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Simultaneous measurement of temperature and refractive index based on a Mach–Zehnder interferometer cascaded with a fiber Bragg grating

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ABSTRACT

An all-fiber sensor for simultaneous measurement of temperature and refractive index (RI) is proposed and demonstrated. The sensor head is composed of a Mach–Zehnder interferometer (MZI) and a fiber Bragg grating (FBG). The MZI consists of a peanut-shape structure and a core-offset structure which are formed only by single mode fibers through different fusion technology. Experimental results show that the temperature sensitivities of the FBG (dip1) and the MZI (dip2) are 0.01228 nm/°C and 0.08329 nm/°C, respectively. Dip1 is insensitive to environmental RI, but dip2 is sensitive to environmental RI, and the sensitivity is −26.965 nm/RIU. Therefore the simultaneous measurement of the temperature and RI is demonstrated based on the sensitive matrix. The novel sensor processes low fabrication cost, simple configuration, high sensitivity etc. It will have attractive potential applications in chemical and biological sensing fields.

1. Introduction

Since the early years of optical fiber sensors, interferometric optical fiber sensors have been explored in various ways [1, 2]. MZI which can realize the function of interference [3] has come into being in order to be widely used in physical, chemical and biological sensing fields [4, 5] with the advantages of small size, high sensitivity, fast response, wide dynamic range, etc. Usually, it needs some special structures to realize the function of inline MZI within a single fiber. So two beams of light signal can pass through different waveguide structures, create certain phase difference, and then get a stable interference spectrum. Following methods are mainly used: cascade of two LPFGs [6], core-offset structure [7], connection of single mode fiber and multimode fiber [8], taper structure [9], special optical fiber (photonic crystal fiber or double core optical fiber, etc.) [10]. Fiber grating-based sensors have been widely investigated for refractive index measurement. For example, fiber Bragg grating etched by submersion in HF solution can be used for refractive index measurement [11]. Measurement of complex parameters based on the combination of Inline MZI and fiber grating has been widely studied in recent years. In 2012, Qi et al. [12] made two core-offset splices at both ends of FBG to realize simultaneous measurement of the temperature and strain. This structure is simple and the spectrum is easy to be monitored. And it is difficult to fabricate because of that the grating area is between the two core-offset splices. In 2014, Yao et al. [13] improved the above structure. They spliced the FBG out of the two core-offset to measure the temperature and refractive index simultaneously. This structure has some advantages such as low fabrication cost and simple configuration. And its sensitivity still needs to be improved. In 2014, Li et al. [14] made a S fiber taper in FBG to realize simultaneous measurement of force and temperature. This sensor structure is compact, with high accuracy. And the repeatability of fabrication is not good. In 2014, Huang et al. [15] cascaded long-period fiber grating (LPFG) with Single mode-Multimode-Single mode (SMS) to realize the simultaneous measurement of the temperature and refractive index. The regularity of the SMS transmission spectrum is poor and difficult to analyze.

In this paper, a novel sensor is proposed. The MZI is composed of a peanut-shape structure and a core-offset structure, and then the MZI is cascaded with FBG to form the sensor head. The Bragg wavelength of the FBG and the interference fringe of the MZI would shift differently with the variation of the temperature and RI. So the simultaneous measurement of the temperature and RI can be demonstrated based on the sensitive matrix. This sensor has the advantages of simple structure, small size and high sensitivity. It would be widely used in physical, chemical and biological sensing fields.

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2. Principle

Experimental system is shown in Fig. 1. Light emitted from the Broadband light source (BBS) is transferred into FBG. The light which satisfy the Bragg condition can be reflected, and the rest of the light transmits through the fiber. Then the interference occurs because of the mode coupling when light passes through the MZI. Finally, these modes are transmitted to optic spectrum analyzer (OSA) through the SMF. FBG and MZI structure act as the sensing area to monitor the change of temperature and the RI in solutions.

According to the mode-coupling theory [16], the center wavelength of FBG satisfies:

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

where n_{eff} is the effective refractive index of the core, Λ is the period of FBG and λ_B is the center wavelength of FBG.

λ_B is not sensitive to the change of environmental RI surrounding the fiber. Yet it is sensitive to the change of temperature which can be expressed as:

$$\frac{\Delta\lambda_B}{\lambda_B} = \left(\frac{1}{\Lambda}\frac{\partial\Lambda}{\partial T} + \frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial T}\right)\Delta T \tag{2}$$

Where $\frac{1}{\Lambda}\frac{\partial\Lambda}{\partial T}$ represents the coefficient of thermal expansion, $\frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial T}$ represents the thermal optic coefficient, ΔT represents the variation of temperature.

Fig. 2 shows the structure of MZI. When the light in the core mode propagates into the peanut-shape structure [17], part of light is coupled into the cladding. Then some cladding modes appear. After both the light in the core mode and the cladding modes propagating through a certain length of fiber to the core-offset structure, the light in cladding modes is partly re-coupled back into the core and interferes with the rest of light in the core mode. We can see the comb-shape spectrum on the OSA. The length of MZI L should not be too long owing to the attenuation at the cladding-coating interface.

