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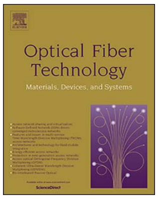

Regular Articles

# Polarization-dependent transverse-stress sensing characters of the gold-coated and liquid crystal filled photonic crystal fiber based on Surface Plasmon Resonance

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ABSTRACT

A transverse-stress sensor with enhanced sensitivity based on nematic liquid crystal (NLC) filled photonic crystal fiber (PCF) is proposed and analyzed by using the finite element method (FEM). The central hole of the PCF is infiltrated with NLC material with an adjustable rotation angle to achieve the polarization-dependent wavelength-selective sensing. And the combined use of side-hole structure and Surface Plasmon Resonance (SPR) technology enhanced the transverse-stress sensitivity enormously. Results reveal that the sensor can achieve a high sensitivity based on the polarization filter characteristic at special wavelengths. Besides that, the temperature and the transverse-stress in either direction can be effectively discriminated through dual-parameter demodulation method by adjusting the rotation angle of the NLC to introduce a new degree of freedom for sensing.

## 1. Introduction

Photonic crystal fibers (PCFs) [1] consisting of pure silica with an array of air holes in the cladding region have attracted the interest of many researchers all over the world. Due to its particular optical properties as compared with conventional fibers, PCF has been an excellent candidate for fiber sensing [2–4]. With the improvement of fabrication technology, PCF-based sensors have been widely used in various aspects of strain or temperature monitoring due to their inherent characteristics [5,6]. However, many studies on the strain sensing are focused on longitudinal component but difficult to measure the transverse component directly. Different indirect ways are proposed to detect the transverse-stress, such as analyzing the influence of transverse-stress on the birefringence [7] or the phase-shift [8] for different optical modes. As an on-going problem, the transverse-stress sensitivity is rather small [9,10]. Side-holes were introduced to PCF-based sensors to enhance the spectral response to the transverse-stress, and higher sensitivity can be achieved by enlarging the side-holes or narrowing their distance to the core [11,12].

In view of the above, a PCF-based sensor with high sensitivity is proposed by introducing four ultra-large side-holes into the cladding layer. The combination use of SPR technology and side-hole structure would bring new vitality to the transverse-stress measurement. The new structural design can improve the device performance with a compact design and easy fabrication process. In fact, the deformations of selective coated air-holes have profound effects on the imaginary part of effective refractive index [13,14]. The loss spectra would be much different when transverse-stress are applied in different directions. In order to detect the transverse-stress in either direction, the applied stress should be divided into two orthogonal components which would cause different peak-shifts at different wavelengths. Moreover, in order to reduce the temperature-induced problem and bending effect, the fiber core is infiltrated with a NLC of type E7. The rotation angle of the NLC can be manipulated by adjusting external electric-field, and this feature can be used for polarization filtering. Based on the polarization filtering ability [15,16], the loss peaks for different polarization states can be set at different wavelength only through adjusting the gold-coated air-holes. The proposed sensor intends to detect the transverse-stress, temperature and curvature based on the refractory index modulation of the NLC material.

Most notably, the infiltration of the NLC can separate two different wavelengths with compact length and large bandwidths for both $x$- and $y$-polarized modes. The polarization-dependent filtering ability to special wavelengths provides a straightforward way to realize the high-sensitivity detection of transverse-stress. And the transverse-stress sensitivity can reach as high as $-6.1$ nm/N in $x$-direction and 4.7 nm/N in $y$-direction, respectively. Additionally, the infiltration of the cladding air holes by the NLC has been experimentally performed by using

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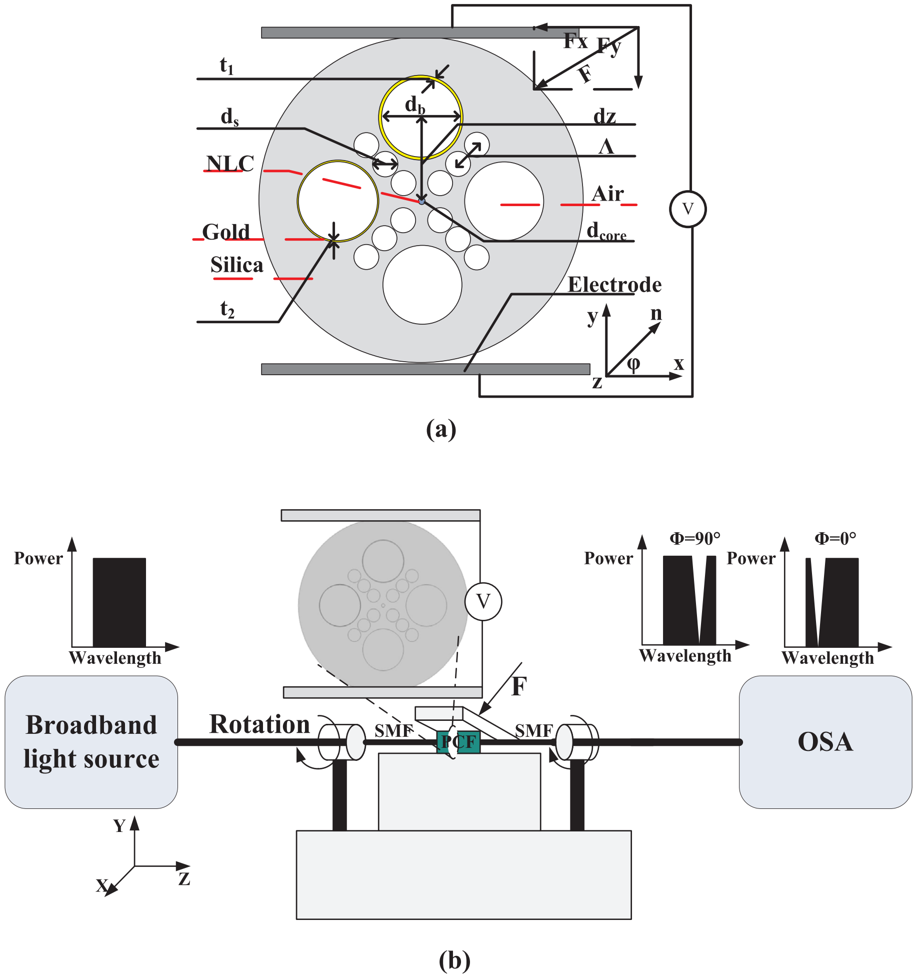

