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Highly sensitive plasmonics temperature sensor based on photonic crystal fiber with a liquid core

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ABSTRACT

An ultra-high sensitivity temperature sensor based on photonic crystal fiber (PCF) is proposed and demonstrated. The central hole and the two holes coated with nanoscale gold film are assumed to be filled with temperature sensitive liquid. The refractive index of the liquid decreases as the temperature increases with the temperature sensitive coefficient of -3.9 × 10^{-4}/°C. The liquid of the central hole with high refractive index supports liquid-core mode. As the phase matching condition is satisfied, the liquid-core mode couples to the surface plasmon polariton mode and presents energy loss. The influences of the PCF structural parameters and the thickness of the gold film on the resonance wavelength, loss value and sensitivity are studied. The resonance wavelength and confinement loss increase as the temperature increases. The average sensitivity can reach to 9.89 nm/°C (∼25359 nm/RIU) as the temperature changes from 35 °C to 45 °C and the R-square is 0.99992. By replacing the liquid core by silica core, we find the sensitivity is very low. We also compare the PCF without liquid in the holes coated with gold film by our structure and find that the sensitivity is nearly unchanged and the confinement loss is slightly decreased.

1. Introduction

Photonic crystal fiber (PCF) [1] is a kind of special optical fiber which has various air holes on its cross section and the air holes extend along the fiber. Compared with ordinary optical fiber, PCF has many distinctive characteristics due to the flexible structure design. The PCF is mainly divided into two types, one is refractive index guided type and the other is band-gap type. In recent years, people have increased the function of this fiber by combining functional materials with the special fiber. Yang [2] proposed a PCF methane sensor by coating the cryptophane A on the walls of the air hole. The refractive index of the cryptophane A decreases as the methane concentration increases. A relative humidity sensor is proposed and demonstrated by filling the agarose gel between the PCF and single mode fiber and the refractive index of agarose gel is tunable by changing the relative humidity [3]. The material of magnetic fluid is sensitive to magnetic field and its refractive index increases as the magnetic field increases [4]. We studied a magnetic field sensor by filling magnetic fluid in the air holes of PCF and the average sensitivity can reach to −430 pm/Oe [5]. Lu [6] demonstrated a refractive index sensor by coating the graphene–Ag layers on the hole walls of the PCF selectively. As the phase matching condition is satisfied, the fiber guided mode couples to the plasma mode.

Surface plasmon is the result of the interaction of free electrons on the metal surface with the input photoelectric magnetic wave. The surface plasmon polariton (SPP) mode propagates on the surface of the metal which is filled or coated on the air hole of the PCF. As the phase matching condition is satisfied, the resonance between fiber guided mode and SPP mode occurs and the fiber mode couples to the SPP mode. And the fiber guided light will appear a maximum loss at the certain wavelength position. Since surface plasmon polaritons are sensitive to the surrounding environment and their transmission constants can be easily changed, surface plasmon resonance sensors have many applications. Homola [7] proposed a surface plasmon resonance biosensor to detect staphylococcal enterotoxin B in milk and it was shown that the biosensor could detect the concentrations of staphylococcal enterotoxin B in buffer as low as 5 ng/ml. Koubova [8] demonstrated a sensor to detect foodborne pathogens based on surface plasmon resonance. The biosensor was capable to detect salmonella and listeria at the concentration down to 10^6 cell/ml. Nooke [9] studied a hazardous gas sensor based on surface plasmon resonance by gold

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layer. Several gases and mixture gases were detect due to that the corresponding gases are flammability, toxicity or greenhouse effect. A surface plasmon resonance sensor was designed based on single-mode polarization-maintaining optical fiber and the result showed that the refractive index detecting limit could reach to 4×10^{-6} [10]. Gauvreau [11] demonstrated a PCF sensor based on surface plasmon resonance. The liquid analyte with low refractive index was detected and the sensitivity could up to 13 750 nm/RIU.

With the development of research, the hole filling technology of the PCF is becoming more and more mature. Selective deposition of metal film in the pores of PCF has been realized by Zhang [12]. The silicon glue was used to plug the air holes of the neck-down region of the fiber preform, these air holes' size is about several millimeters which makes it easy to plug. The fiber end of the neck-down was inserted into a syringe which allows the reaction mixture flow into the unblocked holes of the PCF. Wang [13] realized the selective filling of the PCF by femtosecond laser. The PCF was fused with single-mode fiber firstly and the single-mode fiber was cleaved by the femtosecond laser. Then, the selective laser drilling was operated on the surface of the single-mode fiber which connected with PCF. Finally, the fiber end was inserted into the liquid. Huang [14] filled the big air hole of the PCF by the injection–cure–cleave method using UV curable polymer. The filling method depends on that the flowing speed is different by the different sizes of the air holes. Xiao [15] proposed a method to selective filling the central air hole of the PCF. The central hole maintained open and the cladding holes collapsed by controlling the parameters of the fusion splicer. The gold wire was filled into one air hole by the PCF postprocessing before pumping molten metal [16]. One certain air hole kept open and the other air holes were blocked, then the blocked hole collapsed and the open hole was enlarged through heating by a flame. The open hole could be pumped molten metal by proper pressure. Hence, filling materials into the air holes of our designed PCF structure is easy.

