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Strain-insensitive temperature sensor based on a few-mode dual-concentric-core fiber

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HIGHLIGHTS

- Few-mode dual-concentric-core fiber supporting a few number of guided modes.
- Higher Ge-doping concentration to improve thermo-optic coefficient of the fiber core.
- Modal interference between fundamental mode and high-order mode for sensing.
- Simple structure with relative high temperature sensitivity and strain suppression.

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ABSTRACT

We report on a compact strain-insensitive fiber temperature sensor based on a few-mode dual-concentric-core fiber (FM-DCCF). The proposed sensor simply involves a section of FM-DCCF spliced to lead-in and lead-out single-mode fibers (SMFs). The FM-DCCF with unique refractive index distribution supports a few number of guided modes. The high-order mode in the FM-DCCF is coupled from the fundamental mode in the lead-in SMF, and then the interference spectrum of them can be obtained in the lead-out SMF. By monitoring the variation of the wavelength, the sensor can be applied in temperature measurement with a sensitivity as high as 52.79 pm/°C. In addition, the wavelength drift of the sensor is almost immune to the cross impact of axial strain with the sensitivity of 0.23 pm/με.

1. Introduction

Optical fiber sensors have received great attention because of a wealth of advantages, such as fast response, immunity to electromagnetic interferences and durability against harsh environments. Temperature measurement is one of the most application of optical fiber sensors and fiber-based temperature sensors have been widely adopted in different areas. Fiber grating based temperature sensors using fiber Bragg grating (FBG) and long period grating (LPG) have been developed in recent years [1–3]. To enhance the sensitivity, novel optical fibers and grating structures have been explored. In [4], a polymer optical fiber with higher thermo-optic coefficient and thermal expansion coefficient than those of silica glass was fabricated and used to write a Bragg grating. Dai et al. proposed a temperature sensor based on a LPG inscribed on a ring-core hollow fiber filled with functional liquid, of which the maximum linear sensitivity can reach −618 pm/°C [5]. These fiber grating based sensors with unique fiber material or structure can improve the sensitivity effectively. However, the fabrication complexity of the sensor will be greatly increased.

Another sort of representative fiber-based temperature sensor is fiber interferometers utilizing the modal interference, such as Mach-Zehnder interferometer (MZI) [6], Fabry-Perot interferometer (FPI) [7,8] and Sagnac interferometer [9,10]. By utilizing the interference between guided modes in fiber, an intermodal MZI can be generated. Based on this principle, the classical and frequently-used sensor structure is singlemode- multimode-singlemode (SMS) fiber structure [11]. Liu et al. demonstrated a singlemode-coreless-singlemode (SCS) fiber structure-based fiber ring laser sensing system [12] which has the advantage of high optical intensity for long-distance operation. By using the interference between fiber core and cladding modes in a single mode fiber, multimode-singlemode multimode (MSM) fiber structures [13,14] have been demonstrated to enhance the sensitivity. The MSM fiber structure consists of several short sections of fibers and hence it increased the fabrication complexity. In [15], a microfiber based dual

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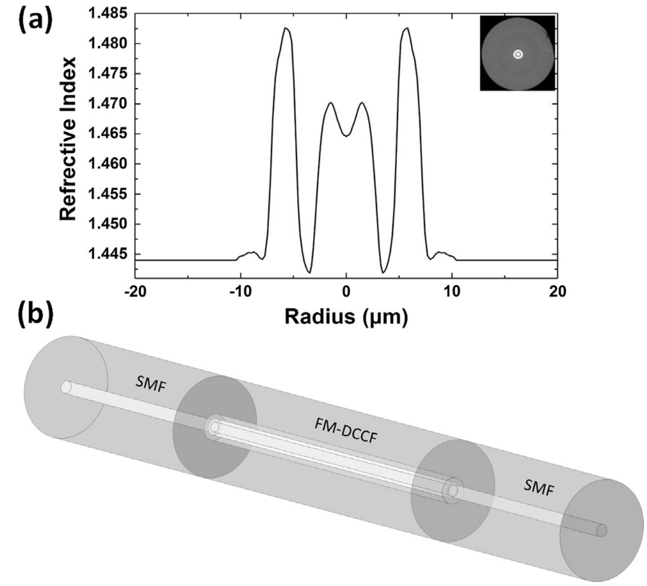

Fig. 1. (a) Refractive index profile of the FM-DCCF. (b) Configuration of the proposed sensor.

MZI for simultaneous measurement of refractive index and temperature was reported, but the sensing fiber is more fragile.

In this paper, we present a fiber temperature sensor with axial-strain insensitivity based on a novel few-mode dual-concentric-core fiber (FM-DCCF). The FM-DCCF which is spliced into lead-in and lead-out single-mode fibers (SMFs) consists of a central core and a relatively high-refractive index concentric ring core. A few number of guided modes are supported due to the unique refractive index distribution of the FM-DCCF. When the light travels through the structure, modal interference occurs between the fundamental mode and the high-order mode supported in the FM-DCCF. Then the whole sensor can be regarded as an in-line MZI. By monitoring the variation of the wavelength, the proposed structure exhibits the temperature sensitivity of 52.79 pm/°C, accompanied by a suppressed axial strain with the sensitivity of 0.23 pm/με. It will have potential in practical applications.

