. The proposed sensor can be standardized in certain application circumstances to achieve accurate liquid level monitoring.

Keywords: multimode interference; SMF–NCF–SMF structure; liquid level monitoring; optical fiber sensor

1. Introduction

Recently, optical fibers have drawn much attention in both scientific research and field applications. Compared with traditional electronic ones, sensors based on optical fibers have numerous superiorities such as small size and weight, low cost and transmission loss, corrosion resistance, and electromagnetic interference immunity, and they have been widely applied in the fields of engineering [1–3], chemistry [4,5], environment monitoring [6], and biology and medicine [7,8]. According to the working principles, optical fiber sensors can be divided into interference-based ones [9–12], grating-based ones [13–15], resonance-based ones [16–18], or many others. Among them, fiber sensors based on multimode interference structures, as one type of interference-dependent sensors, are particularly popular due to their simple and flexible structure and accurate sensitivity, and they have been used to measure numerous physical parameters including strain [19], temperature [20], curvature [21], liquid level [22], refractive index [23–30], and magnetic field [31], etc.

For practical application, the fiber-dependent liquid level monitoring sensor plays a significant role in laboratory and engineering conditions, especially in the fuel and petroleum industry, biomedicine, and chemical processing [32,33]. Up to now, a number of techniques associated with liquid level monitoring have been reported. For instance, sensors based on fiber gratings [34], plastic optical fibers [35], interferometers [36], and the local refractive index curved modulation effect [37] have been proposed for this purpose. However, many of them require complicated procedures or structures, or expensive cost to achieve high sensitivity. Therefore, a simple and economical means to realize real-time liquid level monitoring is worth expecting.
In this work, a fiber multimode interference (MMI) structure fabricated by splicing a self-made silica glass rod between two single mode fibers (SMFs) has been proposed to monitor liquid level variation, whose formation is simple and costless. After rigorous theoretical analysis and experimental verification, the sensor is proved to have high sensitivity, satisfactory linearity, and repeatability, which can be standardized in certain circumstances to realize fast and high-accuracy measurement, and can be further applied in the engineering, chemistry, and biology fields.

2. Fabrication and Principle

The designed liquid level sensor is fabricated by splicing a length of self-made silica glass rod between two SMFs, as shown in Figure 1a. The cross-section of the silica glass rod is presented in Figure 1b, whose diameter is about 125 μm. During light transmission, the input light initially enters into the lead-in SMF (left) and transmits as the fundamental mode. The silica glass rod can be regarded as a no core fiber, and the light is spliced into multiple high-order modes at the left fusion point. After transmitting through the rod, light in numerous directions converges at the right fusion point to a core fundamental mode and forms an interference spectrum at the end of the lead-out SMF.

\[
I = I_1 + I_2 + 2 \sqrt{I_1 I_2} \cos \phi
\]

\[
\phi = \frac{2\pi (n_{eff}^1 - n_{eff}^2) L}{\lambda}
\]

where \(I_1\) and \(I_2\) are the intensity of any two-order mode involved in the interference, \(\phi\) is the phase difference between the two modes, and \(n_{eff}^1\) and \(n_{eff}^2\) are their effective refractive indices, respectively. \(L\) is the length of the silica glass rod and \(\lambda\) is the free space wavelength of the input light. From this formula, we can see clearly that \(I\) is under the direct influence of \(L\), which impacts the

![Figure 1. (a) Designed multimode interference (MMI) structure, (b) Cross-section of the self-made silica glass rod, (c) Liquid level monitoring sensor based on MMI structure. SMF—single mode fiber.](image-url)
mode distribution and interference. Therefore, by observing the variation of the spectrum intensity, liquid level change can be monitored.

3. Numerical Analysis

The transmission properties of the MMI are simulated based on the beam propagation method (BPM). The core refractive index of the SMFs is 1.45, the cladding refractive index 1.445, and the length 1 cm. The length of the silica glass rod is selected to be 4.5 or 9.5 cm, and its refractive index is assumed to be 1.45. The liquid refractive index \( n_{\text{liquid}} \) is set to be 1.33, and the immersing depth grows from 1 to 1.4 cm with a step size of 2 mm. During the numerical simulation, the material dispersion coefficients was not taken into consideration due to its limited influence.

