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Liquid level measurement based on a no-core fiber with temperature compensation using a fiber Bragg grating

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ABSTRACT

An optical fiber sensor for simultaneous measurement of liquid level and temperature is proposed and experimentally demonstrated. The sensor is formed by the integration of a no-core fiber (NCF) with a fiber Bragg grating (FBG).When the liquid level is changed, the interference fringe of the NCF would shift while the Bragg wavelength of the FBG remains the same. On the other hand, the interference fringe of the NCF and the Bragg wavelength of the FBG would shift simultaneously with the variation of temperature. Thus the liquid level sensor with dynamic temperature compensation can be easily achieved by using the temperature sensing property of FBG. For 10 pm wavelength resolution, the resolution of the sensor is 0.046 cm and 1.1 °C in liquid level and temperature, respectively. The fabrication of the proposed sensor is very simple and it is characterized by the dynamic temperature compensation, which makes it desirable in liquid level measurement.

1. Introduction

Research on the liquid level sensing technologies is of great importance in many fields such as chemical industries, petroleum storage, and manufacturing. Mostly, traditional sensors based on mechanical and electrical techniques cannot meet the requirements of liquid level measurements in harsh (conductive, explosive, or erosive) environments. In recent years, optical fiber sensors have received significant attention for their unique advantages in low power consumption, high corrosion-resistance and high sensitivity [1]. Optical fiber liquid level sensors based on other different operating principles have also been demonstrated. Among these methods, the fiber grating is one kind of the commonly used structures for liquid level sensing, such as fiber Bragg grating (FBG), long period grating (LPG), tilted fiber Bragg grating (TFBG), and so on. An etched FBG was used in the first scenario, but the device became fragile due to the use of hydrofluoric acid [2]. Later then, both the LPG and TFBG based liquid level sensors have been widely investigated, however, the complicated and relatively high cost fabrication processes limit their applications [3–6].

Fiber sensors based on modal interferometer can be served as a reliable candidate of liquid level sensor due to its unique properties such as high sensitivity, high degree of integration, simplicity and compact in-line measurement [7,8]. So far, many structures based on modal interferometer have been proposed for liquid level measurement. In 2011, J. E. Antonio-Lopez et al. proposed a liquid level sensor based on multimode interference (MMI) effects. The sensor is based on a standard 105/125 step-index multimode fiber [9]. In 2012, L. Li et al. presented 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 [10]. In 2013, X. Wen et al. reported an optical fiber sensor based on two up-tapers [11]. In 2014, H. Gong et al. proposed an optical liquid level sensor based on polarization-maintaining fiber modal interferometer with waist enlarge splicing [12]. In 2015, Y. Liu et al. presented a liquid level sensor based on coreless multimode fiber [13]. However, among the aforementioned schemes, an unavoidable fact is that the liquid level sensors are sensitive to both liquid level and temperature which makes it difficult to distinct or measure changes between liquid level and temperature. In 2010, a sensor for simultaneous measurement of liquid level and temperature based on a simple uniform FBG was proposed by [14]. In 2014, a reflective liquid level sensor based on modes conversion in the thin-core fiber incorporating one TFBG was proposed, the sensor was low cross-sensitivity to temperature [15]. In 2015, a fiber laser sensor based on two taper structures and a FBG was demonstrated for simultaneous measurement of liquid level and temperature [16]. The proposed sensor has high resolution and

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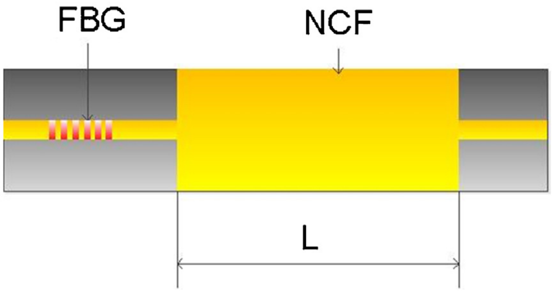

Fig. 1. Schematic diagram of the sensor structure.

high measurement sensitivity. In 2016, a liquid level and temperature sensor based on TFBG was proposed by [17]. Since the core mode and the cladding modes of TFBG respond differently to liquid level and temperature, simultaneous measurement of liquid level and temperature can be achieved. Later, a fiber liquid level sensor based on a LPG and microwave photonics filtering technique was proposed by [18]. The sensor head is a LPG followed by a FBG, which is used to compensate the temperature influence on the LPG wavelength shift.

In this paper, we present an optical fiber liquid level sensor based on MMI effects. The sensor is formed by the integration of a no-core fiber (NCF) with a FBG. By using the temperature sensing property of FBG, the liquid level sensor with dynamic temperature compensation can be achieved. Experimental results show that the sensor has the liquid level sensitivity of 218 pm/cm range from 0 to 4.5 cm and the temperature sensitivity of 9 pm/°C range from 15 °C to 45 °C. The fabrication of the proposed sensor is very simple and it is characterized by the dynamic temperature compensation, which makes it desirable in liquid level measurement.

2. Principle

The schematic diagram of the proposed sensor is shown in Fig. 1. A section of NCF is spliced between a FBG imprinted SMF (SMFBG) and the SMF. The NCF length is about 5 cm. When the light is launched into the NCF through the leading SMF acting as LP_{01} mode, the multiple modes (LP_{0m}) of the NCF will be excited due to the mode field mismatch, and will propagate within the NCF. MMI will occur along the NCF due to the different longitudinal propagation constants of the LP_{0m} modes [19]. The dip wavelength of the response to the MMI can be expressed as [20]:

$$\lambda_0 = P\left(\frac{\mathrm{n}_{NCF} D_{NCF}^2}{L}\right) \mathrm{with} \mathrm{P} = 0, 1, 2, \ldots \tag{1}$$

where $\mathrm{n}_{\mathrm{NCF}}$ and $\mathrm{D}_{\mathrm{NCF}}$ are the effective refractive index (RI) and mode field diameter of the NCF, respectively. L is NCF length. Besides, these factors are all affected by the temperature or liquid level variation. P is the self-image number. The dip wavelength shift caused by temperature variation can be expressed as [21]:

$$\frac{\Delta\lambda_0}{\lambda_0} = \left(\alpha_{NCF} + \xi_{NCF}\right) \Delta T \tag{2}$$

where $_{\alpha\mathrm{NCF}}$ and ξ_{NCF} are the thermal expansion coefficient and fiber thermo-optic coefficient of the NCF, respectively. ΔT denotes the changes of temperature. On the other hand, when a section of the NCF is surrounded by a liquid, the effective diameter of the fundamental mode of the NCF is increased as a result of the Goos–Hänchen shift [20]. According to Eq. (1), the attenuation dips wavelength will shift to a longer wavelength. Nevertheless, the sensor is not entirely covered with a liquid, the dip wavelength is now determined by the contribution of these two sections. The dip wavelength shift can be written as [10]:

$$\lambda_0 = P\left[\frac{\mathrm{n}_{NCF\mathrm{n}} D_{NCF\mathrm{n}}^2}{L}\left(\frac{L_{\mathrm{n}}}{L}\right) + \frac{\mathrm{n}_{NCF} D_{NCF}^2}{L}\left(\frac{L - L_{\mathrm{n}}}{L}\right)\right] \mathrm{with} \mathrm{P} = 0, 1, 2, \ldots \tag{3}$$

where the first part is the contribution of the NCF section in the liquid and the other part is the contribution of the sensor out of the liquid. L_{n} is the NCF length with liquid. $\mathrm{D}_{\mathrm{NCFn}}$ and $\mathrm{n}_{\mathrm{NCFn}}$ are the diameter and effective RI for the NCF section in the liquid, respectively. According to Eq. (3), 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 FBG is characterized by the periodicity Λ of the RI modulation and the effective refractive index of the fiber core n_{eff}. Therefore, the structure shows resonance behavior with a Bragg wavelength given by:

$$\lambda_{FBG} = 2 n_{eff} \Lambda \tag{4}$$

The Bragg wavelength shift caused by temperature variation can be expressed as:

$$\Delta\lambda_{FBG} = \lambda_{FBG}\left[\alpha_{th} + \xi\right] \Delta T \tag{5}$$

where $_{\alpha\mathrm{th}}$ is the thermal expansion coefficient of the glass fiber, and ξ is the fiber thermo-optic coefficient [22].When liquid level and temperature are simultaneously applied to the sensor, the wavelength shifts of the NCF and FBG can be expressed by a matrix [23]:

$$\begin{bmatrix} \Delta\lambda_{NCF} \\ \Delta\lambda_{FBG} \end{bmatrix} = \begin{bmatrix} K_{L,NCF} & K_{T,NCF} \\ 0 & K_{T,FBG} \end{bmatrix} \begin{bmatrix} \Delta L \\ \Delta T \end{bmatrix} \tag{6}$$

where $\Delta\lambda_{\mathrm{NCF}}$ and $\Delta\lambda_{\mathrm{FBG}}$ represent the wavelength shifts of the NCF and FBG, respectively. K_{L} and K_{T} are the sensitivity coefficients corresponding to the liquid level and temperature change, respectively. Subscript NCF and FBG identify the contribution made by the two structures individually. The liquid level and temperature sensitivities can be obtained as:

$$\begin{bmatrix} \Delta L \\ \Delta T \end{bmatrix} = \frac{1}{K_{L,NCF} K_{T,FBG}} \begin{bmatrix} K_{T,FBG} & -K_{T,NCF} \\ 0 & K_{L,NCF} \end{bmatrix} \begin{bmatrix} \Delta\lambda_{NCF} \\ \Delta\lambda_{FBG} \end{bmatrix} \tag{7}$$

3. Experiment

The experimental setup for evaluation of the liquid level sensitivity of the sensor is depicted in Fig. 2, including a broad band light source (BBS, KOHERAS SuperK Versa) with flat output spectrum within the range of 600–1800 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 1549.16 nm at the room temperature, respectively. The length of the FBG is about 5 cm.

The transmission spectrum of the sensor in the air is shown in Fig. 3. As can be seen from the figure, interference fringes with good visibility are observed over the spectral range of 1500–1640 nm. The FBG-induced steep dip is also shown clearly at wavelength around 1549.16 nm.

To obtain the liquid level and temperature coefficients, liquid level and temperature changes are applied to the sensor separately. In the liquid level experiment, the FBG is immersed in the liquid. The sensor is set on a fixing skeleton which is placed vertically inside the beaker. The sensor performance is tested within a liquid level range of 0–4.5 cm and with a liquid level increment step of 0.5 cm. When the spectrum starts to shift, it is chosen as the initial state, and the level is marked as the reference liquid level. Each curve is recorded after 5 min later after the specific liquid level is applied to ensure the stabilization of the spectrum. Fig. 4a and b show the transmission spectra of NCF and FBG in 0, 1.5, 3.0, and 4.5 cm, respectively. It can be observed that the resonant dip to the NCF experiences redshift while the Bragg wavelength remains constant when the liquid level increases. As can be seen from Fig. 4b, the reference level of FBG