2. Experimental principle

The homemade FM-DCCF used in this experiment is fabricated using modified chemical vapor deposition method. The refractive index profile of the fiber is depicted in Fig. 1(a) and the cross section is shown in the inset. The fiber has the same radius of about 62.5 μm as the standard SMF. The radius of the central core is about 3 μm. The inner and outer radii of the ring core are about 4.5 μm and 7.5 μm. By controlling the germanium doping concentrations during the fabrication process, the maximum refractive index differences of the central core and the ring core contrasted to the pure silica cladding are about 0.026 and 0.038, respectively.

The configuration of the proposed sensor is shown in Fig. 1(b). A section of FM-DCCF is simply spliced to the lead-in SMF and the lead-out SMF with carefully axial alignment. The input light is injected from the lead-in SMF to the FM-DCCF and high-order modes can be excited at the interface. The fundamental mode and high-order modes propagate in the FM-DCCF simultaneously but with different velocities. When they meet again at the interface between the FM-DCCF and the lead-out SMF, high-order modes coupled back to the SMF and interfere with the fundamental mode. Then the sinusoidal interference spectrum will be observed from the output light.

The theoretical analysis of the guided modes supported in the FM-DCCF was conducted using the simulation software COMSOL Multiphysics®. We built a 2D circular symmetry model and import the measured refractive index. Then the electric field distributions and effective indices of the first 32 modes were calculated in a wavelength range from 1500 nm to 1600 nm. Fig. 2 depicts the results of the simulation including effective indices of the first 32 modes and their corresponding electric field distributions shown as the insets. The black dashed line represents the refractive index of cladding. The results reveal that there are 9 group modes supported in the whole core, which can be classified as LP_{01}-LP_{61} modes referring to the naming convention of linearly polarized (LP) modes in the step-index fibers.

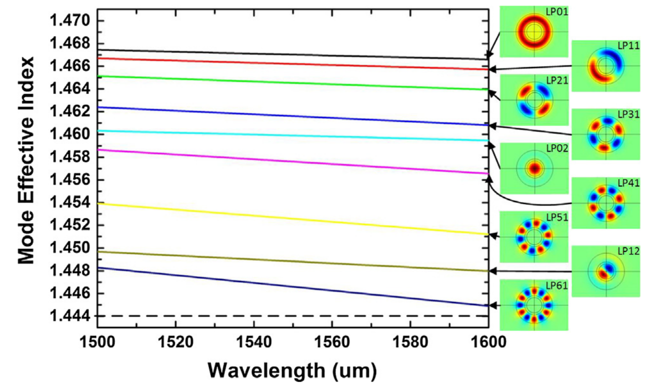

Fig. 2. Calculated mode effective indices of the guided modes supported in the FM-DCCF.

Attributed to the symmetry of the fibers' cross sections and guided modes, only linearly polarized radial modes (i.e., LP_{01} and LP_{02}) can be excited and transmitted in the FM-DCCF. A large portion electric field of LP_{01} mode distributes in the ring core and most electric field of LP_{02} mode spreads over the central core. The intensity of these modes are determined by the excitation coefficient from the LP_{01} mode in the SMF to these modes in the FM-DCCF shown as the following equation:

$$c_k = \frac{\int_0^\infty \psi_s(r)\psi_k(r)rdr}{\int_0^\infty \psi_k(r)\psi_k(r)rdr} \tag{1}$$

where ψ_s is the field distribution of the fundamental mode in the SMF, ψ_k is the field distribution of the excited mode in the FM-DCCF and k represents LP_{01} or LP_{02}. Using the finite element method, we calculate the excitation coefficients of LP_{01} and LP_{02} to be about 0.36 and 0.29, respectively. And the excitation coefficients of other modes are much less than them. Due to the fact that LP_{01} and LP_{02} modes propagate along different optical paths in the sensing FM-DCCF, an intrinsic fiber MZI based on modal interference is constructed.

Suppose the length of the FM-DCCF in this sensor is L. After travelling a distance of L in the FM-DCCF, these two modes interfere and the intensity I of the interference pattern should satisfy the following equation:

$$I = I_{LP_{01}} + I_{LP_{02}} + 2\sqrt{I_{LP_{01}} I_{LP_{02}}}\cos\varphi \tag{2}$$

where $I_{LP_{01}}$ and $I_{LP_{02}}$ are the intensity of the LP_{01} mode and the LP_{02} mode respectively, φ is the phase difference between the LP_{01} mode and the LP_{02} mode. The phase difference can be expressed as:

$$\varphi = \frac{(n_{eff}^{LP01} - n_{eff}^{LP02})L}{\lambda}\cdot 2\pi = \frac{2\pi\Delta n_{eff} L}{\lambda} \tag{3}$$

where Δn_{eff} is the effective index difference between the LP_{01} mode and the LP_{02} mode, λ is the characteristic wavelength. Because the sinusoidal behavior of the interference fringe originates from the cosine term of Eq. (2), the phase difference between the adjacent fringe dips becomes 2π. When the phase difference equals to the odd times of π, i.e. $\varphi = (2m + 1)\pi$, the mth order resonant wavelength of the interference spectrum can be expressed by: