Highly Sensitive Tapered Fiber Mach–Zehnder Interferometer for Liquid Level Sensing

Jui-Ming Hsu, Cheng-Ling Lee, Hun-Pin Chang, Wen Cheng Shih, and Chai-Ming Li

***Abstract*— A low cost, simple, and in-line liquid level sensor based on a dual-tapered fiber Mach–Zehnder interferometer (DTFMZI) is proposed. In this letter, the configuration, operation principle, experimental results, and discussion for the proposed fiber-optic liquid level sensor are investigated. Experimental results show that the proposed DTFMZI sensor is highly sensitive and linear in the response; a good sensitivity of ∼2.8 nm/cm within the whole measurement range of 10 cm is achieved in this letter.**

***Index Terms*— Optical fiber sensors, optical interferometry, fiber Mach–Zehnder interferometer (FMZI), fiber-optics component.**

I. Introduction

FIBER-OPTIC liquid level sensors (FOLLSs) with many smart and hybrid structures have been proposed in recent years. These FOLLSs especially based on the in-line fiber interferometer have attracted much attention due to their compact, highly sensitive and especially long distance sensing properties. Furthermore, FOLLSs are particularly suitable for using in a storage tank of chemical or industry liquor due to its anti-corrosiveness.

In general, there are two types of FOLLSs: point sensors [1]–[3] and continuous level sensors [4]–[13]. The point sensors detect the liquid level at one or more discrete points to provide information whether the liquid level exceeds the setting points. On the other hand, the continuous level sensors detect the liquid level in a certain range continuously. This fully distributed sensing capability makes continuous level sensors a preferred solution for many applications. For the continuous level sensors, the interference scheme based on long period gratings (LPGs) [4], fiber Bragg gratings (FBGs) [5]–[8], fiber Fabry-Pérots (FPs) [8], fiber Michelson [9]–[11], fiber Sagnac [12], and multimode fiber interferometers [13] had been proposed. The sensitivities represented in the previous works are about 0.15 nm/cm [6], 0.06 nm/cm [7], 0.01491 nm/cm [8], 0.0021 nm/cm [11], and 0.047 nm/cm [12], respectively.

In this letter, we present a low cost, simple, and in-line liquid level sensor by using a dual-tapered fiber Mach–Zehnder interferometer (DTFMZI) which can be effectively fabricated by tapering a single-mode fiber (SMF) twice with an interval of certain length. The new configuration of DTFMZI was subsequently pasted onto a slice of uniform elastic-plastic to form a sensing element of bending cantilever; a stick of polyamide adheres to the cantilever and droops into the liquid tank. The bending curvature of the sensing element varies with the liquid level rising and makes the interference spectra shifts during the liquid level rises or drops.

Experimental results show that the proposed DTFMZI-FOLLS is extremely sensitive and linear in response; a sensitivity of about 2.8nm/cm was achieved. Comparing with the previous works, the proposed DTFMZI-FOLLS has extremely high sensitivity, easy to fabricate and has all-fiber configuration characteristics which can be further developed into a favorable fiber-optic liquid level sensor for a wide range of applications.

II. Configuration and Principles

Figure 1 indicates the experimental setup of the proposed DTFMZI-FOLLS. The sensor was pasted onto a slice of uniform elastic-plastic to form a sensing element of bending cantilever; a stick of polyamide adhered to the cantilever and drooped into the liquid tank. Light from a broadband light source (BBS) launched into the DTFMZI, and transmission spectra were directly obtained by an optical spectrum analyzer (OSA). The abrupt tapers in the DTFMZI shown as Figure 2(a) were simply fabricated by a commercial fusion splicer. For the first and second tapers, the lengths of the tapered regions were measured as 776μm and 783μm, while the waist diameters were about 42.3μm and 41.5μm, respectively. Figure 2(b) indicates the configuration of the DTFMZI, the interval L between two tapers was 1.0cm. The SMF with dual-taper was embedded in a capillary tube with an internal diameter of 150μm and a length of 2cm. The two ends of the tube were fixed with epoxy resin. The abrupt taper with a suddenly changed profile breaks the adiabaticity of light power to generate higher-order cladding modes. Therefore, a light beam from the first taper split into two parts, the core and cladding modes, and propagated through the fiber. By the second taper, the core and cladding modes are collected. A phase difference is thus introduced to bring about a periodic oscillation spectrum in the OSA due to optical path difference (OPD).

