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Comparative study on a core-offset fiber temperature sensor between the faraday rotation mirror structure and the double coupling structure

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ABSTRACT

A temperature sensor based on core-offset single mode fiber (SMF) and a Faraday rotation mirror (FRM) has been proposed and experimentally demonstrated in this paper. This sensor was fabricated by splicing in a section of SMF between two SMFs with a core-offset at two splicing joints. The end of the joint is connected to the FRM, which can double the sensitivity and improve the polarization state stabilization at the sensor output. The variation of the transmission spectrum of the sensor with respect to the surrounding temperature has been experimentally studied. A comparison is made between this design and a laser temperature sensor made of the same core-offset fiber utilizing a double coupling (DC) structure. The results show that, within the range of 1539.42–1553.90 nm, the sensitivity of the proposed sensor is 0.89039 nm/°C and in the range of 47–63 °C. Additionally, the power attenuation is 2.257 dB/°C. The temperature sensitivity in the SMF and FRM sensor is increased by an order of magnitude in comparison with the DC sensor. The instability and low sensitivity characteristics of a laser temperature sensor constructed with DC structure can be solved through the use of core-offset SMF and FRM.

1. Introduction

Compared to traditional sensors, optical fiber temperature sensors have attracted attention in chemical, bio-medical and other fields because of their small volume, strong immunity to electromagnetic interference, long service life, and smooth fiber-optic networking, etc. [1–3]. In particular, optical fiber temperature sensors are suitable to be used in temperature control systems where high sensitivity and measurement stability are required but the sensor dielectric cannot function, such as in a liquid storage system [4], aerospace applications, nuclear power applications, in the presence of strong electromagnetic interference or other harmful environments. Recently, the use of optical fiber temperature measurement has become common. Various measuring instruments utilizing optical fiber temperature measurement have been designed, including interferometer structure, laser structure [5], core-offset fiber structure, and structures that are combinations of them. The device proposed in 2013 was based on a fiber modal interferometer in combination with an embedded fiber Bragg grating [6], which consists of an Up-Fusion-Bitaper (UFBT) pair to excite high-order cladding-modes and re-couple them to the fiber core. The sensor yielded a sensitivity of 63.7 ± 1.84 pm/°C for temperatures ranging from 20 °C to 80 °C. An all-fiber sensor consisting of a core-offset Mach–Zehnder interferometer (MZI) and a fiber Bragg grating (FBG) measured the refractive index and temperature simultaneously in solutions [7]. Utilizing a similar method, a fiber laser sensor based on two taper structures and one FBG, was proposed in 2014. It was designed to simultaneously measure liquid levels and temperature [8]. Corresponding to the two filters, the laser outputs are stable dual-wavelength outputs with different characteristics to measure the liquid level and the temperature. Although dual measurement was achieved, the light beams via the core-offset optical fiber and FBG are separated and are coupled into the lead-out, making it difficult to avoid optical crosstalk interference. In 2015, a compact optical fiber MZI was designed to simultaneously measure temperature and strain or temperature and curvature [9]. This design consisted of input SMF and a FBG, a short section of multimode fiber (MMF) and output SMF, of which the FBG is offset spliced with upstream input SMF. Based on these works, an all-fiber sensor designed to simultaneously measure temperature and refractive index (RI) was built in 2015 [10]. This was composed of one MZI and one FBG. The MZI consisted of a peanut-shaped structure and a core-offset structure, which are formed using different fusion technologies utilizing only single mode fibers. However, the complicated fabrication processes (multi pulse exposure and etching, side-polishing, excimer laser micromachining, etc.) of these devices or the

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special fibers used in their construction (double core fiber [11], PCF [12] and other factors [13]) may limit their practical application.

Several methods utilizing simpler techniques and varied structures have been reported, and some have included temperature measurement to fabricate an MZI along a core-offset SMF [14,15], a multimode–single mode–multimode (SM–MM–SM–SM) fiber configuration [16], a single mode–multimode–thinned single mode (SMTS) fiber structure [17,18], or a core-offset single mode–single mode–multimode–single mode (SSMS) fiber structure [19]. In 2015, the simultaneous measurement of displacement and temperature was achieved with a design based on a thin-core fiber modal interferometer [20]. However, the high propagation loss and the low signal to noise ratio of this type of design may result in excessive links, which may weaken the fiber sensors during the measurement process.

In this paper, we will present a fiber-optical temperature sensor based on the core-offset single mode fiber and a Faraday rotation mirror. The proposed sensor was fabricated by splicing a section of SMF between two SMFs with a core-offset at the two splicing joints. Then, the end of the joint is connected to the Faraday rotation mirror, which can double the sensitivity and improve polarization state of the sensor output [21]. A comparison between this design and a laser temperature sensor utilizing the same core-offset fiber with DC structure shows that the instability and low sensitivity of the latter can be solved through the use of a temperature sensor based on core-offset SMF and FRM. Within a low temperature range, the sensor based on the core-offset fiber and FRM is suitable for use in a temperature-controlled system such as a thermostatic apparatus. This sensor, due to its simplicity, low cost, and strong practicality of design is expected to be widely used in temperature-controlled applications.

