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Simultaneous measurement of refractive index, strain, and temperature based on a four-core fiber combined with a fiber Bragg grating

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ABSTRACT

A fiber optic sensor capable of measuring refractive index (RI), strain, and temperature simultaneously is proposed and demonstrated. The sensor is formed by the integration of a four-core fiber (FCF) with a fiber Bragg grating (FBG). When the FCF is kept straight, a pronounced interference pattern appears in the transmission spectrum. Compared with previously reported optical fiber modal interferometers, higher fringe visibility can be obtained in our scheme. The maximum fringe visibility of the interference resonance dips exceeds 21 dB. By monitoring the wavelength shifts of three dips, simultaneous measurement of RI, strain, and temperature can be achieved. For 10 pm wavelength resolution, the resolution of the sensor is 0.0004 RIU, 11.06 με, and 0.17 °C in RI, strain, and temperature, respectively. The proposed sensor has the advantages of easy to construct, higher fringe visibility, and the capability to measure RI, strain, and temperature simultaneously, which are desirable features in RI measurement.

1. Introduction

Refractive index (RI) is an important sensing parameter in many applications such as process control in chemical industries, protection of ecosystems and quality control in food industries. Mostly, traditional RI sensors based on electrical techniques cannot meet the requirements of RI measurements in harsh (conductive, explosive, or erosive) environments. In the past years, fiber optic sensors have received significant attention for their unique advantages in low power consumption, high corrosion-resistance and high sensitivity [1,2]. Fiber optic RI sensors based on other different operating principles have also been demonstrated. Among these methods, the fiber modal interferometer is one kind of the most commonly used structures for RI measurement, such as single-mode fiber (SMF)-multimode fiber (MMF)-SMF structure [3,4], SMF-photonic crystal fiber-SMF structure [5,6], double fiber down-tapers or up-tapers [7–9], fiber lateral-offset splicing [10] and combination structures [11]. However, among the aforementioned schemes, an unavoidable fact is that the RI sensors are sensitive to both RI and temperature which makes it difficult to distinct or measure the changes between RI and temperature. In recent years, various fiber optic sensors have also been reported to achieve the simultaneous measurement of RI and temperature by using a fiber Bragg grating (FBG) [12], a surface long period grating (LPG) inscribed in a D-shaped photonic crystal fiber [13], a MMF [14], a MMF-SMF-MMF structure [15], a photonic crystal cavity on a fiber tip [16], a tilted fiber Bragg grating(TFBG) deposited with carbon nanotube [17], an asymmetric Mach-Zehnder interferometer [18], and so on [19–22]. Generally, fiber optic RI sensors exhibit a high degree of cross-sensitivity to strain. Thus an ideal sensing structure should be capable of simultaneous measurement of RI, strain, and temperature. In 2010, a sensor for simultaneous measurement of RI, strain, and temperature based on a FBG was proposed by [23]. An etched FBG was used in the scenario, but the device became fragile due to the use of hydrofluoric acid. In 2013, a temperature and strain compensated RI sensor based on a bend-insensitive fiber was proposed by [24]. Since the different spatial frequency peaks of bend-insensitive fiber respond differently to multiple environmental variables, simultaneous measurement of RI, strain, and temperature can be achieved. However, the information processing of this sensor is complex.

In this paper, we proposed and experimentally demonstrated a novel, simple and compact fiber optic sensor for simultaneous measurement of RI, strain, and temperature. The sensor is formed by the integration of a four-core fiber (FCF) with a FBG. The maximum fringe visibility of the interference resonance dips exceeds 21 dB. By mon-

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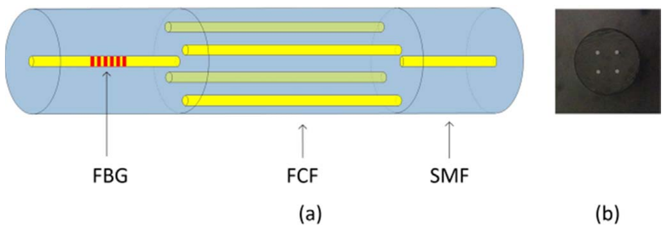

Fig. 1. (a) Schematic diagram of the sensor structure. (b) Cross section of the FCF.

itoring the wavelength shifts of three dips, simultaneous measurement of RI, strain, and temperature can be achieved. The proposed sensor has the advantages of easy to construct, higher fringe visibility, and the capability to measure RI, strain, and temperature simultaneously, which are desirable features in RI measurement.

2. Principle

The schematic diagram of the proposed sensor is shown in Fig. 1. A section of FCF is spliced between a FBG imprinted SMF (SMFBG) and the SMF. The FCF length is about 5 cm. Fig. 1(b) shows the cross-section of the FCF, the four cored distribute in a square shape, and the side length of the square is about 36 µm. The numerical aperture is about 0.15, and the surrounding cladding diameter is 125 µm which is just like the normal SMF. The mode field diameter is about 8 µm at 1550 nm.

When the light is launched into the FCF through the leading SMF, the multiple modes of the FCF will be excited, and then propagate within the FCF. The splicing points act as input/output couplers for mode excitement in the four cores and cladding. A tunable laser was used as light source, and the FCF output patterns were captured by camera at different wavelengths [25]. As shown in Fig. 2(a), the interferences are clearly exhibited when the laser injected into the fiber structure, and the energy in the cores can be distinguished with that in the cladding. Fig. 2(b) shows the FCF output patterns by immersion gel which helps to remove outer cladding modes. It can be observed that the mode propagates in the cladding area between the cores with lower RI. This is the mode of an open cavity analogous to the Bragg mode (see, e.g., [26,27]) being trapped in the center due to index modulation in the transverse direction.

The output spectrum will be the superposition of multiple interference patterns. The accumulated phase difference between two modes involved in the interference can be expressed as [28]:

$$\phi = 2\pi\Delta n_{eff} L/\lambda \tag{1}$$

where λ is the wavelength of the propagating light, L is geometry length of the FCF, Δn_{eff} is the effective refractive indices difference between two modes involved in the interference. From the Eq. (1), when the phase difference satisfies the condition Φ=(2 m+1)π, the wavelength of the attenuation peak can be written as:

$$\lambda_m = 2\Delta n_{eff} L/(2m+1) \tag{2}$$

where m is an integer. And from Eq. (2), the spacing between the adjacent attenuation peak wavelengths can be approximated as:

$$FSR = \lambda_{m-1} - \lambda_m = \frac{2\Delta n_{eff} L}{2m-1} - \frac{2\Delta n_{eff} L}{2m+1} \approx \frac{\lambda_m^2}{\Delta n_{eff} L} \tag{3}$$

It is noted that the FSR of the sensor will decrease as the FCF length L increases. As can be seen from the Eq. (2), the changing of the RI, strain, and temperature related with the Δn_{eff} or the length L of the sensor will lead to the wavelength shift. So it is possible to measure these parameters by simply monitoring the wavelength shifts. The attenuation peak wavelength will be changing along with the external refractive index, and the variation can be expressed as [29]:

$$\Delta\lambda_m = \frac{2(\Delta n_{eff} + \Delta n)L}{2m+1} - \frac{2\Delta n_{eff} L}{2m+1} = \frac{2\Delta n L}{2m+1} \tag{4}$$

where Δn is the change of Δn_{eff} with external refractive index. When a strain is applied to the sensor, a wavelength shift will be introduced because of the change of fiber dimensions and the photoelastic effect of the fiber material. The attenuation peak wavelength shift caused by strain variation can be expressed as [30]:

$$\frac{\Delta\lambda_m}{\lambda_m} = \left(1 + \frac{p_{e1} n_1 - p_{e2} n_2}{n_1 - n_2}\right)\Delta\varepsilon \tag{5}$$

where n_1, n_2 and p_{e1}, p_{e2} are the effective refractive indexes and photoelastic constants of the two modes, $\Delta\varepsilon$ denotes the changes of strain. On the other hand, the change of temperature will lead the variation of both the effective index difference and the FCF length, according to the following equation [29]:

$$\frac{\Delta\lambda_m}{\lambda_m} = \left(\alpha_{FCF} + \frac{\xi_1 n_1 - \xi_2 n_2}{n_1 - n_2}\right)\Delta T \tag{6}$$

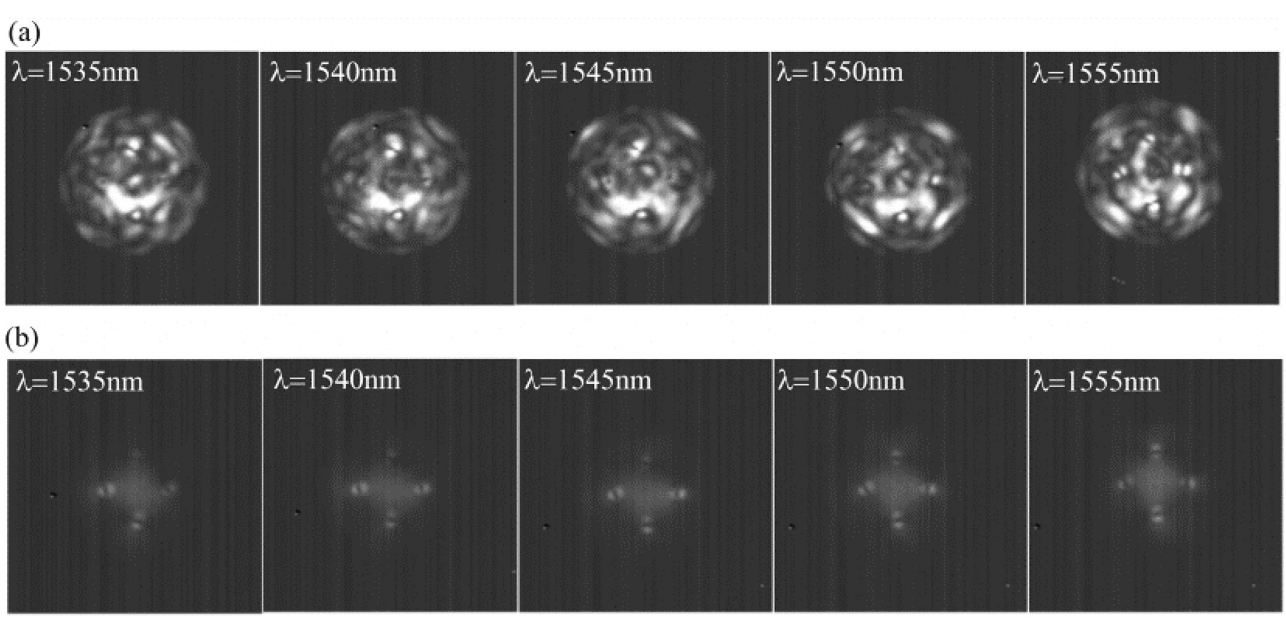

Fig. 2. (a) The 2-D images of the FCF output patterns at different wavelengths. (b) The 2-D images of the FCF output patterns by immersion gel at different wavelengths..