The phase difference between the core and the mth-order cladding modes after propagating through the length L of the taper interval can be easily written as:

$$\phi_m = \frac{2\pi}{\lambda}(n_{eff}^{co} - n_{eff}^{cl,m})L = \frac{2\pi}{\lambda}\Delta n_{eff}^{m} L \qquad (1)$$

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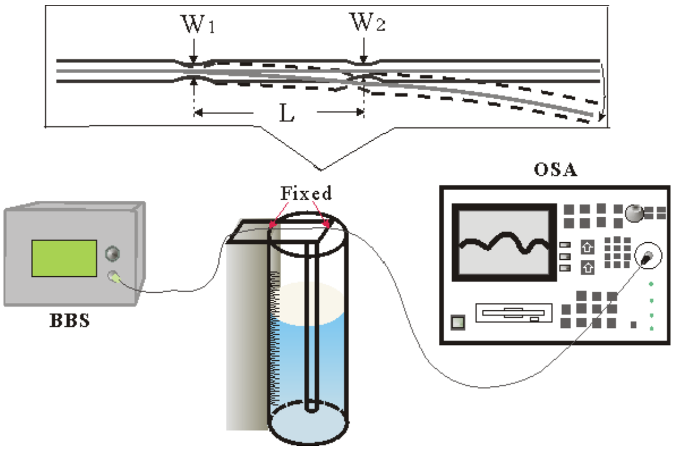

Fig. 1. Experimental setup of the proposed DTFMZI-FOLLS. BBS: Broadband light source. OSA: Optical spectrum analyzer. DTFMZI: Dual-tapered fiber Mach–Zehnder interferometer.

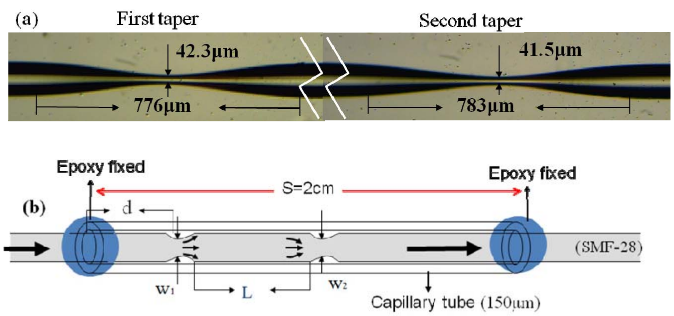

Fig. 2. (a) Micrographs of the abrupt tapers made by a fusion splicer. (b) Configuration of the dual-tapered fiber Mach–Zehnder interferometer (DTFMZI). $w_1 = 42.3\mu$m, $w_2 = 41.5\mu$m, and L = 1.0cm.

where Δn^m_{eff} is the effective index difference between the core mode and the mth cladding modes. λ is the wavelength in vacuum. The wavelength of spectral minima $\lambda^m_{\min}$ can be deduced by substituting the condition of interference minima $\phi_m = (2n+1)\pi$ here n is an integer, into Equation (1):

$$\lambda^m_{\min} = \frac{2}{2n+1}\Delta n^m_{eff} L. \tag{2}$$

The cantilever is most curved initially; it is driven by the buoyancy of the liquid and reduces its bending curvature during the liquid level rises. The buoyancy from the liquid can be displayed below:

$$\mathrm{F} = \rho g \mathrm{H} A. \tag{3}$$

Here, ρ denotes the density (or specific gravity) of the liquid and g is gravitational acceleration. H is the liquid level and A is the cross-sectional area of the polyamide stick used in the structure.

