Optics Communications 405 (2017) 60–65

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Dual-parameter optical fiber sensor based on few-mode fiber and spherical structure

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A R T I C L E I N F O

Keywords:
Optical fiber sensor
Few-mode fiber
Spherical structure
Temperature
Refractive index

A B S T R A C T

An optical fiber sensor based on few-mode fiber and spherical structure is proposed and demonstrated. Temperature and refractive index can be measured simultaneously, since the interference spectrums between certain high core mode and different order cladding modes of the few-mode fiber have different sensitivities for the two parameters. The dips at 1526.4 nm and 1553.77 nm are chosen to measure the temperature and refractive index. The results of the experiment indicate that the temperature sensitivities of the dips are 0.059 nm/°C and 0.05 nm/°C, respectively. The refractive index sensitivities of the dips are −39.15 nm/RIU and −48.82 nm/RIU, respectively. And the temperature and the refractive index resolutions of the sensor are 0.95 °C and 0.0012RIU, respectively. Simultaneous measurement of temperature and refractive index can be realized by the sensor structure. This fiber interferometer sensor can also be applied in other sensing fields and has good prospects.

1. Introduction

Recently, optical fiber sensors have been widely used in strain, liquid level, refractive index (RI) and temperature measuring [1,2]. Since temperature and refractive index are important parameters in chemical industry, biological and medical field, the measurements of them have been a research hotspot in recent years [3,4]. In 2013, Wo Jianmei et al. presented an optical fiber sensor based on multimode–single mode–multimode structure. The experimental results show that the temperature sensitivity is 50.65 pm/°C [5]. In 2014, a sensing structure based on NCF and FBG has been developed by Bai Yunlong et al. The experimental results show that the refractive index sensitivity is −109.573 nm/RIU in the range of 1.333–1.398RIU. The temperature sensitivity is 0.014 nm/°C in the range of 10–70 °C [6]. In 2016, Zhao Yong et al. introduced a temperature sensor based on up taper and multimode, the up-taper is used to excite the cladding mode and high order core mode. The experimental results show that the temperature sensitivity is up to 89.42 pm/°C in the range of 20–80°C [7]. Huaping Gong et al. reported a sensor by cascading core-offset and spherical-shape structures to achieve simultaneous measurement of curvature and temperature, and the temperature sensitivity is 0.0847 nm/°C in the range of 60°C–100°C [8]. In addition, multi-mode fiber (MMF) cascaded with fiber Bragg grating (FBG) [9], thin-core fiber (TCF) cascaded with MMF [10], photonic crystal fiber (PCF) [11,12], spherical-shape structures cascaded with long-period grating (LPG) [13] have also been used to measuring the temperature or refractive index. However, the modes in the MMF are very varied and complicated. The number of modes involved in the interference is out of control. So the theoretical analysis is very difficult and optical energy will be scattered to the multiple modes. The stable interference spectrum is not easily to obtain, which is not beneficial to practical application. So we substituted the few-mode fiber (FMF) for MMF.

The FMF as a new type optical fiber has attracted much interest due to its superiority in interference stabilization [14] and has a promising applications in optical sensing field [15]. Its unique advantages are good capability of mode limited and less number of propagation modes [16,17]. The number of propagation modes can be controlled by relevant manufacturing technology [18]. These optical fiber interference devices based on certain high core modes can be easily theoretical analyzed and designed. K. Nakajima et al. reported a optical sensor based on FMF cascaded long-period fiber gratings (LPGs). It can achieve simultaneous measurement of strain and temperature, however, its sensitivities are relatively low and the LPG is expensive [19]. Huang, TY. et al. used a high GeO_2-doped FMF to fabricated a temperature sensor and gained a temperature sensitivity of 97 pm/°C, however, the length

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http://dx.doi.org/10.1016/j.optcom.2017.07.070
Received 5 June 2017; Received in revised form 20 July 2017; Accepted 26 July 2017
Available online 19 September 2017
0030-4018/

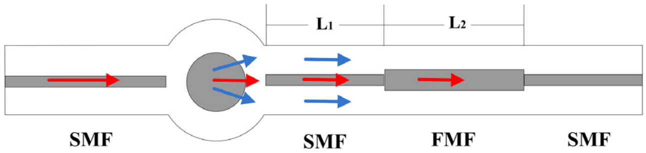

Fig. 1. Schematic diagram of the proposed sensor.

of whole sensing structure is 15 cm, which is not compact or compositive in the practical application of sensing [16]. In 2016, Juan Su et al. studied the property of bent FMF and application in displacement sensor. The experimental results show that the displacement sensitivity is up to 0.172 nm/mm [17], but the sensing structure cannot eliminate the interference of temperature to displacement sensitivity. In 2017, Jingxuan et al. fabricated a FMF–SMF–FMF sensing structure, which indicates that it has a high resolution and accuracy RI measurement, however, the Erbium-doped fiber ring laser sensing device is complex and without considering the effect of temperature on RI [18].

In this paper, an optical fiber sensor based on FMF and spherical-shape structure is proposed and demonstrated. The temperature and refractive index can be measured simultaneously. This structure is composed of lead-in SMF, spherical structure, sensing fiber FMF and lead-out SMF. When the light propagating along the lead-in SMF enters the spherical structure, the cladding modes of the sensing fiber are excited due to the mode field mismatch and transmit along the SMF with different propagation constants. When the light transfers to the FMF, high order core modes will be excited. The core and cladding modes will interference with each other at the fusion between the FMF and lead-out SMF, due to the optical path difference caused by the refractive index difference between core and cladding modes. The temperature sensitivity of the sensor is 0.059 nm/°C, which is higher than the sensitivity of the FMF cascaded (LPGs) structure (17.6 pm/°C) [19]. The refractive index sensitivity is −48.82 nm/RIU, which is higher than the sensitivity of the MZI based on cascading peanut-shape structure with core-offset structure (−26.965 nm/RIU) [20]. In addition, the sensor is higher mechanical strength than core-offset cascaded spherical-shape structure [8]. The proposed structure is cost-effective and easier to fabricate (compared with spherical-shape structures cascaded with LPG [13]). Moreover, it can be used to measure the two parameters simultaneously and eliminate the cross-sensitivity by sensitive matrix.

2. Principle

The schematic diagram of the sensor is illustrated in Fig. 1. The sensor head is composed of lead-in SMF, spherical structure, sensing fiber, FMF and lead-out SMF. The length of the sensing fiber is L_1, and the length of the FMF is L_2.

Fig. 2 shows the micro-graph image of the spherical structure. The detail parameters in manufacturing process are as follow: the fusion splicer model is Fitel S178C, the first discharge start intensity is 150 bit, the first discharge end intensity is 150 bit, discharge time is 12 100 ms, propulsion form is bilateral motor movement, propulsion distance is 18 000 um, and a spherical structure will be made after discharge. The diameter of the spherical structure is $D = 205.3$ μm. A section of SMF was spliced with the spherical structure. And then a section of FMF was spliced with the SMF. The discharge intensity is 150 bit, discharge time is 12 100 ms.

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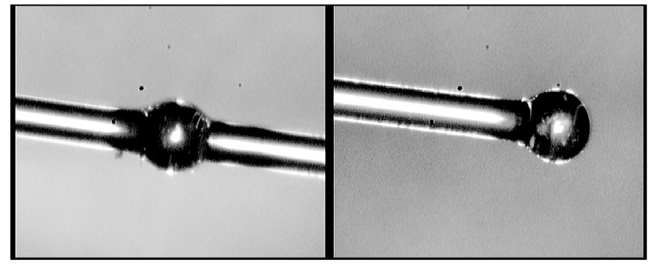

Fig. 2. Micro-graph image of the spherical structure.

between core and cladding modes. And thus finally form a Mach–Zehnder interferometer device.

The intensity of the transmission spectrum can be described as follows [21]:

$$I = I_{co} + \sum_m I_{cl}^m + \sum_m 2\sqrt{I_{co} I_{cl}^m} \cdot \cos\left(\frac{2\pi \Delta n_{eff}^m L}{\lambda}\right) \tag{1}$$

Where I_{co} and I_{cl}^m are the intensities of the core mode and the mth cladding mode, respectively. Δn_{eff}^m is the difference between the effective refractive indices of the core mode and the mth cladding mode, L is the length of transmission fiber, and $L = L_1 + L_2$, λ is the wavelength of the propagating light.

The wavelength separation between two interference minima, known as free spectral range (FSR), can be approximated as:

$$FSR \approx \frac{\lambda^2}{\Delta n_{eff}\left(L_1 + L_2\right)}. \tag{2}$$

It can be seen that the FSR will be impacted by three parameters. The FSR will increase as the transmission length L decreases, it will increase as the propagating light wavelength increases, and it will decrease as the difference between the modes increase.

In the research of the output transmission spectrum, extinction ratio (ER) is also a important parameter. It can be described as:

$$ER = 10\log\frac{I_{\max}}{I_{\min}} = 10\log\left(\frac{\sqrt{I_{co}} + \sqrt{I_{cl}^m}}{\sqrt{I_{co}} - \sqrt{I_{cl}^m}}\right)^2 = 10\log\left(\frac{1 + \sqrt{I_{co}/I_{cl}^m}}{1 - \sqrt{I_{co}/I_{cl}^m}}\right)^2. \tag{3}$$

It can be seen that when I_{co} is equal to I_{cl}^m, the value of ER approaches to infinity, which means that the ER of the interference spectrum tends to infinity. Therefore, the closer intensities of the two beams of light are, the more obvious the interference effect is.

The interference dips formed between the core mode and the different cladding modes will exhibit different sensing characteristics. Select two interference dips as the observation spots and the simultaneous measurement can be realized by the sensitive matrix [22]:

$$\begin{bmatrix} \Delta\lambda_{dip1} \\ \Delta\lambda_{dip2} \end{bmatrix} = \begin{bmatrix} K_{dip1}^T & K_{dip1}^{RI} \\ K_{dip2}^T & K_{dip2}^{RI} \end{bmatrix} \begin{bmatrix} \Delta T \\ \Delta RI \end{bmatrix} \tag{4}$$

where $\Delta\lambda_{dip1}$ and $\Delta\lambda_{dip2}$ represent the wavelength shifts of the dip1 and dip2, respectively. K_{dip1}^T and K_{dip2}^T are the temperature sensitivity coefficients of the dip1 and dip2, respectively. K_{dip1}^{RI} and K_{dip2}^{RI} are the refractive index sensitivity coefficients of the dip1 and dip2, respectively. ΔT and ΔRI denote the changes of temperature and refractive index.

By using matrix inversion method, variations of temperature and refractive index can be simultaneously obtained and described as:

$$\begin{bmatrix} \Delta T \\ \Delta RI \end{bmatrix} = \frac{1}{D} \begin{bmatrix} K_{dip2}^{RI} & -K_{dip1}^{RI} \\ -K_{dip2}^T & K_{dip1}^T \end{bmatrix} \begin{bmatrix} \Delta\lambda_{dip1} \\ \Delta\lambda_{dip2} \end{bmatrix} \tag{5}$$

where $D = K_{dip1}^T K_{dip2}^{RI} - K_{dip2}^T K_{dip1}^{RI}$. So the temperature and the refractive index can be measured simultaneously by observing the two dips, respectively.