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Simultaneous measurement of refractive index and temperature based on a core-offset Mach–Zehnder interferometer combined with a fiber Bragg grating

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ABSTRACT

An all-fiber sensor for simultaneous measurement of refractive index and temperature in solutions is proposed and demonstrated. The sensing head contains a core-offset Mach–Zehnder interferometer (MZI) and a fiber Bragg grating (FBG). The interference fringe of the MZI and the Bragg wavelength of the FBG would shift with the variation of the ambient refractive index (RI) and/or temperature. The experimental results show that the RI sensitivity and the temperature sensitivity for the sensor are 13.7592 nm/RI and 0.0462 nm/°C, respectively. Its low fabrication cost, simple configuration and high sensitivity will have attractive potential applications in chemical and biological sensing.

1. Introduction

Optical fiber sensors have many unique advantages over conventional sensors and they have been extensively investigated to measure various parameters, such as strain, curvature, temperature, displacement, RI, pressure and so on. Temperature and refractive index (RI) are the most important parameters in these applications, especially in chemical or food industries for quality control and in environmental industries for contamination assessment. Lots of ways can realize fiber-optic RI sensors, such as IST-MZ interferometer [1], LPG refractometer [2], Michelson interferometer [3–6]. Although they can detect the RI with smart configuration, yet they miss the temperature. It is well known that the RI of solution has a dependence on temperature, and therefore temperature effect should not be neglected in order to obtain an accurate value of the RI. With the development of the research, a few papers reported simultaneous measurement of RI and temperature using Fabry–Perot cavity, Tapered fiber, thinned fiber, fiber Bragg grating (FBG), and two-mode fiber structures [7–12], with complicated fabrication procedure, high cost, difficult operation, instable system, which limits their practical applications.

In this letter, we present a new fiber sensor for simultaneous measurement of RI and temperature, which is composed of a core-offset Mach–Zehnder interferometer (MZI) and a FBG. The core-offset MZI is realized by splicing two single mode fibers (SMFs) with a minute lateral offset. Due to this intentional offset, the interference will occur between the core mode and the cladding mode. The evanescent field of the cladding modes extends beyond the cladding of the host fiber, then the variation of the ambient material can be detected. The FBG located upstream from the core-offset MZI can sense the variation of temperature and select the guide modes. The spectral pattern of the device will change when the RI and/or temperature of the ambient material vary. The theoretical analysis is in good agreement with the experimental results. The results indicated that this new sensor has the advantage of simple configuration, low cost, easy operation, high sensitivity and stability.

2. Sensor fabrication and operation principle

In a conventional SMF, the RI of the overlay is higher than that of the cladding. Therefore, the light is confined to the host fiber and the cladding modes are absorbed there, which prohibits the formation of an MZI with the coating. In order to solve this problem, we offset two SMF cores by several micrometers, just as Fig. 1 shows. Light from the transmission fiber is split into two paths, with a fraction of

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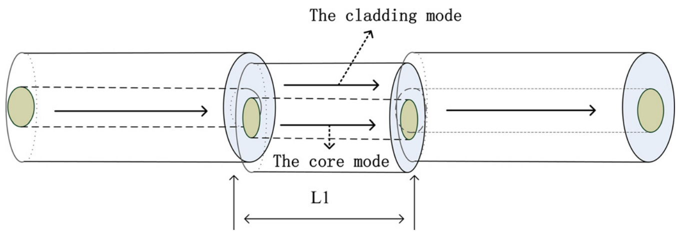

Fig. 1. Structure of the core-offset Mach–Zehnder interferometer.

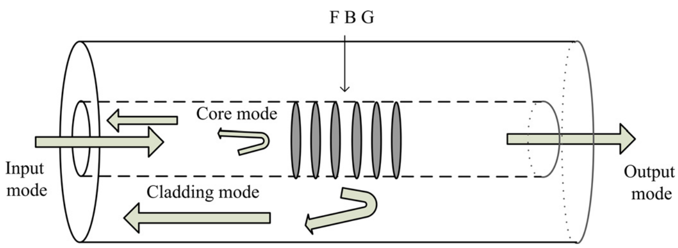

Fig. 2. Couplings of the forward guided modes to the backward guided modes in the FBG.

light remaining in the core of the receiver fiber, while the remainder is transferred to the cladding and subsequently propagates as cladding modes. After then, another core-offset is introduced only several centimeters after the first one, light in the cladding can be coupled back to the core. Due to the phase difference of the cladding and core modes, an in-line MZI is realized by the second offset [3].

However, most of the fiber optic in-line MZIs are based on multimode interference. Because of the offset, a part of the core mode beam is coupled to several cladding modes. The cladding part of a SMF is a multimode waveguide, so that the number of cladding modes involving the MZI is more than one in general. Such multimode interference affects the sensing performance because each mode has a different sensitivity to the external variations. Therefore, it is necessary to control the number of involving cladding modes [13]. In this letter, we can make it by regulating the lateral offset and introducing a FBG. The FBG can reflect Bragg wavelength and some other wavelengths within its bandwidth. And it couples energy from the forward traveling mode to the backward core mode, as well as to the backward cladding mode, as illustrated in Fig. 2 [14]. Compared with the input mode, the output mode has been changed significantly. As shown in Fig. 3, the claddings modes would be excited when the output mode passes the offset. In general, although there is more than one cladding mode, only one cladding mode is dominant [15].

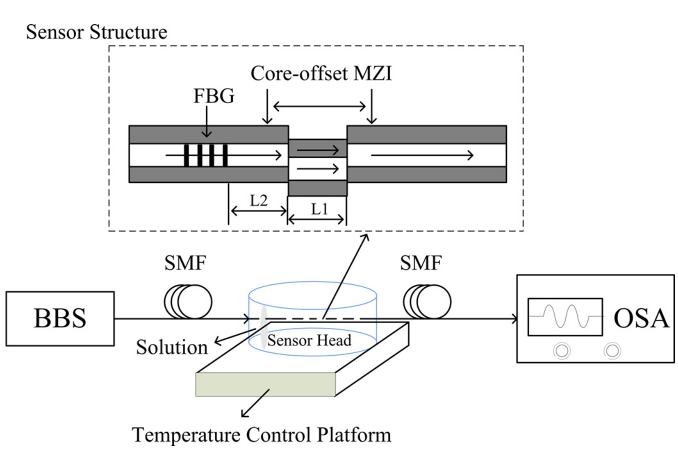

Fig. 3. Schematic diagram of the experiment setup.

Assume that only two modes are excited in the offset, as Fig. 1 shows. The accumulated phase difference between the core mode and the cladding mode is $2\pi\Delta nL_1/\lambda$, where Δn is the effective index difference between the core and cladding, L_1 is the length of offset, and λ is the operating wavelength. When environmental temperature and/or RI are varied, the optical path difference between the two parts of light will be changed. Consequently, wavelength shift of the interference pattern will occur with the span depending on the change of the phase difference induced by the applied RI and/or temperature [16].

The FBG is characterized by the periodicity Λ of the RI modulation and by the effective RI of the waveguide mode n_{eff}. Therefore, these structure show resonance behavior with a Bragg wavelength given by [17]

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

The temperature sensitivity of the Bragg wavelength arises from the coefficient of thermal expansion α_{th} of silica and the thermo-optic phenomena of the material quantified by the coefficient ξ. The Bragg wavelength shift caused by temperature can be expressed as

$$\Delta\lambda_B = (\alpha_{th} + \xi) \times \lambda_B \times \Delta T \tag{2}$$

For silica, the values of α_{th} and ξ are 0.55×10^{-6} and $8.0 \times 10^{-6}/^\circ C$, respectively, which indicates that the temperature response of the FBG (0.01 nm/°C at 1550 nm) is dominated by the thermal dependence of the RI [17].

The propagation constants of the interfering modes are changed by the applied RI and/or temperature, consequently causing a detectable wavelength shift of the interference pattern. It can be described by

$$\Delta\lambda_{\mathrm{MZI}} = K_{R1}\Delta n_x + K_{T1}\Delta T \tag{3}$$

where K_{R1} and K_{T1} are sensitivities of the core-offset MZI to RI variation Δn_x and temperature variation ΔT, respectively. Bragg wavelength of the FBG shifts with applied RI and temperature as

$$\Delta\lambda_{\mathrm{FBG}} = K_{R2}\Delta n_x + K_{T2}\Delta T \tag{4}$$

where K_{R2} and K_{T2} are sensitivities of the FBG to the RI and temperature, respectively [16]. K_{T2} is related to the thermal expansion and the thermo-optic effect of the SMF, as previously described. The $K_{R2} \approx 0$, because the Bragg wavelength is independent on the RI of the ambient material.

Simultaneous measurement of RI and temperature thus can be achieved by measuring a certain resonant dip of the core-offset MZI and Bragg wavelength of the FBG. That can be expressed in the following matrix form

$$\begin{pmatrix} \Delta n_x \\ \Delta T \end{pmatrix} = \frac{1}{K_{R1}K_{T2} - K_{T1}K_{R2}} \begin{pmatrix} K_{T2} & -K_{T1} \\ -K_{R2} & K_{R1} \end{pmatrix} \begin{pmatrix} \Delta\lambda_{\mathrm{MZI}} \\ \Delta\lambda_{\mathrm{FBG}} \end{pmatrix} \tag{5}$$

The matrix coefficients can be obtained from the experimentally measured RI and temperature sensitivities of the core-offset MZI and the FBG, respectively [16].

3. Experiments and discussions

Fig. 3 shows the experimental arrangement, including a broad band light source (BBS) with flat output in the range from 1525 to 1565 nm, and an optical spectrum analyzer (OSA, Yokogawa AQ6370) with a wavelength resolution of 0.02 nm. The structure of the sensor is shown in the upper dotted area. The reflectivity and Bragg wavelength of the FBG used in the experiment are 70% and 1539.52 nm at the room temperature, respectively. The separation (L_2) between the FBG and the core-offset MZI is 7.1 cm and the offset length (L_1) is 3.6 cm. Splicing of the core-offset MZI was