The F reduces the bending effect on the taper region when the H increases. Thus, the coupling cladding modes, which dominate the interference in the DTFMZI, are determined upon the evanescent mechanism resulted from the bending taper regions. Therefore, the interference spectra will shift during the liquid level rises or drops. The quantitative data of the liquid level is then obtained from the wavelength shifts based on the above-mentioned bending interference.

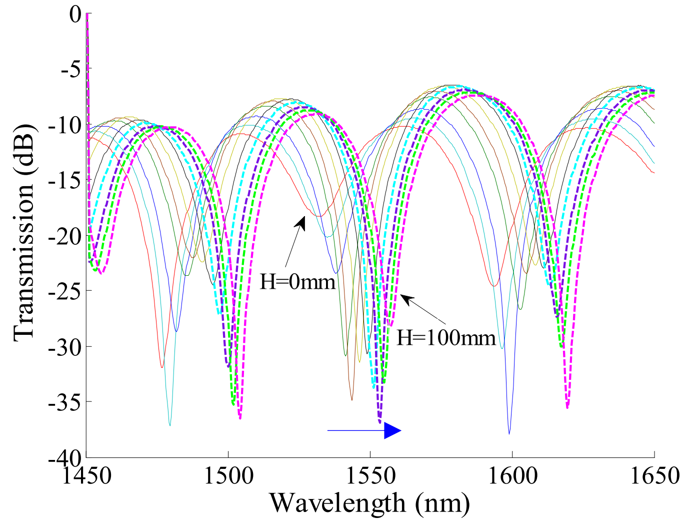

Fig. 3. Experimental transmission spectra of the proposed DTFMZI-FOLLS with L = 1.0 cm, L_p = 2 cm, and w $\approx 40\mu$m, for various liquid levels (H).

III. Experimental Results and Discussion

Figure 3 displays the experimental transmission spectra of the proposed DTFMZI-FOLLS for various liquid levels (H). As shown in the figure, the interference minima shift to longer wavelengths as the liquid level H increases. This phenomenon can be explained as follows: for lower liquid level, the DTFMZI is more curved as mentioned previously. The higher order cladding modes are prone to evanesce from the bending taper regions. The remaining lower order cladding modes couple with the core mode and dominate the interference in the proposed DTFMZI-FOLLS. Because the effective index of the lower order cladding modes is close to the core mode, thus results in a smaller Δn^m_{eff}. Therefore, according to Equation (2), the spectral minima locate at a shorter wavelength for a lower liquid level.

To investigate the influence of some geometric parameters of the DTFMZI, we changed the taper waists and the length of elastic-plastic (L_p) and observed the transmission spectra as well. Figure 4(a), (b) and (c) present the transmission spectra of the DTFMZI-FOLLSs with L = 1.0cm and the different waist diameters (w) of about 30μm, 40μm and 50μm, respectively. A group of the spectral data near a wavelength of λ = 1550nm is used to depict the sensitivity of the proposed DTFMZI-FOLLSs. Figure 4(d) displays the fitted linear response of the sensitivity for these three cases. Linear sensitivity of about 2.8nm/cm and 2.1nm/cm are achieved for the case of w = 40μm and 50μm, respectively. For the linear region on the sensitivity curve of w = 30μm, the sensitivity is even up to 3.8nm/cm. However, the sensitivity fitting curve of the case is nonlinear as well as saturated especially in the high liquid level. Fig. 4 indicates that the thinner the taper waist, the higher the sensitivity. It is not difficult to realize, a bent fiber taper with a thinner waist suffers higher loss and achieves a greater bending curvature by the same force acting on. Referring to our published study [14], a maximum sensitivity of a tapered fiber Michelson Interferometers (TFMI) is achieved when a force is applied toward the thinnest diameter