2. Operation principle and fabrication

A diagram of the sensor is given in Fig. 1. A segment of SMF with a length of L approximately 5 cm is spliced into two SMFs in two stages, and the end of SMF is connected to a FRM. D gives the value of the offset, which is approximately 4 μm. The core and cladding diameters of the SMF used in the experiment are 9.2 and 125 μm, respectively. All of the fibers utilized in the experiment were produced by the Yangtze Optical Fiber and Cable Company, Ltd. The key component of the sensor is the FRM, with a length of 58.5 mm. This FRM was chosen to obtain an output independent of the polarization state and could thus enhance the temperature sensitivity.

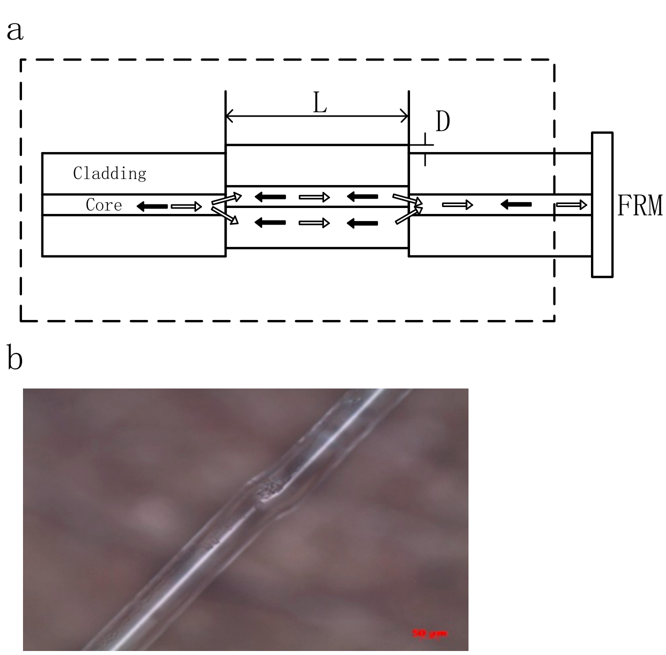

Fig. 1. (a) Schematic diagram of the SMF-FRM fiber structure and (b) the core-offset fiber under the electronic microscope.

When the optical signal passes through the core-offset, the multitude of the cladding mode is excited due to the mode field mismatch [22] and the cladding is transmitted along the single mode fiber. The input optical signal is split into two optical paths at the first splicing joint along the core and the cladding of the fiber, respectively. The energy within the core is the largest, and the cladding mode loss is large as well. Thus, the cladding mode is simplified in this new design as possessing one of the largest energy and submaximum energy losses among temperature controls. Then, the two modes in the each optical path are recombined together at the second coupling point.

Due to the mode effective index of the core mode and cladding difference, there will be a difference in the optical path in the transmission process. The MZI caused by the core-offset fiber could be used to measure temperature, strain, curvature, etc., by utilizing the phase difference between the core and cladding modes. Both the core mode and the cladding modes will propagate along the SMF-FRM, and the cladding modes will interfere with the core modes when the light is re-coupled back to the input of SMF. The effect of random variation of the polarization state in the fiber could be effectively eliminated using FRM [23]. The FRM can also compensate for signal fading due to polarization and eliminate the influence of the external perturbations. Furthermore, the effects of double refraction on temperature measurement, and the measurement stability of this structure should be significantly improved.

The interference pattern after the reflection from the FRM is based on the interference between the core and the cladding modes. Its intensity is calculated by (1)

$$I_s = \sum_{\mathrm{m}} 4I_{core}I_{cladding,m}\left(\cos\Delta\varphi_m - \frac{I_{core} + \sum_{\mathrm{m}} I_{cladding,m}}{\sum_{\mathrm{m}} 2\sqrt{I_{core}I_{cladding,m}}}\right)^2 \tag{1}$$

I_s is the output light intensity in the reflection, I_{core} and $I_{cladding,m}$ are the initial light intensities of the core and the cladding mode, and ϕ_m is the phase delay, which is proportional to the length of SMF and the effective index difference between core and cladding mode. ϕ_m can be approximated as

$$\varphi_{\mathrm{m}} = \frac{4\pi\left(n_{\mathrm{eff}}^{\mathrm{core}} - \mathrm{n}_{eff}^{\mathrm{clad},m}\right)L}{\lambda_{\mathrm{m}}} = \frac{4\pi\Delta n_{eff}^{m}L}{\lambda_m} \tag{2}$$

where n_{eff}^{core}, $n_{eff}^{clad,m}$, L, λ_m, and Δn_{eff}^{m} are the effective indices of the core mode and the m-th cladding mode, the length of SMF, light wavelength and the effective index difference, respectively. According to interference theory, when the light signal occurs at twice the interference through the FRM structure, it is equivalent to a fiber-optic Michelson interferometer. The maximum attenuation of wavelength can be expressed as

$$\lambda_m = 4\cdot\frac{\Delta n_{eff}^{m}\cdot L\cdot\pi}{(2m+1)\pi} \tag{3}$$

As the interference of the output light intensity is doubled, the maximum wavelength attenuation is doubled. Interference wavelength, effective refractive index and length of core-offset fiber change simultaneously as the temperature changes. The interference wavelength can be observed to vary at different temperatures by observing the peak of the wavelength as the temperature changes. The wavelength shift is as follows: