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Liquid level and temperature sensor based on an asymmetrical fiber Mach–Zehnder interferometer combined with a fiber Bragg grating

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ABSTRACT

A fiber optic sensor capable of simultaneous measurement of liquid level and temperature is proposed and demonstrated. The sensor is formed by the integration of an asymmetrical fiber Mach–Zehnder interferometer (aFMZI) with a fiber Bragg grating (FBG). The aFMZI was realized by concatenating a fiber taper and a lateral-shifted junction. By using the temperature sensing property of FBG, the liquid level sensor with dynamic temperature compensation can be achieved. For 10 pm wavelength resolution, a resolution of 0.15 cm in liquid level and 1.01 °C in temperature can be achieved. The prototype has the advantages of low fabrication cost and temperature compensated, which are desirable features in liquid level measurement.

1. Introduction

Measurements of liquid level are important in many fields, such as chemical industries, petroleum storage, and manufacturing. However, the traditional electric sensors cannot satisfy the demands of liquid level measurements in harsh environments, for example, conductive, explosive, flammable, and erosive environments [1]. In the past years, fiber optic sensors have attracted significant attention in various areas with its outstanding advantages, such as lightweight, immunity from electromagnetic interference and capability of multiplexing [2]. Various fiber optic sensors have also been reported to implement the measurement of the liquid level, such as FBG [3–5], long period fiber grating [1,6], tilted fiber Bragg grating [7–9], and so on. Recently, fiber sensors based on modal interferometer have attracted much attention with the merits of high sensitivity, high degree of integration, simplicity and compact in-line measurement [10–12]. Consequently, it has been successfully applied as liquid level sensors. In 2011, J.E. Antonio-Lopez et al. proposed a liquid level sensor based on a multimode fiber (MMF) [13]. In 2012, L. Li et al. proposed a fiber Mach–Zehnder interferometer for liquid level measurement. The sensor head was formed by all-fiber in-line singlemode-multimode-thinned-singlemode fiber structure [14]. In 2013, X. Wen et al. proposed a liquid level sensor based on two up-tapers [15]. In 2014, Q. Rong et al. proposed a sensor for liquid level measurement. The sensor consists of a short piece of small-core fiber followed by a standard single-mode fiber (SMF) where its end-face is terminated by a thick silver film [16]. However, among the aforementioned schemes, an unavoidable fact is that the liquid level sensors are sensitive to both liquid level and temperature, leading to a difficulty in discrimination between them or simultaneous measurement of them. In 2012, an all-silica Fabry–Perot fiber-optic sensor for simultaneous measurement of pressure and temperature was proposed by [17]. The sensor can also be used to measure the liquid level and temperature. In 2015, a fiber laser sensor for simultaneous measurement of liquid level and temperature was proposed by [18]. The sensor is based on two taper structures and a FBG. The sensor has high measurement sensitivity. However, the sensor is complicated design and high cost, which restrict their practical applications.

In this paper, we present a fiber optic sensor for simultaneous measurement of liquid level and temperature. The sensor is formed by the integration of an aFMZI with a FBG. The aFMZI is realized by concatenating a fiber taper and a lateral-shifted junction. By using the temperature sensing property of FBG, the liquid level sensor with dynamic temperature compensation can be achieved. Its low fabrication cost and temperature compensated will have attractive potential applications in liquid level measurement.

2. Principle

The schematic diagram of the proposed sensor is shown in Fig. 1. A FBG is imprinted the leading SMF (SMFBG). An aFMZI is spliced between the SMFBG and SMF. The aFMZI contains a fiber

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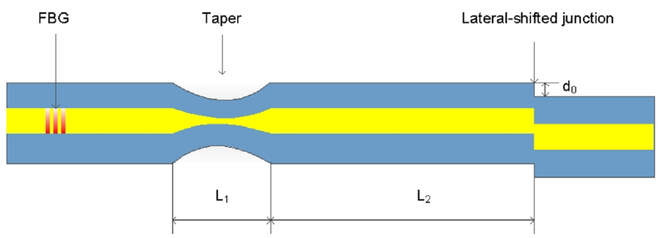

Fig. 1. Schematic diagram of the liquid level and temperature sensor based on an aFMZI combined with a FBG. (L_1, length of the tapered region; L_2, distance between the fiber taper and the lateral-shifted junction; d_0, fiber core offset).

taper and a lateral-shifted junction. The fiber taper and lateral-shifted junction works as the beam splitter and beam combiner, respectively. The fiber taper was shaped by tapering a standard telecommunication single-mode optical fiber using a fusion splicer (FSU-975). The length of the tapered regions L_1 was measured as about 800 µm, while the waist diameter was about 67 µm. The splicing method of lateral-shifted junction is very simple because it only involves cleaving and fusion splicing procedures. In our design, the lateral-shifted junction with a fiber core offset d_0 of 9 µm. The distance between the fiber taper and the lateral-shifted junction L_2 is about 8 cm.

