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Enhanced sensitivity of temperature sensor by a PCF with a defect core based on Sagnac interferometer

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A B S T R A C T

We propose a high-sensitivity temperature sensor based on Sagnac interferometer with a PCF. The diameter of the central hole of the PCF is decreased to form defect core which supports fiber mode. All the air holes are injected with liquid which is sensitive to temperature. The simulation result demonstrates that the birefringence of the PCF is low. The loss, the overlap between fiber mode and the liquid in the central hole increases as the wavelength increases. The sensitivity has a great relation with group birefringence Bg. Therefore, we analyze the influences of the structural parameters d_1, d_2, d_3 and the RI of the liquid on the group birefringence Bg. By adjusting the corresponding parameters, we can change the wavelength of zero-point group birefringence Bg. The high sensitivity can be obtained near the special wavelength. The sensitivities can reach to 79.2 nm/°C and −69.9 nm/°C as the temperature is 23 °C. The average sensitivities are 26.4 nm/°C, −17.9 nm/°C as the temperature changes from 27 °C to 35 °C, and the linear fitting degrees are 0.99489 and 0.98832. The RI sensitivity is also studied as RI changes from 1.404 to 1.409. The average sensitivities are 43,400 nm/RIU and −73,743 nm/RIU respectively. The high sensitivities are 77,000 nm/RIU and −106,000 nm/RIU as the RI of the liquid is 1.409.

1. Introduction

Photonic crystal fibers (PCFs) can be filled with a variety of functional materials due to its porous structure and have attracted our interests in recent years. The properties of the PCF can be extended by filling different materials. Many sensors based on PCF with sensitive materials have been proposed and demonstrated, such as gas sensor [1], humidity sensor [2], electric field sensor [3], magnetic field sensor [4] and temperature sensor [5]. Temperature sensor is the first developed and the most widely used sensor. The market share of the temperature sensor is much more than the other sensors. Optical fiber temperature sensor is mainly used in the fields of electric power system, building area, chemical industry, aerospace field, medical system and marine development, and has made a lot of reliable applications. The measurement and control of the temperature are very significant to ensure product quality, improve production efficiency, save energy, guarantee production safety, and promote the development of the national economy. The sensitivity, measurement range and resolution have been greatly developed. But according to the specific application, we need more and more sensors with high precision, simple structure, low cost and more practical scheme to be proposed.

Xu [6] demonstrated the influence of the distance between the silica core and glycerin core on the temperature sensitivity. The results showed that the highest sensitivity could reach to −3.06 nm/°C as the glycerin core is the nearest to the silica core. Hu [7] studied a temperature sensor by filling the liquid crystal into one air hole of the PCF, and the sensitivity could reach to −3.9 nm/°C based on directional coupler. Liang [8] designed a Mach-Zehnder interferometer by selectively filling liquid into one air hole of the PCF for temperature sensor with sensitivity of 16.49 nm/°C. Bozolan [9] proposed a fiber temperature sensor based on colloidal quantum dot luminescence and the sensitivity was 70 pm/°C. A temperature sensor by the bandgap-like effect in a PCF was realized, the first ring holes around the core were filled with liquid possessing high refractive index and the sensitivity was as high as −5.5 nm/°C [10]. We designed a temperature sensor based on PCF, the central hole was coated with nanoscale gold film and filled with temperature sensitive liquid, the six holes in the second layer were removed to act as fiber cores, as the phase matching conditions were satisfied the core mode coupled to plasma mode and the sensitivity was −2.15 nm/°C [11]. We also simulated a temperature sensor by coupling between core mode and defect mode with sensitivity of

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−1.95 nm/°C [12]. But we think the sensitivities of the above PCF temperature sensors were not enough high.

The fiber sensors based on Sagnac interferometer have many unique characteristics and have attracted our interests in recent years. Qian [13] proposed a temperature sensor based on Sagnac interferometer by filling alcohol into PCF and the sensitivity was 6.6 nm/°C. Wu [14] studied a Sagnac interferometer including a ethanol-filled PCF with the sensitivity of 0.8833 nm/°C. Zhao [15] demonstrated the sensing characteristics of a PCF which was not full-filled with alcohol based on Sagnac interferometer and the sensitivity was −1.17 nm/°C. Zheng [16] showed the temperature sensing characteristics of a selectively liquid-filled photonic bandgap fiber based on Sagnac interferometer with sensitivity of −0.4 nm/°C. We [17] studied a fiber Sagnac interferometer based on a fluid-filled PCF for temperature sensor with average sensitivity of −7.54 nm/°C, the air holes of the PCF were arranged in a square lattice and the central air hole was removed to support fiber fundamental mode.

In this paper, a high-sensitivity temperature sensor based on Sagnac interferometer including a PCF injected with liquid is proposed. We design a small hole in the fiber core to form defect core. By this way, the sensitivity can be enhanced. The influences of diameters d_1, d_2, d_3 and the RI (refractive index) of the liquid on the group birefringence Bg are analyzed. The sensitivities are up to 79.2 nm/°C and −69.9 nm/°C as the temperature is 23 °C. The average sensitivities are 26.4 nm/°C, −17.9 nm/°C better than [6,17] as the temperature changes from 27 °C to 35 °C. We also calculate the RI sensitivity as the RI changes from 1.404 to 1.409 and the average sensitivities are 43,400 nm/RIU (refractive index unit) and −73,743 nm/RIU respectively. The high sensitivities are 77,000 nm/RIU and −106,000 nm/RIU as the RI is 1.409. The detected RI range is narrow due to the high sensitivity.