Figure 2 demonstrates the simulated transmission property of MMI using a 9.5 cm long silica glass rod. In Figure 2a, it is clear that light is, at first, confined to the core of the lead-in SMF. After entering into the silica glass rod, various modes are excited and couple with each other to fluctuate regularly between the maximum and minimum. In other words, with the different length of the no core fiber, the distribution of the optical field will periodically reproduce, which is the self-imaging effect [39,40]. Finally, the light returns to the lead-out SMF, and due to the different mode coupling condition, the light intensity varies slightly at different wavelengths, which produces an interference spectrum. Figure 2b presents the output light intensity at different free space wavelengths and the evolution of the interference spectrum when the immersing depth rises by 4 mm. We can see that with the increase in liquid level, the interference spectrum tends to red shift and the sensitivity mounts to 300 pm/mm.

Figure 3 describes the transmission and sensing properties of MMI structure when a 4.5 cm long silica glass rod is adopted. Compared with Figure 2, it can be seen that a shorter MMI structure brings about less interference peaks but the sensitivity is enhanced to 400 pm/mm. This is because the increased length enlarges the loss, resulting in a rising number of loss peaks in the transmission spectrum, which is adverse to the sensing sensitivity.

In addition, to simulate different liquid detection environments, we adjust the liquid refractive index to 1.36 and 1.39 and analyze, respectively, the sensitivities, as shown in Figure 4. There is no doubt that the sensitivity climbs with the increase in the liquid refractive index, and 400 pm/mm for \( n_{\text{liquid}} = 1.333 \), 500 pm/mm for \( n_{\text{liquid}} = 1.36 \), and 800 pm/mm for \( n_{\text{liquid}} = 1.39 \). This is because the larger the liquid refractive index, the more significant the contrast with the air, and in turn, the more sensitive the mode coupling is to the liquid/air interface, which finally leads to a higher sensitivity to liquid level monitoring.

![Figure 2](image-url) **Figure 2.** Simulation of MMI using a 9.5 cm long silica glass rod, (a) Electric field distribution of MMI in Z axis, (b) Analysis of the liquid level monitoring sensitivity \( (n_{\text{liquid}} = 1.333) \).
Figure 3. Simulation of MMI using a 4.5 cm long silica glass rod, (a) Electric field distribution of MMI in Z axis, (b) Analysis of the liquid level monitoring sensitivity ($n_{\text{liquid}} = 1.333$).

Figure 4. Sensitivities in different liquid conditions (a) $n_{\text{liquid}} = 1.36$, (b) $n_{\text{liquid}} = 1.39$.

4. Experimental Results and Discussion

The experimental setup is shown in Figure 5. Light was emitted by an ASE (amplified spontaneous emission) light source passed through the designed MMI-based sensor, which was immersed in the measured liquid. The output light was collected by an optical spectrum analyzer (OSA: Yokogawa AQ6375B) to monitor the interference spectrum. For fabrication of the MMI-based sensor, we firstly used a wire stripper to remove the coating layer of the single mode fiber, and used a cutting knife (CT-50, Fujikura) to make the fiber tip flat. After selecting an appropriate length of silica rod according to the liquid level, an optical fiber fusion machine (S179c, Furukawa) was used for the connection of the fiber rod and single mode fibers. During the fusion process, a built-in program (single mode-multimode, SM-MM) was used, and each fiber was cleaned with alcohol before fusion.

Figure 5. Experimental setup of the liquid level monitoring sensor. ASE- amplified spontaneous emission; OSA-optical spectrum analyzer.
Figure 6 presents the respective sensing properties when using different NCF lengths (4.5 and 9.5 cm) during the measurement of pure water ($n_{\text{liquid}} = 1.333$). We can see that the longer NCF is superior to the shorter one in terms of visibility of the fringe pattern and the number of the interference peaks, and as the liquid level went up, the interference spectrum moved towards the longer wavelength. According to Equations (1) and (2), the interference spectrum of different silica glass rod lengths was obtained using Fast Fourier Transform (FFT), as shown in Figure 7a. In comparison, the longer MMI structure has more peaks in frequency domain space, which means it has more cladding modes to interfere and an increasing number of interference peaks and dips. The respective sensitivity of the MMI-based sensor using different silica glass rod lengths is shown in Figure 7b. We can see clearly that the sensor using the shorter MMI length (4.5 cm) has a sensitivity twice higher than that of the other one (9.5 cm), which is 204 pm/mm for the former and 106 pm/mm for the latter. Thus, the increasing number of interference peaks and the larger modulation depth of the longer MMI length were not conducive to improving sensitivity. This conclusion is consistent with the theoretical simulation result. The 4.5 cm long MMI was selected for the following discussion.