When the light is launched into the aFMZI through the leading SMF, multimode interference (MMI) will occur. The interference pattern is based on the interference between the core mode and the dominant low-order cladding mode, and its intensity is calculated as [19]:

$$I(\lambda) = I_{core} + I_{clad} + 2\sqrt{I_{core}I_{clad}}\cos\varphi \tag{1}$$

where I_{core}, I_{clad} are the light intensity of the core mode and dominant low-order cladding mode of the aFMZI, respectively. It should be noted that although many cladding modes are excited in the sensing SMF, only one cladding mode dominates the interference with the core mode. So we only consider the dominant interference in Eq. (1). The phase differenceφ between the core mode and the dominant low-order cladding mode can be expressed as [19]:

$$\varphi = \frac{2\pi\Delta n_{eff}L_2}{\lambda} \tag{2}$$

where Δn_{eff} is the effective refractive indices difference between the core mode and the cladding mode, L_2 is the length of the aFMZI, and λ is the wavelength of the propagating light. When the phase difference satisfies the condition $\varphi=(2m+1)\pi$, the wavelength of the mth order attenuation peak can be written as:

$$\lambda_m = \frac{2\Delta n_{eff}L_2}{(2m+1)} \tag{3}$$

It can be seen from the equation that the Δn_{eff} or L_2 are the factors that will influence the wavelength shift. Besides, these factors are all affected by the temperature or liquid level variation. When a section of the aFMZI is surrounded by a liquid, the wavelength of the mth order attenuation peak can be written as:

$$\lambda_m = \frac{2}{(2m+1)}\left[\Delta n_{eff}\left(L_2 - L\right) + \Delta n_{effn}L\right] \tag{4}$$

where L and Δn_{effn} are the length and the difference of the effective refractive indices between the core mode and cladding mode for aFMZI section in the liquid. As the liquid level is increased, the difference of the effective refractive indices between the core and cladding modes becomes smaller. According to Eq. (4), it is known that the attenuation peak wavelengths will shift to shorter wavelengths. So when the sensor is placed in the vertical direction, the change in the liquid level can be easily detected by monitoring the wavelength shifts. The structure shows resonance behavior with a Bragg wavelength given by:

$$\lambda_{FBG}=2n_{eff}\Lambda \tag{5}$$

where n_{eff} and Λ are the effective refractive index and the grating period, respectively. The Bragg wavelength shift caused by temperature variation can be expressed as:

$$\Delta\lambda_{FBG} = \lambda_{FBG}\left[\alpha_{th} + \xi\right]\Delta T \tag{6}$$

Where α is the coefficient of thermal expansion of the glass fiber, and ξ is the fiber thermo-optic coefficient. ΔT denotes the changes of temperature [20,21].

Under condition of the liquid and air temperature are same, when liquid level and temperature change of ΔL and ΔT, the wavelength shifts of the aFMZI and FBG can be expressed as [20]:

$$\begin{bmatrix}\Delta\lambda_{aFMZI}\\ \Delta\lambda_{FBG}\end{bmatrix} = \begin{bmatrix}K_{L,aFMZI} & K_{T,aFMZI}\\ K_{L,FBG} & K_{T,FBG}\end{bmatrix}\begin{bmatrix}\Delta L\\ \Delta T\end{bmatrix} \tag{7}$$

Where $\Delta\lambda_{aFMZI}$ and $\Delta\lambda_{FBG}$ represent the wavelength shifts of the aFMZI and FBG, respectively. K_L and K_T are the sensitivity coefficients corresponding to the liquid level and temperature change, respectively. Postscripts aFMZI and FBG identify the contribution made by the two structures individually. The matrix equation for liquid level and temperature sensitivities of the resonant wavelength can be expressed by

$$\begin{bmatrix}\Delta L\\ \Delta \boldsymbol{T}\end{bmatrix} = \frac{1}{M}\begin{bmatrix}K_{T,FBG} & -K_{T,aFMZI}\\ -K_{L,FBG} & K_{L,aFMZI}\end{bmatrix}\begin{bmatrix}\Delta\lambda_{aFMZI}\\ \Delta\lambda_{FBG}\end{bmatrix} \tag{8}$$

where $M=K_{L,aFMZI}K_{T,FBG}-K_{T,aFMZI}K_{L,FBG}$, is the determinant of the coefficient matrix.

3. Experiment

Fig. 2 shows the experimental arrangement, including a broad band light source (KOHERAS, superK versa) with flat output in the range from 600 to 1800 nm, and an optical spectrum analyzer (OSA, YOKOGAWA AQ6375) with a wavelength resolution of 0.05 nm. The reflectivity and Bragg wavelength of the FBG used in the experiment are 77% and 1549.74 nm at the room temperature, respectively.

Fig. 3 shows the transmission spectrum of the sensor at room temperature. As can be seen from the figure, interference fringes with good visibility are observed over the spectral range of 1540–1590 nm. The maximum fringe visibility of the interference resonance dips is about 8 dB. The FBG-induced steep dip is also shown clearly at wavelength around 1549.74 nm.

To obtain the liquid level and temperature coefficients, liquid level and temperature changes are applied to the sensor

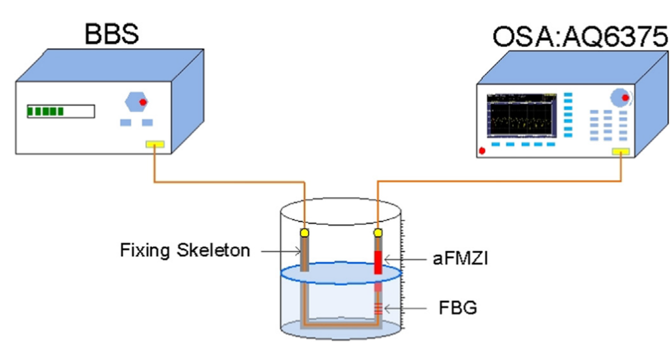

Fig. 2. Schematic diagram of the experiment setup.(BBS, broadband source; OSA, optical spectrum analyzer).