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Polarization-insensitive temperature sensor based on liquid filled photonic crystal fiber

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ABSTRACT

In this paper, a polarization-insensitive temperature sensor based on photonic crystal fiber is proposed. Using finite element method, coupling between core and defected clad is analyzed. A high refractive index temperature sensitive liquid is infiltrated into the air holes of the second cladding ring. Numerical simulation shows as the phase matching between core and defect-clad super modes satisfied, resonance and peak confinement loss happen. A blue shift in resonance wavelength is obtained when temperature increases. Excellent linearity, simplicity and symmetrical structure, FOM of −0.272/°C and especially the same sensitivity of −1.96 nm/°C for both X and Y polarizations make the peak loss wavelength more detectable.

1. Introduction

Photonic crystal fibers (PCFs) [1,2] have been widely used in accurate sensing of physical phenomena such as strain [3], refractive index [4,5], biological events [6], pressure [7], temperature, and so on. These sensors have unique advantages such as high sensitivity, good physical stability, immunity to electromagnetic wave, corrosion resistance, and great design flexibility compared with conventional fiber [8].

PCF temperature sensors with different structures and principles which are mostly based on the coupling or interfering between two guided modes have been widely studied in recent years. The operation phenomena relies on energy transfer between two modes. The phase matching and coupling condition of the guided modes has to be satisfied [9]. Fabry-Perot interferometric temperature sensors were proposed by Hu et al. [10] which are formed by just splicing a section of PCF with a single-mode fiber (SMF) showing the low response of 11.12 pm/°C (30–80 °C). Fiber Bragg grating (FBG) temperature sensors [11] have a very sharp reflection peak, but low sensitivity of −19.6 pm/°C.

Functionality of PCF temperature sensors can be improved using core doping, metal coating, infiltrations such as polymer and liquid into the air holes. PCF interferometer sensors with germanium doped fiber core [12] have a wide temperature range (0–500 °C) however they have low sensitivity of 78 pm/°C. Mach–Zehnder interferometer using a selectively polymer-filled two-core photonic crystal fiber, leads to a large thermo-optic mismatch between two cores and sensitivity of 1.595 nm/°C can be achieved [13]. Liquid or high refractive index liquid crystals (LCs) such as ethanol [14], chloroform, and nematic liquid crystals (NLCs) are good infiltration candidate due to their large thermo-optic coefficient and tuneability [15]. LC filled PCF temperature sensors [16–18] have different polarization sensitivities (1.7, 2.82 and 3.86 nm/°C for X polarization and 2.0, 1.99 and 5.5 nm/°C for Y polarization respectively). NLC filled PCF temperature sensors reported by Hu et al. [19] achieved

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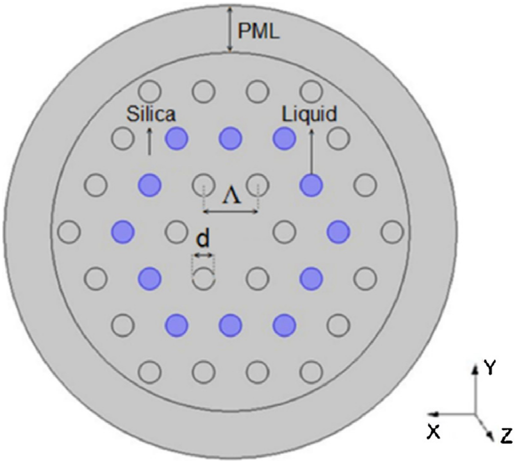

Fig. 1. Cross section of the PCF temperature sensor in XY plane.

good response of 3.90 nm/°C but the temperature detecting window was just 9/°C. PCF temperature sensor based on surface plasmon resonance coated with metal-sensitivity material such as gold [20] or filled with liquid and silver nanowire [21–23] have the different polarization sensitivity as well.

In this paper, at first a PCF temperature sensor will be designed based on complete coupling between core and defect-clad super modes. A large thermo-optic coefficient LC is supposed to be injected into the second cladding air hole ring of PCF. Then the sensor will be analyzed theoretically using the finite element method (FEM). Simulation results show that as the phase matching condition between core and defect-clad super modes is satisfied, resonance is obtained and the power in the transferring core couples to the defect core and the confinement losses increase remarkably. The sensitivity of both X and Y polarizations is −1.96 nm/°C and because the peak resonance for both X and Y polarizations happen approximately at the same wavelength, this sensor is very suitable for detecting the peak confinement loss. The proposed temperature sensor, shows excellent linearity, high figure of merit (FOM = −0.272/°C) with the temperature detecting window between 20 °C and 80 °C. The results shows a better performance compared with some similar proposed sensors. At the rest, the influence of changing some geometrical parameter such as the first ring cladding air hole size on the sensor functionality will be discussed.

2. Structure designed and simulation method

The cross section of the designed PCF temperature sensor in XY plane is shown in Fig. 1. The air holes are arranged in a triangular lattice. The pitch and the diameters of all air holes are $\Lambda = 4\,\mu m$ and $d = 1.6\,\mu m$ respectively.

The background material of the fiber is fused silica whose dispersion relationship corresponding to temperature is calculated by Sellmeier equation [24]:

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

where T is the temperature in Celsius, and λ is the free space wavelength in microns. A temperature sensitive liquid [16] with the refractive index of 1.65 at room temperature (25 °C) supposed to be filled into the air holes of the second cladding ring by capillary effect [8]. The refractive index of liquid between 20 °C and 80 °C can be expressed by:

$$n_{liq} = 1.65 - 4.65 \times 10^{-4}(T - 25) \quad (2)$$

where -4.65×10^{-4}/°C is the thermo-optic coefficient of liquid and T is the temperature in Celsius. The refractive index profile of silica and liquid as a function of temperature are shown in Fig. 2.

To investigate the influence of temperature on the PCF temperature sensor, the modal analysis in XY plane (while light propagation is along Z direction) was performed using Comsol Multiphysics software for different temperatures (20, 35, 50, 65, and 80 °C). To reduce the boundary reflections, anisotropic perfectly matched layers (PMLs) with absorbing boundary conditions are employed. The whole section of the sensor is divided into 10,520 triangular mesh elements. In order to determine the operating temperature, the real part of effective refractive index curve of core super mode and liquid-clad super mode as well as peak confinement loss when resonance between core and liquid-clad super mode happens will be extracted.