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Miniature optical fiber temperature sensor based on FMF-SCF structure

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ABSTRACT

We proposed and experimentally demonstrated a miniature optical fiber temperature sensor consisting of a seven core fiber (SCF) and a few mode fiber (FMF). The device is fabricated by splicing a section of FMF with a segment of SCF to form a FMF-SCF based sensing structure, and during the FMF region, few modes can be excited and will propagate within the SCF. In experiment, the proposed device has good quality interferometric spectra, and the highest extinction ratio of 27 dB was achieved. When the temperature increases from room temperature to 110 °C, the temperature response properties of the sensor have been investigated, the wavelength sensitivity of about 91.8 pm/°C and the amplitude sensitivity of about 1.57×10^{-2} a.u./°C are obtained, respectively. Due to its easy and controllable fabrication, the sensor can be a suitable candidate in temperature sensing applications.

1. Introduction

In recent years, optical fiber temperature sensors have attracted tremendous attention due to the advantages like small size, immunity to electromagnetic interference, linear response and high sensitivity over conventional sensors. This kind of temperature sensors have been playing increasingly roles in many applications, like security monitoring, biochemical sensing. In previous work, there are various type of configurations have been developed for temperature sensing, such as fiber Bragg gratings (FBGs) [1,2], long-period gratings (LPGs) [3]. Aside from the sensing sensitivity, they require precise and expensive phase masks or high-frequency CO_2 laser pulses. In 2017, Sun et al. proposed an automatic arc discharge technology for helically twisted long period fiber gratings (H-LPFGs) [4], the temperature sensitivity of the sensing structure can reach up to 70 pm/°C. Fabry-Perot interferometer (FPI) is another configuration of the fiber sensors [5–7]. However, in fiber air-cavity based FPIs are usually insensitive to temperature because of the negligible thermal optic coefficient of air and the low thermal expansion coefficient of silica (typical value of 5.5×10^{-7} °C^{-1}). In 2015, Zhang et al. reported a novel fiber tapered tip based FPI that can provide controllable temperature sensitivity between 0 pm/°C and 1.97 pm/°C [8]. Next year, Cao et al. proposed a fiber optic FPI sensor with cascaded polymer-microbubble cavities, such a sensor exhibits a temperature sensitivity of 5.013 nm/°C in the temperature range between 20 °C and 55 °C [9]. Although these sensors have higher sensitivity, the structures need stringent fiber fabrication process and the cascaded polymer-microbubble is easily disturbed in a particular environment.

Because of its high extinction ratio, stable structure and high temperature sensitivity, some fiber optic temperature sensors based on multi-core optical fiber (MCF) interference are proposed. In 2012, a twin-core fiber (TCF) Michelson interferometer was evaluated as a temperature sensor [10]. In 2014, Li et al. proposed a TCF based Mach–Zehnder interferometer (MZI), a micro-channel was drilled through one core by means of femtosecond laser micromachining, and such a fiber interferometer exhibits an temperature sensitivity of 43.6 pm/°C [11]. In 2015, a novel all-fiber laser sensing configuration for measurement of temperature based on the TCF with an in-line embedded fiber Bragg grating was demonstrated, although the optical signal-to-noise ratio is higher than 40 dB, the temperature sensitivity is only 9.2 pm/°C [12]. In 2016, Geng et al. proposed a interferometer made of tapered three-core fiber and CO_2 laser notch long-period fiber grating for temperature sensing, the sensing sensitivity is 47 pm/°C [13]. In addition, there are some special structures of MCF used as temperature sensors. In 2015, Guan et al. reported a linear five-core fiber and sandwiched in between two single-mode fibers (SMFs) to construct an all-fiber Mach–Zehnder interferometer, and realized a temperature fiber sensor with a relatively high sensitivity of 87 pm/°C [14]. In the same year, a compact temperature sensor was reported by integrating a cladding Bragg grating in a section of all-solid photonic bandgap fiber. The temperature sensitivity of this structure is 50.9 pm/°C [15].