Temperature sensors based on fiber combined with metal can be used in many fields and attract people's attention. Hameed [17] designed a temperature sensor by the liquid-crystal-core PCF based on surface plasmon resonance. The influences of the number, diameter of the metal rod and the diameter of the liquid-crystal core on the sensitivity were discussed. The sensitivity could reach to 10 nm/°C based on the optimized structure. Peng [18] studied a plasmonics temperature sensor based on PCF. The air holes in the second layer of the PCF were filled with temperature-sensitive liquid and the air holes were coated with metal film selectively. The sensitivity of the temperature sensor was 720 pm/°C. Yang [19] demonstrated the sensing characteristics of a PCF filled with Ag nanowire on experiment and the sensitivity was up to −2.08 nm/°C. Luan [20] realized a refractive index and temperature sensor based on surface plasmon resonance in an exposed-core PCF and the sensitivity could reach to 6.18 nm/°C. We also designed a temperature sensor based on PCF [21]. The temperature-sensitive material was filled into the central hole which coated with nanoscale gold film. The six air holes in the second layer were removed to act as fiber core. The average sensitivity was −2.15 nm/°C as the temperature changed from 20 °C to 80 °C.

In this paper, we propose a high-sensitivity PCF temperature sensor based on surface plasmon resonance. The innovation point of this paper is that we introduce a liquid core in the central hole. By this way, the sensitivity can be enhanced to a great extent and it can reach to 9.89 nm/°C better than [18–21] as the temperature changes from 35 °C to 45 °C. As we replace the liquid core by a solid core, the sensitivity becomes very low. The influences of the diameters d_1, d_2, d_3 , the fiber length L and the thickness of the gold film on the resonance wavelength, loss value and sensitivity are analyzed.

2. Geometry and principle

Fig. 1 shows the cross section of our proposed PCF. The distribution of the air holes is in triangular lattice with the lattice pitch of 2.0 μm.

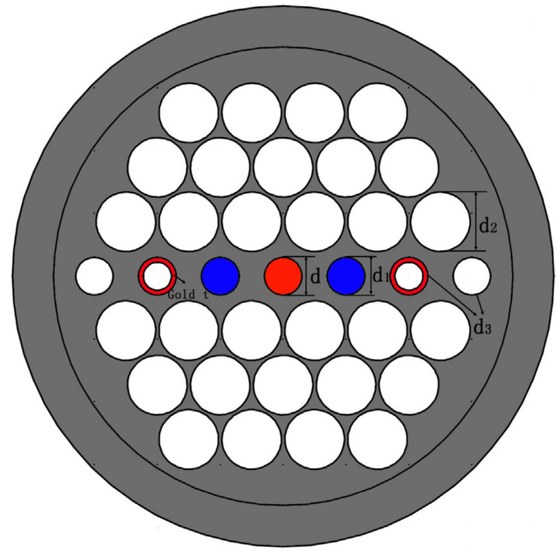

Fig. 1. The cross section of the proposed PCF. The central hole is assumed to be filled with temperature-sensitive liquid to enhance sensitivity. The red regions represent gold layer. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The diameter of the pink air hole is d and it is assumed to be filled with temperature-sensitive liquid to enhance sensitivity. The refractive index of the temperature-sensitive liquid is 1.4501 as the temperature is 35 °C and the temperature-sensitive coefficient is -3.9×10^{-4} [22]. The diameters of the blue holes are represented by d_1. The big air holes in the top and bottom area are denoted by d_2. And the diameters of the other air holes are d_3. The red region represents gold layer and its thickness is t. The structural parameters of d, d_1, d_2 and t on the influences of the resonance wavelength, loss value and sensitivity are analyzed. The dielectric constant of the gold is described in [23] in detail. We do not consider the temperature characteristics of the gold which can be ignored compared with temperature-sensitive liquid. The blue holes separate liquid core and gold layer and the two air holes coated with gold layer are also assumed to be filled with temperature-sensitive liquid. The background material of the PCF is fused silica and its dispersion coefficient can be analyzed by the Sellmeier equation [24]

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

where the units of wavelength λ and temperature T are micron and Celsius.

The central hole of the PCF is filled by temperature sensitive liquid with high refractive index which supports fiber fundamental mode. Surface plasmon polaritons can form on the surface of gold when they are stimulated by light. As the phase matching condition is satisfied, the energy of the liquid-core mode will couple to SPP mode. There will be a loss peak in the output spectrum for the fiber mode. Fig. 2 shows the mode field distributions of the fiber fundamental mode (a), SPP mode (b) and the coupling mode between fiber mode and SPP mode (c). And the modes in y-polarized direction are considered in this paper. The coupling happens between fiber mode and the first order SPP mode in our considerable wavelength range. A part of energy transfers from fiber mode to SPP mode which is shown in Fig. 2(c). The coupling styles include complete coupling and incomplete coupling which are analyzed in detail in [25]. The schematic diagram of the sensing system is shown in Fig. 3. The main instruments include broadband light source (BBS),