![Figure 6](image1.png)

**Figure 6.** Experimental results of the proposed sensor using different silica glass rod lengths (a) Length = 9.5 cm, (b) Length = 4.5 cm.

The spatial frequency information of the interference spectrum of the MMI structures with different silica glass rod lengths was obtained using Fast Fourier Transform (FFT), as shown in Figure 7a. In comparison, the longer MMI structure has more peaks in frequency domain space, which means it has more cladding modes to interfere and an increasing number of interference peaks and dips. The respective sensitivity of the MMI-based sensor using different silica glass rod lengths is shown in Figure 7b. We can see clearly that the sensor using the shorter MMI length (4.5 cm) has a sensitivity twice higher than that of the other one (9.5 cm), which is 204 pm/mm for the former and 106 pm/mm for the latter. Thus, the increasing number of interference peaks and the larger modulation depth of the longer MMI length were not conducive to improving sensitivity. This conclusion is consistent with the theoretical simulation result. The 4.5 cm long MMI was selected for the following discussion.

![Figure 7](image2.png)

**Figure 7.** (a) Fast Fourier Transform (FFT) of the experimental interference spectrum, (b) Sensitivities of the MMI structures using different silica glass rod lengths.

Figure 8a gives information about the sensitivities of two varying interference dips, namely, Dip A and Dip B in Figure 6b. It can be seen that the sensitivity of Dip A is 204 pm/mm, and that of Dip B is 158 pm/mm. This sensitivity disparity of the dips in the experiment resulted from the existence of a surface evanescent field induced by various higher order modes. The external environment refractive

![Figure 8](image3.png)

**Figure 8.** (a) Sensitivities of Dip A and Dip B in 4.5cm length, (b) Repeatability of the liquid level monitoring sensor (Data from Dip A@ 4.5cm length).
index would affect the higher order modes to numerous extents, and the loss of these modes is different. When modes interfere with each other, dips will be formed and affected by the diverse interference conditions. Therefore, when the external environment changes, different dips would have different sensitivities. The ideal simulation fails to take these complexities into consideration. Because the sensing sensitivity decreases with the blue shift of the dip position, thus Dip A is chosen for sensitivity calibration of the liquid level monitoring sensor. Repeatability of this sensor is verified, as shown in Figure 8b. It is clear that during the rising up and falling down of the liquid level, the sensitivity only exhibits a slight fluctuation, which is 204 and 196 pm/mm (Dip A@ 4.5 cm length), respectively. Consequently, the designed sensor is experimentally proved to have satisfactory repeatability.

![Figure 8](image)

**Figure 8.** (a) Sensitivities of Dip A and Dip B in 4.5 cm length, (b) Repeatability of the liquid level sensor (Data from Dip A@ 4.5 cm length).

Figure 9 illustrates the stability of the sensor, and a 10 cm high liquid level test was repeated five times. The mean wavelength of the interference spectrum Dip A is 1589.34 nm, and the standard deviation is 0.055, which shows a fine stability. Furthermore, for the response time of the sensor, spectrum changes were observed by OSA after adjusting the liquid level. After a few scanning cycles, the response time is measured to be about five to six seconds when the liquid level increases. This value rises a little bit as the liquid level drops, since when the liquid level decreases, there is some residual liquid on the surface of the sensor and it takes more time for the liquid to fall back.

