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Fiber ring laser for axial micro-strain measurement by employing few-mode concentric ring core fiber

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ABSTRACT

We proposed and demonstrated a novel few-mode concentric-ring core fiber (FM-CRCF) for axial micro-strain measurement with fiber ring laser based on few-mode-singlemode-few-mode fiber structure. The core area of CRCF consists of four concentric rings which refractive indices are 1.448, 1.441, 1.450, 1.441, respectively. LP_{01} and LP_{11} are two dominated propagating mode groups contributing in the CRCF. In this few-mode-singlemode-few-mode structure, two sections of CRCF act as the mode generator and coupler, respectively. The basis of sensing is the center single mode fiber. Moreover, this structure can be used as an optical band-pass filter. By using fiber ring cavity laser, the axial micro-strain sensing system has high intensity (∼20 dB), high optical signal to noise ratio (∼45 dB) and narrow 3 dB bandwidth (∼0.1 nm). In the axial micro-strain range from 0 to 1467 με, the lasing peak wavelength shifts from 1561.05 nm to 1559.9 nm with the experimentally sensitivity of ∼ 0.81 pm/με.

1. Introduction

Optical fiber sensors have distinctive advantages of low-cost, fast response, high sensibility, anti-erosion and immunity to electromagnetic interference, which draw a great deal of attention to the measurements of axial micro-strain in harsh environment. In recent years, axial strain sensors based on fiber Bragg gratings (FBGs) [1,2], long period fiber gratings (LPFGs) [3,4] and Mach–Zehnder interferometers (MZIs) [5–7] have been theoretically and experimentally demonstrated. In addition, fiber sensors based on multimode interference (MMI) are also typical sensing devices [8]. Compared with dual-arm MMI interferometers, in-line MMI interferometers are more compact [9]. There are many novel sensing structures based on multimode interference which have been proposed and experimentally demonstrated, such as two peanut-shape structure [10], cascaded no-core square fibers structure [11], biconical taper in FBG structure [12], core-offset structure [13,14]. However, these structures are complex to fabricate and fragile, limiting the applications of fiber sensors. The typical all-fiber MMI structure, multimode-singlemode-multimode (MSM), is simple and compact which can be made by splicing a section of common single mode fiber (SMF) between two sections of multimode fiber (MMF). This structure gives us a solution to simplify the production process and reduce the cost of fiber sensors.

Nevertheless, the shortcomings of the sensors based on multimode interference are low extinction ratio, low intensity, and wide 3 dB bandwidth, which lead to relatively poor application in the long distance measurement. The intrinsic features of fiber laser are high optical signal to noise ratio (OSNR), high optical peak intensity and narrow 3 dB bandwidth [15]. Nowadays, it is investigated extensively that the combination of the fiber laser and the fiber sensor is a good solution in the sensing field [16]. And a highly agreement between the peak wavelength of laser and the dip of conventional transmission spectrum provides the application possibility of fiber laser sensing system. Thus, the fiber laser sensing system can be applied in the environment where a long measured distance is required.

In this paper, we present a novel home-made concentric ring core fiber (CRCF) which consists of four concentric rings in the core area. On account of this particular structure, the CRCF can support two dominated propagating mode groups of LP_{01} and LP_{11}. We used the CRCF to fabricate axial micro-strain sensor employing concentric ring core fiber-singlemode fiber- concentric ring core fiber (CRCF-SMF-CRCF) structure. Different from the MSM fiber structure using the interference between many modes in the MMF, this axial micro-strain sensor is based on the interference between few modes in the CRCF. Due to the fact that the CRCF can support few modes, the stable interference is produced so as to get clean transmission spectrum and fiber laser sensing system with good stability, which is convenient to measure the change of lasing peak wavelength. Moreover, the laser sensor with the advantages of

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high intensity, high optical signal to noise ratio (OSNR) and narrow bandwidth has great potential applications in long distance measurement.

2. Characteristics of novel fiber

The important part of sensing head is the home-made few-mode concentric ring core fiber (FM-CRCF) which is fabricated by the modified chemical vapor deposition (MCVD) technique. The photomicrograph of cross-section is illustrated in Fig. 1(a). The diameter of the CRCF is 116 μm. The CRCF consists of concentric ring core area and conventional cladding. The ring core area totally has four concentric rings which can be regarded as four layers. Two high index layers are doped with germanium, and two low index layers are doped with fluorine. As shown in Fig. 1, the vertical ordinate of figure is the difference between the refractive index (RI) of conventional cladding ($n_5 = 1.444$) and the actual RI of core area which is measured by the optical fiber analyzer (EXFO NR9200). However, it is difficult to fabricate the ideal RI distribution in the practical production process. An approximate step-index core is achieved according to the actual RIs. The RIs of Layer 1 and Layer 3 are higher than that of conventional cladding ($n_5 = 1.444$), and are opposite to that of the Layer 2 and Layer 4 ($n_1 = 1.448$, $n_2 = n_4 = 1.441$, $n_3 = 1.450$).

The mode filed distributions and electric vector distributions in the core area of the CRCF can be calculated by the finite element method [17]. As shown in Fig. 2, the fields of the fundamental HE_{11} mode (LP_{01} mode group) and the TE_{01}, HE_{21}, TM_{01} modes (LP_{11} mode group) can propagate in the CRCF at the wavelength of 1550 nm. Consequently, the home made CRCF is dual-mode fiber which supports mode group LP_{01} and high-order mode group LP_{11} at 1550 nm.