**Fig. 1.** (a) The schematic and cross section of the PCF sensor and (b) the experimental setup for transverse-stress measurement.

capillary forces [17]. The manufacturing procedure to form a coating on the inner surface of the selected air-holes has already been described previously [18], and the process will become easier when the air-holes get larger. The study will play an important role in the fields of polarization-dependent wavelength-selective applications and other PCF-based sensing devices.

## 2. Model and method

The theoretical model is established based on the finite element method (FEM), and the perfectly matched layers (PML) boundary condition [19] is chosen to calculate the effective indices of the electromagnetic mode in a complex domain. The cross-section of proposed PCF-based sensor is shown in Fig. 1(a). As is shown, the smaller air-holes are arranged along the angle of 45 degree and 135 degree, and four large-diameter air-holes distributed vertically and horizontally. The fiber core is infiltrated with NLC of type E7. The fiber is placed between two electrodes and the NLC director's orientation can be controlled by applying an external static electric field [17]. The gold layer is coated in the inner surfaces of the left and top ultra-large air-holes, respectively. Meanwhile, an effective experimental setup is designed for the transverse-stress measurement which is shown in Fig. 1(b). The sensor is configured by using two segments of SMF which are fixed at two graduated rotational fiber holders. The distance between the two electrodes is controlled using two silica rods. The PCF-based sensor is laid between a solid block (down) and a glass plate (top). Then, the device can be used to adjust the applied force directions. The transmission spectra could be analyzed by the use of ASE source and optical spectrum analyzer (OSA).

The background material is pure silica, and the material dispersion is determined by the Sellmeier equation [20] which can be seen from Eq. (1). The dielectric constant of gold layer [21] is described as Eq. (2), where $\varepsilon_{Au}$ is the permittivity of the metal, $\varepsilon_\infty$ is the permittivity in infinite frequency, $\omega_p$ and $\omega_z$ are the plasma frequency and collision frequency.

$$n^2 = 1 + \frac{0.6961663\lambda^2}{\lambda^2-(0.0684043)^2} + \frac{0.4079426\lambda^2}{\lambda^2-(0.1162414)^2} + \frac{0.8974794\lambda^2}{\lambda^2-(9.896161)^2} \quad (1)$$

$$\varepsilon_{Au}(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\omega\omega_\tau} \quad (2)$$

The NLCs used in the proposed structure are anisotropic materials consisting of rod-like molecules, which are characterized by ordinary index $n_o$, and extraordinary index $n_e$. The relative permittivity tensor of the NLC [22] is shown in Eq. (3), where $\varphi$ is the rotation angle.

$$\varepsilon_r = \begin{pmatrix} n_o^2\sin^2\varphi + n_e^2\cos^2\varphi & (n_e^2-n_0^2)\sin\varphi\cos\varphi & 0 \\ (n_e^2-n_0^2)\sin\varphi\cos\varphi & n_e^2\sin^2\varphi + n_o^2\cos^2\varphi & 0 \\ 0 & 0 & n_o^2 \end{pmatrix} \quad (3)$$

The values of $n_o$ and $n_e$ can be calculated using the following Cauchy models [23]:

$$n_e = A_e + \left(\frac{B_e}{\lambda^2}\right) + \left(\frac{C_e}{\lambda^4}\right) n_o = A_o + \left(\frac{B_o}{\lambda^2}\right) + \left(\frac{C_o}{\lambda^4}\right) \quad (4)$$

The Cauchy coefficients at different temperature are listed in Table.1. Under the uniform electric-field, the director of the NLC will have good alignment with constant rotation angle $\varphi$. Additionally, the