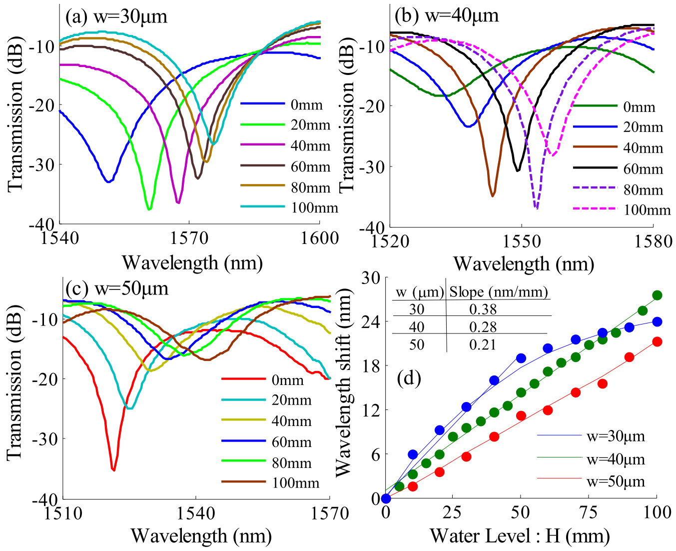

Fig. 4. Transmission spectra of the DTFMZI-FOLLSs with L = 1.0cm, L_p = 2cm and waist diameter of about (a) 30μm, (b) 40μm, (c) 50μm. (d) Sensitivity of spectral shifts in wavelengths of the above DTFMZI-FOLLSs.

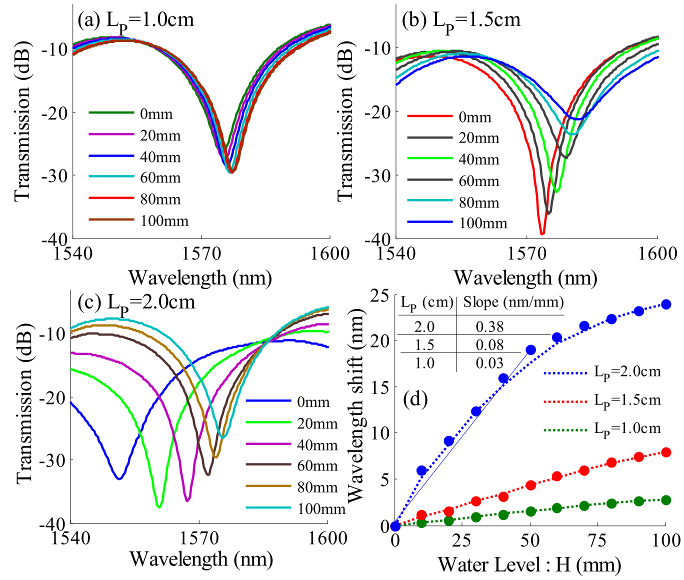

Fig. 5. Transmission spectra of the DTFMZI-FOLLSs with L = 1.0cm, w = 30μm and the plastic length Lp of (a) 1.0cm, (b) 1.5cm, (c) 2.0cm. (d) Sensitivity of spectral shifts in wavelengths of the above DTFMZI-FOLLSs.

of the taper. In the present study, the operating mechanism of the proposed DTFMI is similar to the TFMI in [14]. Thus, a thinner taper waist results in a higher sensitivity is reasonable. The theoretical explanation for this phenomenon of our device can be depicted as follows. Eq. (2) expresses the wavelength of spectral minima $\lambda^m_{\min}$ for the taper without bending. Once the taper is bent, $n^{cl,m}_{eff}$ varies by a variation of $\delta n^{cl,m}_{eff}$, and n^{co}_{eff} is almost unchanged. Thus the wavelength shift of the spectral minima is given by

$$\lambda^m_{\min}\big|_{bent} = \frac{2}{2n+1}(\Delta n^m_{eff} \pm \delta n^{cl,m}_{eff})L. \tag{4}$$