The transfer function of our MZI can be given by

$$I = I_{co} + I_{cl} + 2\sqrt{I_{co}I_{cl}}\cos(2\pi\Delta nL/\lambda) \tag{3}$$

where I is the intensity of the interference signal, I_{co} and I_{cl} are the intensities of the core mode and the cladding mode, respectively, $\Delta n = n_{co} - n_{cl}$ is the difference of the effective refractive indices between the core mode and the cladding mode, L is the separation length between the peanut-shape structure and the core-offset structure, and λ is the operating wavelength.

It can be noted from Eq. (3) that the interference signal reaches its minimum value when $2\pi\Delta nL/\lambda = (2m+1)\pi$ (where m is a positive integer). Thus, the dip wavelength of the MZI transmission spectrum can be expressed as

$$\lambda_{MZI} = 2\Delta nL/(2m+1) \tag{4}$$

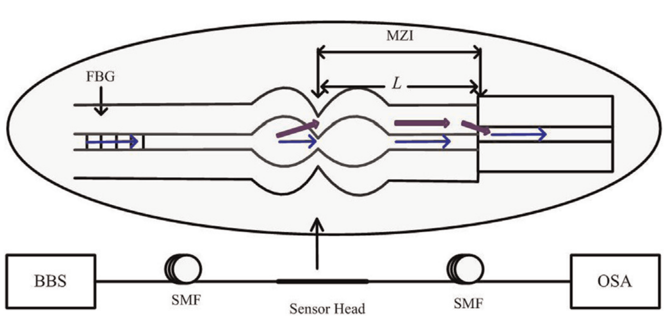

Fig. 1. Schematic diagram of the experimental system and the sensor structure.

When the temperature and/or RI varies, there will be a change in Δn and/or L, and consequently, in λ_{MZI}. The relative shift of λ_{MZI} can be expressed as

$$\frac{\Delta\lambda_{MZI}}{\lambda_{MZI}} = \left(\alpha + \frac{\xi_{co}n_{co} - \xi_{cl}n_{cl}}{n_{co} - n_{cl}}\right)\Delta T + \frac{-\partial n_{cl}}{\partial n_{ext}}\frac{1}{n_{co} - n_{cl}}\Delta n_{ext} \tag{5}$$

Where α is the coefficient of thermal expansion, ξ_{co} and ξ_{cl} are the effective thermal optical coefficients of the core mode and the cladding mode, respectively. ΔT and Δn_{ext} are the variation of temperature and RI, respectively.

It can be concluded from above analysis, especially from Eqs. (2) and (5), that the wavelength of the FBG λ_B is sensitive to temperature and the interference fringe of the MZI λ_{MZI} is both sensitive to temperature and RI. Moreover, temperature sensitivity of λ_B is different from that of λ_{MZI}, therefore simultaneous measurement of temperature and RI can be demonstrated based on the sensitive matrix.

3. Experimental results and discussion

Experimental system is shown in Fig. 1, including a BBS and an OSA. The SMF is made by YOFC whose diameters of core and cladding are 8.3 μm and 125 μm, respectively. The center wavelength of FBG λ_B is 1550.28 nm under room temperature.

The separation length between the peanut-shape structure and the core-offset structure L is 2 cm, and one end of L is offset spliced by about 4 μm, the other end is fabricated as peanut-shape. The peanut-shape structure is made by a commercially available fusion splicer (FITEL S176). Firstly, we should fabricate two spherical structures with two period of SMF respectively. In this step, fusion splicer's discharge intensity is 200, discharge time is 750 ms. Secondly, the two spherical structures are welded to form the peanut-shape structure. In this step, the fusion splicer's discharge intensity is 115, discharge time is 1350 ms. Then the MZI is combined with FBG. The transmission spectrum of the cascaded device in pure water at room temperature is shown in Fig. 3.

In Fig. 3, dip1 is the center wavelength of FBG, dip2 is one transmission spectrum dip wavelength of the MZI.

3.1. Temperature characteristic experiment

Temperature characteristic experiment is carried out under water bath from hot to cold, as shown in Fig. 4

Mercury thermometer is used to read the value of the temperature. The shifts of the two dips are recorded every 5 °C from 75 °C to 25 °C. After test, output spectrum and temperature response characteristics curve is achieved as Fig. 5. It can be seen from Fig. 5(a) that the two dips both show blue shift along with the temperature decreasing and the shift of dip2 is faster. As shown in Fig. 5(b), dip1 moves from 1550.68 nm to 1550.28 nm, with the sensitivity of 0.01228 nm/°C, meanwhile, dip2 moves from 1575 nm to 1570.8 nm, with the sensitivity of 0.08329 nm/°C.

3.2. RI characteristic experiment

The sensor head is placed into NaCl solution of different concentrations under room temperature 25 °C to get the RI sensitivity of the sensor as shown in Fig. 6.

By increasing the concentration of NaCl, the RI of the liquid sample varies from 1.33 to 1.38 which can be read by a commercial Abbe refractometer. Output spectrum and RI response characteristics curve is achieved as Fig. 7. As shown in Fig. 7(b), dip1 is insensitive to the change of RI, but dip2 moves from 1570.28 nm to 1569.36 nm, with the sensitivity of −26.965 nm/RIU (Refractive Index Units).