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Low coherence technique to interrogate optical sensors based on selectively filled double-core photonic crystal fiber for temperature measurement

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ABSTRACT

In this paper, an optical fiber sensing system based on low coherence interferometry (LCI) is proposed and demonstrated to interrogate sensors comprised of selectively filled double-core photonic crystal fiber (SFDC-PCF). The sensor used here is made by selectively filling about 1/3 area of air holes in the cladding of photonic crystal fiber with distilled water. *So the dual-core in the sensor has different effective refractive indices, resulting in a phase delay between two lights transmitting in the fiber*. The phase delay of the sensor can be compensated by a Mach-Zehnder interferometer with a scanning optical tunable delay line in one arm of the interferometer, namely temporal interrogation. By tracking the value of phase delay, the change of the measurand can be detected. Temperature measurement is carried out to testify the system performance. An average sensitivity of 0.9 μm/°C is achieved within the temperature range of 29–92 °C. This work provides a new thinking for fiber sensing technology based on LCI. The proposed all-fiber sensing system, with the merits of cost-effective, stability, and flexibility, can demodulate the SFDC-PCF sensor signals well. Further improvements such as better sensitivity, larger measurement range and multiplexing efficiency can be realized by tailoring the PCF sensor's structure.

1. Introduction

Recent years, photonic crystal fibers (PCF) have attracted much research interest in many fields, such as optical fiber sensors, optofluidics, and optical fiber lasers. PCF is generally formed by pure silica with a core surrounded by a periodic lattice of air-holes running along its propagation axis. The air-silica structure of cladding exhibits lower effective refractive index than that of silica-core, which makes the confinement of light possible. The other type of PCF is called photonic bandgap-guiding fiber. Propagation in such fibers relies on the coherent reflection of light in a microstructured periodic cladding surrounding the core. Because the light does not propagate due to total internal reflection, the core index can be lower than that of the surrounding cladding. The optical properties of PCFs are strongly decided by the cross-section geometry of photonic crystal fiber, so it is available for tailoring them by adjusting the PCFs' cross-section structure [1,2]. The technique of selectively filling liquid or gas into air holes of PCF, as a direct and effect method, is widely applied in functional device integration. By generating designated photonic crystal structure, the PCF can act as optical fiber sensors for temperature [3–5], refractive index [6], electric field intensity [7]; filter [8]; optofluidics [9]; wavelength conversion devices [10]; semiconductor-fiber hybrid devices [11,12]. However, most PCF sensors are demodulated in wavelength domain by expensive equipment like an optical spectrum analyzer. Few works have been reported on the sensing signal demodulation of those PCF sensors.

Low coherence interferometry (LCI) can be formed by a variety of classical interferometers, such as Michelson interferometers, Mach-Zehnder interferometers, Fabry-Perot interferometers, for capturing and tracking optical signals with the advantages of high accuracy, real time and quick response. By a temporal scan of the phase delay in one arm of the demodulation interferometer, the phase delay introduced by sensors can be compensated and the interferogram can be obtained. Most importantly, low coherence interferometry can multiplex many sensors into one fiber string without requiring any other complex time or frequency demodulation system. Plenty of investigations have been carried out for sensing applications of temperature and strain [13], fiber optical vibrometer [14], fiber gratings [15] and other devices under test [16,17] based on this cost-effective technique. However, the interferometers based on spatial light have a strong dependence on the stable environment and the experimental performance is vulnerable to disturbance of circumstance. In addition, the fixed setup lacks enough flexibility for practical engineering applications. The all-fiber interferometers based sensing system can improve the stability and

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flexibility quite well, which overcomes the drawbacks of traditional LCI system with good performance.

In this paper, a selectively filled double-core photonic crystal fiber (SFDC-PCF) sensor is designed and fabricated as self-interfering fiber sensors. Fiber modes of the SFDC-PCF and its optical characteristics for temperature are theoretically investigated by finite element method (FEM). By reference to the reported techniques [11,18,19], the manual processing [20] is exploited to produce the SFDC-PCF sensor due to its simplicity. An optical fiber sensing system based on LCI technique is demonstrated for demodulation of the sensing signal from the SFDC-PCF sensor. Temperature measurement is carried out to testify the performance of sensing system. The experimental results agree with the theoretical simulation. In the end, the potential solutions for further improvement are discussed.

2. Principle

2.1. Fiber modes in SFDC-PCF

The PCF we used here is a solid double-core fiber designed for operation at 1550 nm, as shown in Fig. 1(a). The core and cladding diameters of the double-core PCF are 3.8 μm and 125 μm, respectively. The diameter of air hole is 2.2 μm and the pitch Λ is 3.5 μm. *About 1/3 area of air-holes in cladding are selectively filled with distilled water in our experiment, because the structure of this SFDC-PCF can provide enough phase delay and meanwhile avoid excessive loss caused by light absorption of distilled water*. Fig. 1(b) shows the end face of the PCF after the process of selective filling. The filled area is brighter than the unfilled area. The fundamental modes of each core are simulated with different material indices in. The effective refractive index of the fundamental mode in one core is 1.435667 (near the air-holes filled with distilled water and described as slow core) as shown in Fig. 1(c). And the effective refractive index of the fundamental mode in the other core is 1.433544 (described as fast core) as shown in Fig. 1(d).