Therefore, a wavelength shift caused by taper-bending, $\delta\lambda^m_{\min}$, can be derived as

$$\delta\lambda^m_{\min} = \lambda^m_{\min}\big|_{bent} - \lambda^m_{\min} = \frac{2}{2n+1}(\pm\delta n^{cl,m}_{eff}L). \tag{5}$$

The sensitivity S_b for taper-bending can be obtained from differentiating $\delta\lambda^m_{\min}$ by the order of cladding mode m:

$$S_b = \frac{\partial(\delta\lambda^m_{\min})}{\partial m} = \pm\frac{2L}{2n+1}\frac{\partial(\delta n^{cl,m}_{eff})}{\partial m}. \tag{6}$$

G. Yin et al. had verified that the change rate of $\delta n^{cl,m}_{eff}$ to the order of cladding mode is larger for a taper with thinner waist [15] and consequently a thinner-waist taper is more sensitive as it bends.

Figure 5(a), (b), and (c) show the transmission spectra of the same DTFMZI with L = 1.0cm, w = 30μm but with different length of cantilevers. The DTFMZI was pasted onto the elastic-plastics with a length (L_P) of 1.0cm, 1.5cm and 2.0cm, respectively. Figure 5(d) demonstrates the fitted response of the sensitivity for the three cases. From the figure, it is clear to see that the longer the elastic-plastic, the higher the sensitivity. The experimental results agree closely with the theoretical results in the previous study [14]. One can figure the phenomenon out by intuition. A longer elastic-plastic must have a larger curvature variation when it is under a same bending force.

In this work, the liquid level sensing range is from 0 to 100mm, which depends on the length of the polyamide stick. Therefore, the sensing range can be easily varied by changing the length of the hanging stick. Actually, the measurement range can be extended unlimitedly by increasing the length of the stick. However, there are some disadvantages for the too high liquid level measurement. The first, the sensing cantilever may reduce its bent curvature to a minimum and saturate the measurements as the liquid level is high. Secondly, the coupling cladding mode may change due to the over bending in a wide range of measurement which would break the linear response of the sensitivity. Moreover, a longer stick causes the cantilever bends seriously due to its heavier weight that makes the stick always drop to the bottom before the liquid is poured to a certain level, this results a bias in liquid level measurement. Thus, entire structure parameters of the proposed DTFMZI-FOLLS—such as plastic length (L_p), taper waist diameter (w) and stick length—can be designed optimally for more advance applications.

From the above experimental results, a high sensitivity of linear response was accomplished in this letter. It is considerably larger than that of the other previous published studies mentioned in the introduction. It is worth to emphasized, the proposed sensor doesn't contact with the liquid that would improve the lifetime of the fiber device. Furthermore, because the measuring mechanism is based on the increase of floating force from the liquid; the DTFMZI-FOLLS also can be applied on the measurement of different kinds of liquids with other specific gravity that would make the proposed devices more practical.

IV. Conclusion

This letter proposes an in-line fiber-optic liquid level sensor (FOLLS) based on a dual-tapered fiber Mach–Zehnder interferometer (DTFMZI). The sensing element with two abrupt tapers, which were easily fabricated by a fusion splicer, was setup with a bending cantilever to accomplish an all-fiber liquid level sensor. Experimental results reveal that an extremely high sensitivity of about 2.8nm/cm and a good linear response of the sensor have been achieved. Comparing with the previous works, the advantages of the proposed fiber-optic sensor are low cost, simple tool-using and easy to fabricate, in-line, and long distance sensing and extremely sensitive. The sensor has considerable potential applications, and can be further improved to enhance the sensing capabilities of multi-sensing parameters, such as refractive index and specific gravity of liquids.

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