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More recently, seven core fiber (SCF) is used for temperature sensing, like weak-coupling SCF [16] and strong-coupling SCF [17]. In 2016, a novel in-line MZI system has been designed in the weak-coupling SCF with fiber tapering process, the temperature sensitivity was about 53.2 pm/°C [18]. In 2017, Wang et al. fabricated an in-line interferometer by splicing a segment of SCF and two segments of multimode fibers (MMFs), with a sensitivity of 55.8 pm/°C for the temperature range of 25 °C–175 °C [19]. Some of the structures mentioned above have relatively high extinction ratio and sensitivity, but the fabrication is complicated. Some structures are simple to make, but their sensitivity is not high. In this paper, we propose a novel optical fiber temperature sensor based on FMF-SCF structure, which is fabricated by fusion–splicing a section of FMF with a segment of SCF. Due to the multipath evolutions of light, the mode induced interference pattern can used for measurement. A strong interference with the highest extinction ratio of 27 dB was achieved. The temperature response characteristics of the sensor have been investigated, a temperature sensitivity of 91.8 pm/°C in the temperature range of 25 °C–110 °C was also obtained. We also looked at the FFT-spatial frequency spectrum of the sensor, with the change of temperature, the sensitivity of 1.57×10^{-2} a.u./°C is obtained. With the fabrication process of the sensor is much simpler and faster, the sensor can be a good candidate for sensing applications.

2. Sensor fabrication

Fig. 1(a) shows the schematic diagram of the proposed FMF-SCF based interferometer. Fig. 1(b) and (d) show the cross-sectional morphology of the fabricated FMF and SCF by using an optical microscope, respectively. The FMF has a cladding diameter of 125 μm, and a core diameter of 18 μm. Four modes can be supported in the core of the FMF, like LP01, LP11, LP21 and LP02. The SCF (Yangtze Optical Fiber And Cable Company Ltd, YOFC) has seven Ge-doped cores surrounded by low refractive index (RI) trench and pure silica cladding. The SCF has a center core and six identical ambient cores distributed in the vertices of the regular hexagon. The core diameter, the cladding diameter and the pitch size (Λ) between the adjacent cores are measured to be 9.14 μm, 145 μm, and 52.9 μm respectively. It is worth mentioning that the core in the SCF differs from cladding in RI with the difference of about 10^{-3} orders of magnitude. To fabricate the sensor structure, firstly, we spliced a segment of FMF with normal SMF-1 by a commercial fusion splicer (Ericsson, FSU-975) with the SMF splicing program. Secondly, cleaved the FMF with a desired length of 1 cm and spliced with a segment of SCF to form a FMF-SCF sensing structure, and the splicing point as shown in Fig. 1(c). Then cleaved the end of the SCF with a short length of 1.5 cm and align with a section of pre-processed SMF-2, and fixed the sensing structure on the fusion splicer. After the process above, the two pigtails of the fabricated device were connected to a

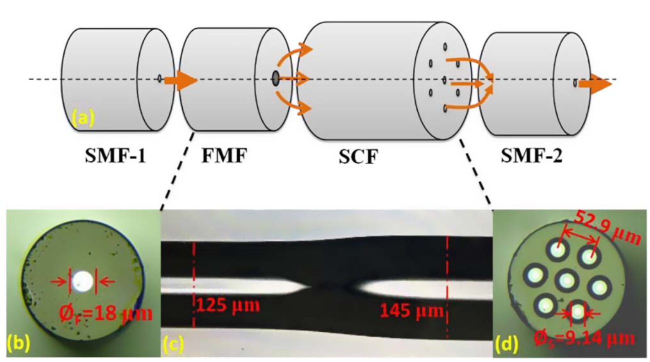

Fig. 1. (a) Schematic diagram and operation principle of the sensor structure fabricated by the splicing procedures. (b) Microscope image of the cross section of FMF. (c) Microscope image of the splicing point between FMF and SCF. (d) Microscope image of the fabricated SCF.