2.2. Low coherence interferometry

The sensing system is simply formed by connecting the fabricated SFDC-PCF sensor with a Mach-Zehnder interferometer, as shown in Fig. 2. Input light is coupled into the SFDC-PCF, and propagates through fast core and slow core respectively. *After the two beams are coupled back to single-mode fiber (SMF), the phase delay between two beams can be expressed:*

$$\Delta t = \frac{L}{\frac{c}{n_{eff}^{s-c}}} - \frac{L}{\frac{c}{n_{eff}^{f-c}}} = \frac{L}{c}(n_{eff}^{s-c} - n_{eff}^{f-c}) = \frac{\delta_1}{c} \tag{1}$$

where L is the length of the SFDC-PCF; n_{eff}^{s-c}, n_{eff}^{f-c} are the effective refractive indices of slow core and fast core respectively; c is the speed of light in the vacuum and δ_1 is the optical path difference (OPD) introduced by the SFDC-PCF sensor.

The electric components of the light in the fast core and slow core can be expressed as follows [21,22],

$$E_{f-c}(\omega t, \varphi) = A_{f-c}(\omega t)\exp(i\varphi)$$
$$E_{s-c}(\omega t, \varphi) = A_{s-c}(\omega t)\exp[i(\varphi + k\delta_1)] \tag{2}$$

where A is the electric amplitude, φ is the phase angle, k is the propagation constant. After the two beams are coupled into the

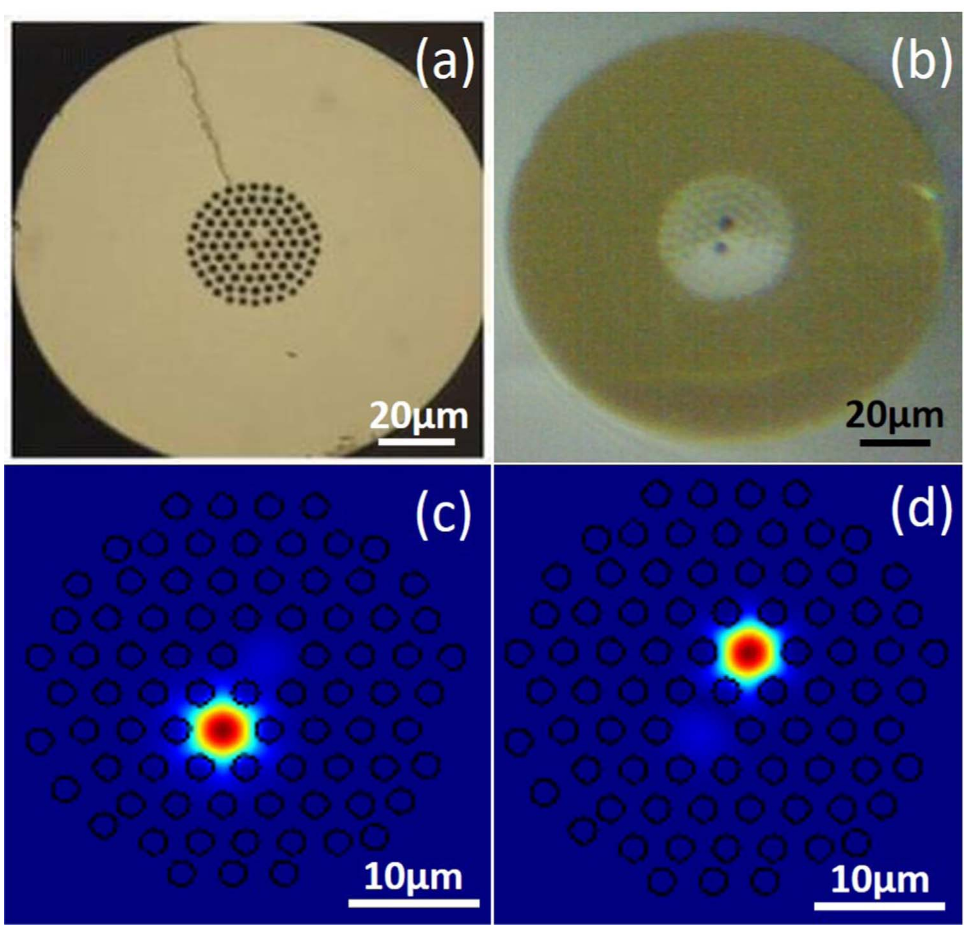

Fig. 1. (a) Cross-section of the double-core PCF (b) Microscope picture of PCF with distilled water filled in (c) The fundamental mode of slow core with the effect refractive index of 1.435667 (d) The fundamental mode of fast core with the effect refractive index of 1.433544.

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