The relationship between the wavelength and the effective indices of all modes is shown in Fig. 3. Neglecting polarization degenerate modes of HE_{11}, HE_{21}, HE_{31}, and EH_{11}, it is obvious that mode group LP_{01} which consists of the HE_{11} mode, mode group LP_{11} which consists of the TE_{01}, HE_{21}, TM_{01} modes, and mode group LP_{21} which consists of the EH_{11}, HE_{31} modes are exited and propagate in the CRCF in the wavelength range from 1300 nm to 1800 nm. When the wavelength is higher than 1440 nm, the effective indices of mode group LP_{21} is below the RI of cladding (1.444) leading to the cut-off of this mode group. That is to say, the CRCF can support mode groups of LP_{01} and LP_{11} in the wavelength range

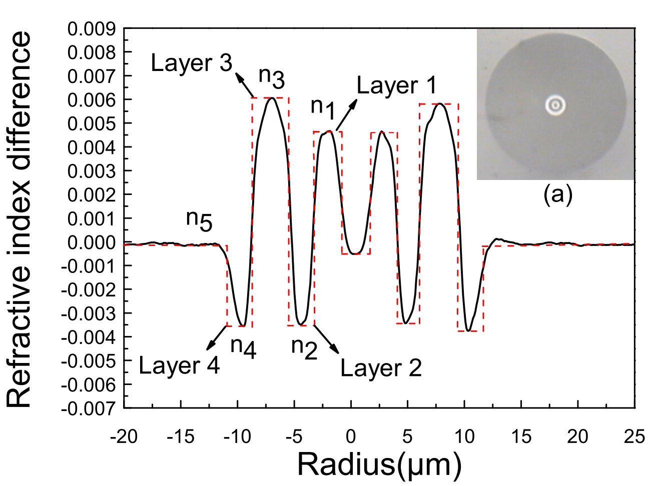

Fig. 1. The actual refractive index of the CRCF (black line) and the approximate step-index of the CRCF (red dash line) (a) The photomicrograph of cross-section of the CRCF. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

from 1440 nm to 1800 nm. Furthermore, the CRCF will show the polarization insensitivity because the maximum effective index separation between TE_{01} and TM_{01} is about 9×10^{-5} which is lower than 10^{-4} [18].

Therefore, the propagation constants, $\beta_{LP_{01}}$ and $\beta_{LP_{11}}$, in given wavelength can be calculated by the effective indices. According to the definition, L_π is the beat length:

$$L_\pi = \frac{\pi}{\beta_{LP_{01}} - \beta_{LP_{11}}} \quad (1)$$

L_π of the CRCF is calculated ~0.97 mm. In order to obtain the maximum interference performance, the length of the CRCF should be fixed to the odd times of half L_π. It is convenient to design the structure and length of sensing head.

3. Sensing principles and experimental laser setup

3.1. Sensing structure and principle of the MI

Fig. 4 shows the schematic diagram of the CRCF-SMF-CRCF (CSC) structure, which is fabricated by splicing a section of SMF (Corning SMF-28) between two same length of the CRCFs with the commercial fusion splicer (Fujikura, FSM-60S). An input SMF and an output SMF are respectively spliced with the ends of CSC structure. The SMF and the CRCFs have no coatings, so that the CSC structure is sensitive to the surrounding environment. When an approximate Gaussian beam is injected from the input SMF to the first section CRCF (lead-in CRCF), two dominated core mode groups (LP_{01} and LP_{11}) and other cladding modes will be excited because of mode field mismatch. As the light transfers into the central SMF, a part of light continues to propagate in the core of SMF and the other part of light is coupled to the cladding of SMF. Then the second section of the CRCF (lead-out CRCF) collects the light in the core mode and cladding modes back to the core area of the CRCF. Due to the different optical paths between core mode and cladding modes which propagate in the central SMF, modes will interfere with each other in the lead-out CRCF. In this CSC structure, the first and second sections of the CRCF act as the mode generator and coupler, respectively.

In general, $\varphi^{(l)}$ is the phase difference between the core mode and the l-th cladding mode, which can be expressed as [19]:

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

where the Δn_{eff} is effective index difference between the core mode and the lth cladding mode in the middle uncoated SMF. L is interference length, and λ is operating wavelength.

Accordingly, the intensity of interference spectrum in the air can be expressed as:

$$I_\lambda = \sum I_{core} + \sum_l I_{clad}^{(l)} + \sum_l 2\sqrt{I_{core} I_{clad}^{(l)}} \cos \varphi^{(l)} \quad (3)$$

where I_{core} and $I_{core}^{(l)}$ are the light intensities of the core mode and the lth cladding mode, respectively.

In order to reach the maximum of intensity, $\varphi^{(l)}$ should be $2N$ times of π. The N is an integer. The peak wavelength should satisfy the following equation [20]:

$$\lambda_N = \frac{2\pi \Delta n_{eff} L}{2N\pi} = \frac{\Delta n_{eff} L}{N} \quad (4)$$

when the mth mode and the nth mode interfere with each other in the lead-out CRCF, the phase difference is determined by the length of SMF and the longitudinal propagation constants of guided modes, which can be expressed as [21]: