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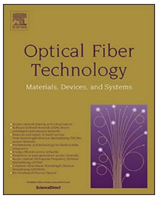

Regular Articles

Micro-structured optical fiber sensor for simultaneous measurement of temperature and refractive index

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ABSTRACT

Through using micro-machining method for optical fiber sensor, a kind of miniature, compact and composite structural all-fiber sensor is presented. Based on manufacturing two micro-holes with certain distance in ordinary single-mode fiber Bragg grating (FBG) by excimer laser processing technique, we fabricate a dual Fabry–Perot-FBG (FP-FBG) composite fiber interferometric sensor, which can be used in simultaneous measurement for liquid's refractive index (RI) and temperature change. Due to every micro-hole and the dual micro-holes in fiber acting as different Fabry–Perot (FP) cavities, this kind of sensor has not only different RI sensitivities but also different temperature sensitivities, which are corresponding to the wavelength shifts of the fine interference fringes and spectral envelope, respectively. The experimental results show that the spectral wavelength shift keep better linear response for temperature and RI change, so that we can select the higher temperature and RI sensitivities as well as the analyzed sensitivities of FBG to utilize them for constituting a sensitivity coefficients matrix. Finally, the variations of liquid's temperature and RI are detected effectively, and the resolutions can reach to 0.1 °C and 1.0×10^{-5} RIU. These characteristics are what other single-type sensors don't have, so that this kind of all-fiber dual FP-FBG composite fiber interferometric sensor can be used in extremely tiny liquid environment for measuring different physical quantities simultaneously.

1. Introduction

With the development of sensing technique and measuring requirements, temperature and refractive index (RI) sensing technology have been put forward in various fields, such as oil and gas field exploitation, coal industry, aerospace, power system, medicine and biochemical engineering [1–4]. Especially, since the optical fiber sensing technique was paid much attention, researchers have demonstrated many different structural fiber sensors for the measurements of temperature [5–7] or RI [8–14], and even the simultaneous measurement of them [17–22]. In 2011, literature [11] demonstrated an all-optical fiber sensor with ultrahigh RI sensitivity, which is through making use of femtosecond laser pulses removing the fiber core partially and forming a U-shape micro-cavity in a single-mode optical fiber. In 2015, Cao et al. [20] proposed an optical fiber sensor based on a Mach Zehnder interferometer (MZI) cascaded with fiber Bragg grating (FBG) for simultaneous measurement of RI and temperature. The temperature sensitivities of two MZI dips are 0.0607 nm/°C and 0.0563 nm/°C, and RI sensitivities are −18.025 nm/RIU and −55.06 nm/RIU, respectively. In 2016, literature [7] proposed a Michelson Fabry–Perot hybrid fiber interference sensor by integrating a Michelson interferometer in a two-core fiber and a Fabry–Perot interferometer (FPI) in a micro silica-capillary. The measurement sensitivity of the axial train is 0.015 nm/$\mu\varepsilon$ and the measurement sensitivity of radial bending is 1.393 nm/m^{-1}. Although these fiber sensors with different structure have their own advantages, they still have some shortcomings in fabricating method, structural design or measuring functions. So the composite structural optical fiber sensors need be studied in further.

In this paper, we design and demonstrate an all-fiber, micro-structured optical fiber sensor. Because of the fabrication of two micro-holes in FBG, each micro-hole acts as a FPI, and other FPIs with different cavity-length between the different parallel surfaces of each micro-hole are also formed. Due to the micro-holes fabricated in FBG, the resonant wavelength of reflection spectrum of FBG can be affected by the location and distance of two micro-holes. The composite sensor has several different response sensitivities for temperature and RI change, which can be used in the simultaneous measurement of them. Compared with femtosecond laser fabricated method [10–12], the method we proposed, due to the use of 193 nm excimer laser, can decrease equipment cost and partially manufacturing difficulty, and has higher sensing

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sensitivities and simple machining process in contrast to chemical preparation and arc discharge method [15,16].

2. Fabrication and sensing principle

The proposed sensor consists of two FPIs which are carved into FBG by using excimer laser (ATLEX-500, ATL, Germany) with pulses, center wavelength, frequencies, and repetition rates of 30 mJ, 193 nm, 300 Hz, and 50 Hz, respectively. The FBG used in this experiment was obtained by using ultraviolet light to irradiate single-mode fiber (SMF) (9 µm/125 µm, ChangFei, China) with phase mask method. Frist, we stretch FBG and fix it on a glass slide, and then put the whole structure on a precise tunable three-dimensional micro-displacement platform. We adjust the X, Y axis of platform to make FBG located on the field of view that is displayed in the screen of computer through a Charge-coupled Device (CCD) which is fixed on the setups, and the image point has been adjusted on the vicinity of the focus spot of laser. Then, we adjust Z axis to make laser spot focused on the FBG, choose carving way of rectangular hole, and begin to fabricate the sensor. After finishing the above steps, through moving all the structure along the axial direction of fiber by controlling the precision platform (10 µm, China), we can remanufacture another micro-hole. Thus far the dual FP-FBG composite fiber interferometric sensor has been finished. After finishing all process, the 2% solution of hydrofluoric acid is used to clean the machined holes before measuring temperature and RI characteristics, so that the chippings in micro-holes can be cleared up. And then a high-quality resonant cavity is formed.