![Figure 9](image)

**Figure 9.** Stability of the liquid level sensor (Data from Dip A@ 4.5 cm length).

Apart from the liquid level detection of pure water, the designed sensor was also used to measure a glycerin solution with a volume fraction of 10% and 25% to test its sensing property. Figure 10 illustrates the respective sensitivities, which is 204 pm/mm for pure water, 265.8 pm/mm for the 10% glycerin solution, and 352.5 pm/mm for the 25% glycerin solution. The refractive index of the glycerin solution is larger than that of pure water, and its value climbs with the increase in glycerin volume fraction [41], as does the sensitivity of the MMI-based sensor. As a matter of fact, as long as the test liquid has
a refractive index lower than that of the fiber, the proposed sensor can exhibit a good performance in detecting its liquid level change. If the refractive index of the liquid surpasses that of the fiber MMI structure, light would leak to the liquid based on optical transmission theory, leading to a detection failure.

As is evidenced by all the figures released above, the goodness of fit \(R^2\) concerning each linear fit line is larger than 0.97, which means the sensor has satisfactory linearity and accuracy. In this experiment, we used a shorter MMI structure to achieve higher sensitivity, but this did not mean the shorter the better. A shorter length would naturally limit the sensing range, which would mutually restrict the sensitivity and the measuring range. Therefore, in field applications, the MMI length needs to be adjusted according to the actual environment. Meanwhile, surface cleaning of the sensor should be taken into consideration to avoid measuring errors. Table 1 presents a comparison of the designed sensor and other liquid level sensors reported previously, which highlights the advantages such as high sensitivity and wide measuring range aside from its easy fabrication.

### Table 1. Comparison with other fiber liquid level sensors.

| Method                              | Sensitivity | Measurement Range | Reference |
|-------------------------------------|-------------|-------------------|-----------|
| Long period fiber grating (LPFG)    | 250 pm/mm   | 0–100 mm          | [42]      |
| Michelson interferometer            | 8.44 pm/mm  | 0–100 mm          | [43]      |
| Mach-Zehnder interferometer (MZI)   | 288 pm/mm   | 0–65 mm           | [44]      |
| based on thin core fiber            |             |                   |           |
| S-bend plastic optical fiber        | 0.04 dB/mm  | 0–100 mm          | [45]      |
| Etched chirped fiber Bragg grating  | 1214 pm/mm  | 0–7 mm            | [46]      |
| (FBG)                               |             |                   |           |
| Multimode-Single mode-Multimode (MSM)| 264.6 pm/mm | 0–26 mm           | [47]      |
| Curved modulation of refractive index (RI) | 712 pm/mm | 0–24 mm           | [30]      |
| MMI based on NCF                    | 352.5 pm/mm | 0–45 mm           | This work |

5. Conclusions

In summary, a refractive index-sensitive liquid level monitoring sensor was proposed based on a fiber MMI, and theoretical and experimental investigation was carried out in detail in this work. The influence of the NCF length and liquid refractive index on the sensing sensitivity was analyzed with discretion. By comparing the performance of sensors made by different silica glass rod lengths (4.5 and 9.5 cm), it is proved that the sensor with the shorter length had high sensitivity, satisfactory repeatability, and favorable stability. The sensitivity of the proposed sensor climbed with the increase in refractive index of the measured liquid, which was 204 pm/mm for pure water,
265.8 pm/mm for 10% glycerin solution, and 352.5 pm/mm for 25% glycerin solution. The theoretical analysis was consistent with the experimental results. The proposed sensor can be standardized in certain application circumstances to achieve fast and accurate liquid level monitoring, which can be applied in the engineering, chemistry, and biology fields.

**Author Contributions:** Conceptualization, F.Z. and T.C.; methodology, F.Z.; software, F.Z.; validation, F.Z., S.L. and T.C.; formal analysis, S.L.; investigation, X.Z.; resources, T.C., X.Y., X.Z., and S.L.; data curation, T.S. and F.W.; writing—original draft preparation, F.Z.; writing—review and editing, F.Z. and T.C.; visualization, Y.O.; supervision, T.C.; project administration, T.C.; funding acquisition, T.C., X.Y., X.Z., and S.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work is supported by the National Key Research and Development Program of China (2019YFB2204001), National Natural Science Foundation of China (61775032 and 11604042), Fundamental Research Funds for the Central Universities (N18040602, N180408018, and N2004021), JSPS KAKENHI Grant(17K18891 and 18H01504), JSPS and CERN under the JSPS-CERN joint research program, and 111 Project (B16009).

**Acknowledgments:** The authors thank Liao Ning Revitalization Talents Program.

**Conflicts of Interest:** The authors declare no conflict of interest.

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