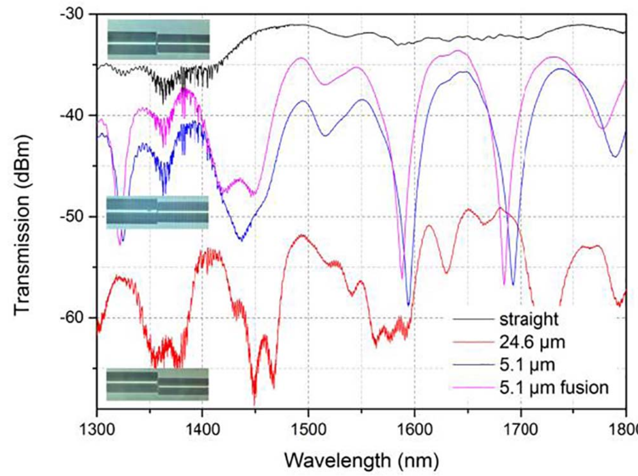

Fig. 2. Transmission spectra of three cases with different core offset. Inset: Three microscope images of the fabricated core offset structure.

broadband light source (BBS) (KOHERAS, SuperK Uersa) 1200–2400 nm and an optical spectrum analyzer (OSA) (YOKOGAWA AQ6375) with resolution bandwidth set at 0.05 nm, respectively. To achieve a stable and high extinction ratio interference spectrum, we optimized the core offset between SCF and SMF-2, here are three cases, 0 μm, 5.1 μm and 24.6 μm, as shown in Fig. 2. We can notice that, when the core offset is 5.1 μm, a much better interference spectrum can be obtained. However, with a larger offset (24.6 μm) of SMF-2 would allow for more cladding modes interfering. And thus it would lead to a low extinction ratio as the red line shown in Fig. 2, which is not suitable in the sensing field.

Furthermore, in order to make stable spectrum, we reduce the discharging current and splicing time of fusion splicer from 12 mA to 10.5 mA and from 9 s to 6 s, respectively. As we can see from the figure, the spectral is basically unchanged after splicing, and because of the stress caused by the fusion, the spectral is just slightly drifts to the left. We also note that the loss of the spectral is reduced by 2–3 dB, as the pink line shown in Fig. 2.

Considering the principle of the sensing structure, few modes are split around the interface between FMF and SCF, and are combined around the interface between SCF and SMF-2. More concretely, at first splicing interface, the core mode of the SMF-1 is split into the four core modes of the FMF. Due to the miss match of core radius in FMF-SCF structure region, core mode and cladding modes of the SCF are excited simultaneously. Then the split modes are recombined into the SMF-2 at splicing interface. Due to the fact that the interference pattern is mainly formed by the core and cladding mode interference, the interference intensity can be expressed as [20],

$$I = I_{co} + \sum_{m} I_{cl}^{m} + \sum_{m} 2\sqrt{I_{co} I_{cl}^{m}} \cos\varnothing^{m} \quad (1)$$

where I, I_{co}, and I_{cl}^{m} are the intensity of the interference signal, the light intensity of the core, and the mth cladding mode, respectively. And $\varnothing^{m}$ is the phase delay, which can be approximated as

$$\varnothing^{m} = \frac{2\pi \Delta n_{eff}^{m} L}{\lambda} \quad (2)$$

where Δn_{eff}^{m} is the effective indices difference between the core and the mth cladding modes, L is the interaction length, and λ is the input wavelength. According to the interference theory, the interference signal reaches the minimum value when the following condition is satisfied

$$\frac{2\pi \Delta n_{eff}^{m} L}{\lambda_m} = (2m + 1)\pi \quad (3)$$