In Fig. 1(a), the schematic diagram of carving micro-holes in SMF is shown, in which the shaded rectangles represent the inscribed micro-holes. Two parallel end surfaces of each micro-hole form a FP cavity which we can name as the 1st FPI, and the two surfaces of different micro-holes also form four FP cavities with different cavity length. Because the two micro-holes have same geometries, the numbers of FP cavities will reduce one, and the rest three FP cavities will produce different interference spectra with different free spectrum range (FSR). Nevertheless, the difference of optical path difference (OPD) between the arbitrary two of three FP cavities is very little, which results that it is difficult to distinguish the spectra of every FP cavity in the interference spectra. Therefore, we can regard the three FP cavities as one equivalent FP cavity which corresponds to the cavity length between the centers of two micro-holes. We define the equivalent FP cavity as the 2nd FPI. Consequently, the two FPIs corresponding to different FSR can form complex interference pattern. Due to the OPD of 1st FPI less than that of 2nd FPI, the 1st FPI and the 2nd FPI will correspond to the lower and the higher frequency spectrum, respectively, as shown in Fig. 2. We can get the spectrum of 1st FPI by using the signal processing function of software Origin9.0, which is called spectral envelope, as is shown in Fig. 2 with red line.

As two micro-holes are symmetrically fabricated in FBG, it will lead to two abrupt phase changes in FBG and make an ordinary FBG into a dual phase-shifted FBG. As the two micro-holes are located uniformly on the FBG, we define L_1 as the distance between one end of FBG and the nearest phase shift point, and L_2 as the distance between two points of phase shift, as shown in Fig. 1(b). The shadings in Fig. 1(b) indicate periodic variation of RI, which is called grating period. During the course of our experiment, the length of micro-hole and FBG is 35.0 µm and 1.5 cm, respectively. The distance between the midpoints of the two cavities is about 1.0 mm, so the length of L_1 is 0.7 cm.

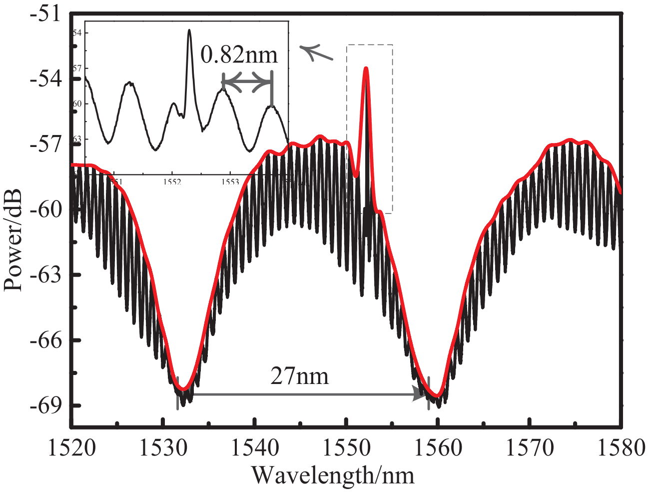

Fig. 2. Spectrum of dual FP-FBG composite fiber interferometric sensor, distance between micro-holes: 1 mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

From literature [23], when the length of section satisfies the equation of

$$2L_1 \leqslant L_2 \tag{1}$$

the reflection spectrum should be a single peak. But in fact, the corresponding geometries don't satisfy the above condition, so that the reflection spectrum of FBG has the characters of phase-shifted FBG, as shown in Fig. 2. Simultaneously, we can get two FSRs, 27.0 nm and 0.82 nm, from the fine interference fringe and the spectral envelope, which are corresponding to the 1st FPI and the 2nd FPI, respectively.

The FSR of interference spectrum can be expressed as [21]

$$\Delta_{FSR} = \frac{\lambda^2}{2nL}. \tag{2}$$

From the analysis of FSR in Fig. 2, we can calculate the cavity length of micro-hole and the equivalent cavity length between the two micro-holes. The length of two kinds of FPI is 33.5 µm and 997.9 µm, respectively, which is very in accord with the measurement values. These results sufficiently support our analysis about how the sensor work and how the composite interference spectra come into being.

The working mechanism of sensor for simultaneous measurement of RI and temperature is defined as follows. The response of FPI to temperature and RI can be expressed as

$$\Delta\lambda_{Dip-FPI} = k_{T_1}\Delta T + k_{n_1}\Delta n \tag{3}$$

where $\Delta\lambda_{Dip-FPI}$ is the wavelength shift of one spectral dip of FPI, k_{T_1} and k_{n_1} are the corresponding sensitivity coefficients of temperature and RI for interference dip of FPI, respectively. The symbols ΔT and Δn represent the variation of temperature and RI, respectively.

The wavelength response of FBG can be expressed as

$$\Delta\lambda_{Peak-FBG} = k_{T_2}\Delta T + k_{n_2}\Delta n \tag{4}$$

where $\Delta\lambda_{Peak-FBG}$ is the peak wavelength shift of FBG, and k_{T_2} and k_{n_2}

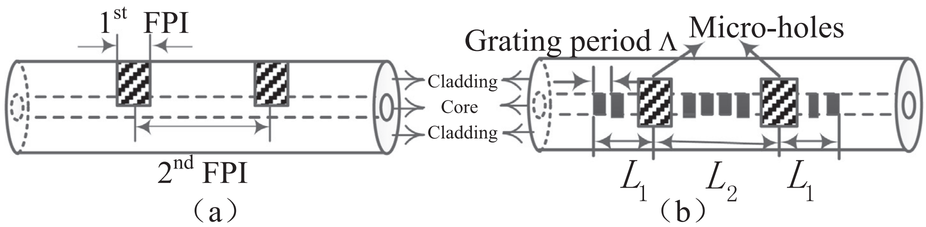

Fig. 1. Schematic diagram of the sensors. (a) Schematic diagram of carving micro-holes in SMF. (b) Schematic diagram of dual FP-FBG composite fiber interferometric sensor.