2. Geometry and theory

The cross section of the structure of the PCF is shown in Fig. 1. The air holes are arranged in triangular lattice and the lattice pitch is 4 μm. The diameters of the white holes are d_1. The diameters of the blue holes are represented by d_2. The central red hole is decreased to form fiber core which supports defect mode and it is denoted by d_3. The background material of the PCF is fused silica whose dispersion coefficient could be calculated by the Sellmeier equation [18]

$$n^2(\lambda, T) = (1.31552 + 6.90754 \times 10^{-6}T) + \frac{(0.788404 + 23.5835 \times 10^{-6}T)\lambda^2}{\lambda^2 - (0.0110199 + 0.584758 \times 10^{-6}T)} + \frac{(0.91316 + 0.548368 \times 10^{-6}T)\lambda^2}{\lambda^2 - 100} \tag{1}$$

where the units of the wavelength λ and the temperature T are micron and Celsius, respectively. All the air holes are assumed to be filled with temperature sensitive liquid of which the refractive index is 1.37 at the room temperature 25 °C. And the sensitive coefficient is −0.0004/°C. The relation between refractive index and

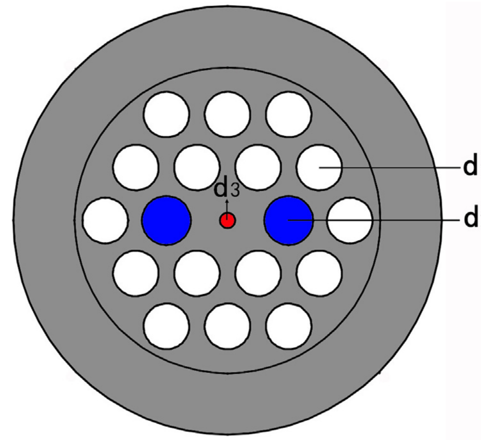

Fig. 1. The structure of the proposed PCF. The air holes are arranged in triangular lattice. The diameter of the central air hole is decreased to form fiber core which supports defect mode. All the air holes are assumed to be filled with temperature sensitive liquid. (For interpretation of the references to color in the text, the reader is referred to the web version of the article.)

temperature can be expressed as $n = 1.37 - 4 \times 10^{-4}(T - 25)$. The liquid of alcohol is used in this paper and the index-matching liquid also can be produced by Cargille Laboratories Inc. [8]. The dispersion relation of the liquid is not considered in this paper. The fabrication techniques for the PCF perform include ultrasonic drilling, cast rod in tube, extrusion, stacking and so on. The technology is very mature, and we think the structure of the PCF could be drawn. If we want to fill all the air holes of the PCF with liquid, we can dip the fiber end into the liquid, and the other end stays in the air, then the liquid slowly flows into the fiber due to the capillary force.

The finite element method (FEM) is used to simulate the optical characteristics of the PCF. Perfect matching layer and scattering boundary condition are set. The calculation area is divided into 3274 triangular regions as d_1 is 3 μm, d_2 is 3.2 μm, d_3 is 1 μm and the temperature is 25 °C. The mode field distributions of x-polarized and y-polarized mode as the wavelengths are 0.8 μm (a, b), 1.2 μm (c, d), 1.6 μm (e, f) and 2.0 μm (g, h) shown in Fig. 2. The arrow direction represents the polarized direction of the mode. We find the energy of the mode begins to spread into the cladding region slightly for the x-polarized and y-polarized mode as the wavelength increases. The corresponding refractive index and loss dependence on the operable wavelength λ are shown in Fig. 3. It can be seen that the refractive index decreases as the wavelength increases. And the loss, the overlap between fiber mode and liquid in the central hole increase with the wavelength increasing. The loss has little influence on the spectrum due to the short length of the fiber. The straight lines and curve lines between the x-polarized and y-polarized mode are almost overlapping respectively. It also illustrates that the birefringence effect is not enough obvious. The illustration shows the three dimensional surface plots.

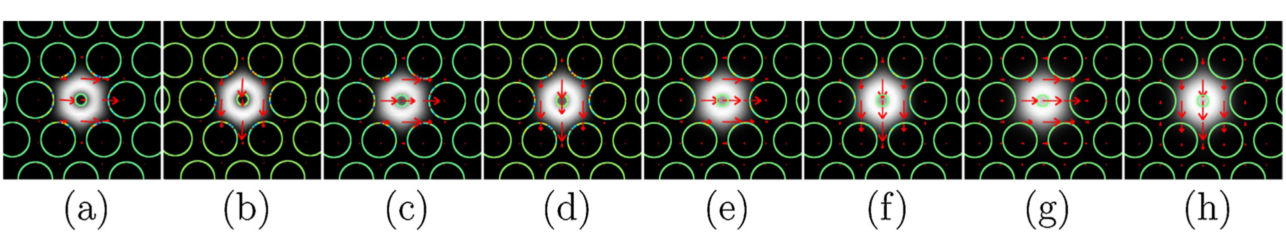

Fig. 2. The mode field distributions of x-polarized and y-polarized mode as the wavelengths are 0.8 μm (a, b), 1.2 μm (c, d), 1.6 μm (e, f) and 2.0 μm (g, h). The arrow direction represents the polarized direction of the mode. It can be seen that the energy of the mode begins to spread into the cladding region slightly as the wavelength increases.