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Pressure and temperature sensor based on a dual core photonic quasi-crystal fiber

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ABSTRACT

A new type of microstructured fiber known as dual core photonic quasi-crystal fiber is proposed for pressure and temperature sensor based on the mode coupling of the two fiber cores. The proposed fiber is highly birefringent and hence efficiently useful for sensing application. Temperature sensitivity of about 20 pm/°C is observed over the range of 0 to 1000 °C and a pressure sensitivity of −10.5 nm/MPa is observed under a pressure of range 0 to 1000 MPa.

1. Introduction

Optical sensors are analysed using physical parameters such as temperature, curvature, displacement, torsion, pressure, refractive index, electric field, and vibration. The measurement, monitoring, and control of these parameters are of great interest for many applications. Fiber sensors are used for this purpose, since they provide continuous measurement and analysis of key structural and environmental parameters under operating conditions [1,2]. The microstructured fiber also known as photonic crystal fiber (PCF) [3] has attracted considerable attention because of their properties like high birefringence, high nonlinearity, high negative and flattened dispersion, etc. Unlike conventional optical fiber, PCF is a novel optical fiber which guides light in a single material with an ordered array of air holes running along its length. PCF guide light by two mechanisms i.e., index guiding mechanism [5] and photonic band gap mechanism [4,5]. An optical fiber with a quasi-periodic array of air holes in cladding known as photonic quasi-crystal fiber (PQF) [6].

The proposed PQF comprises of both square and triangular lattice symmetry in cladding. Classical theory allows only 2, 3, 4 and 6 folds rotational symmetries but quasi-crystal introduced other order folds like pentagonal (5-folds), octagonal (8-folds), decagonal (10-folds) and dodecagonal (12-folds) according to their rotational symmetries. Compared to conventional optical fiber, PCF offers eminent features such as single-mode transmission, flexible dispersion [7–9] and high nonlinearity. In the future for optical networks, the PCF coupler is the most important component which is mainly based on PCF devices. Realization of multi-core specifically, dual-core PCFs [10–13] has enabled a new efficient way of designing PCF couplers, wavelength multiplexers and de-multiplexers, polarization splitters, narrow band pass filters, and sensors [13–25]. Dual-core PCF couplers have many advantages over the conventional optical couplers. They are more flexible to design, easy to make, and have shorter coupling length.

Dual core PCF are used in sensing applications. PCFs are widely used in optical communications, supercontinuum sources, fiber lasers etc. Because of the remarkable flexibility in the structural design of the PCF compared with the conventional single mode fiber, fiber sensors based on PCFs have many advantages such as high sensitivity to gas sensing, refractive index sensing, biochemical sensing, and pressure sensing and temperature insensitivity to strain sensing. A pressure or a temperature sensor based on dual core PCF works on the principle of thermo elastic and thermo-optic effect.

In this paper, we have proposed a dual core PQF with two fiber cores separated by an air hole in the cross-section of the fiber for pressure and temperature sensing. The working principle of pressure and temperature sensing is based on photoelastic effect/thermo-optic effect and mode coupling between the two fiber cores which is sensitive to pressure and temperature applied on the DC-PQF. The DC-PCF based pressure/temperature sensor has potential advantages of compact, good stability, low cost and capability for mass production.

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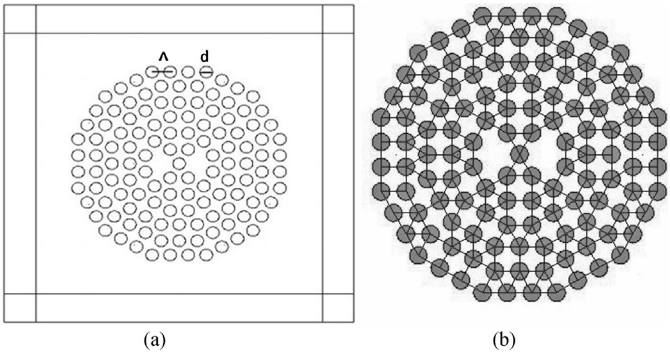

Fig. 1. Cross-sectional view of dual core PQF for, Λ=2 μm, d = 1.4 μm (a) with PML (b) with square and triangular lattice.

2. Dual core photonic quasi crystal fiber

The structure of proposed dual core PQF is shown in Fig. 1 where, Λ is the air hole pitch and d is the diameter of the air holes. The PQF structure is enclosed by PML layer [12] shown in Fig. 1(a). PML layer is drawn to absorb the scattered light in x and y direction. We have proposed a dual core PQF structure with pitch, Λ of 2 μm and air holes diameter, d of 1.4 μm. The two cores are encircled by 12 air holes in the slab and separated by inner holes as shown in Fig. 1(b) with square and triangular lattice symmetry. The proposed structure is 12-fold quasi photonic fiber. The material used is silica of refractive index 1.45 and the light is guided by the index guiding mechanism. The proposed dual core PQF can be fabricated by the stack and draw technique. Fig. 2 shows the two dimensional plot of the confined light into the two cores at 1.55 μm.

Two fiber cores inside the DC-PQF form two waveguides, which are independent due to small spacing between two cores accompanying with mode coupling. By using the FEM we tend to calculate the two basic modes i.e., the even mode and the odd mode of the DC-PQF. Fig. 3 shows the electric field amplitude and the electric field vector of (a) the x-polarized even mode and (b) the x-polarized odd mode of the DC-PQF.

3. Optical properties

3.1. Birefringence

Birefringence is responsible for the phenomenon of double refraction, when a ray of light incident upon a birefringent material, it is split by polarization into two rays taking slightly different paths. The mode birefringence B can be given as

$$B = \left| Re\left(n_{\text{eff}}^{x}\right) - Re\left(n_{\text{eff}}^{y}\right) \right| \tag{1}$$

where n_{eff}^{x} and n_{eff}^{y} are the effective indices in the x-polarized and y-polarized directions, respectively.

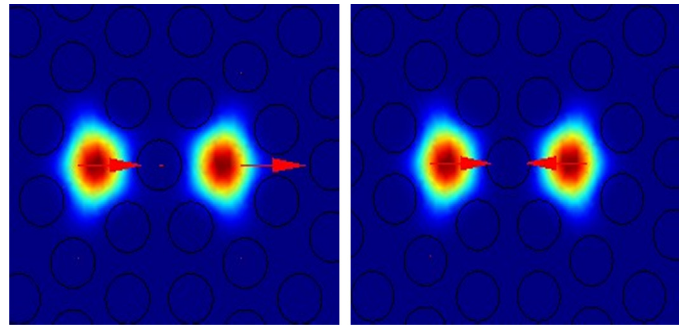

Fig. 3. Electric Field Intensity (a) x-polarized even mode (b) x-polarized odd mode.

3.2. Coupling length

According to the theory of mode coupling, the coupling of a dual-core fiber can be described by the use of the even and odd super modes [21], which are formed by modes of the individual cores and have symmetric and anti-symmetric field distributions, respectively. In dual-core PCFs the coupling length is defined as

$$L_i = \frac{\pi}{\beta_e^i - \beta_o^i} = \frac{\lambda}{2\left(n_e^i - n_o^i\right)}, \quad i = x, y \quad (\mu\text{m}) \tag{2}$$

where β_e^i and β_o^i are the propagation constants of i-polarized even and odd super modes and n_e^i and n_o^i are the effective refractive indices of i-polarized even and odd super modes, respectively. The effective index for x-polarized even mode at 1550 nm is 1.407962 and 1.407612 for x-polarized odd mode. Coupling length calculated for x-polarized is 2.21 mm.

Coupling length of the fiber is dependent on the structural parameters of the fiber. Coupling length for both x and y polarized light is calculated. We have noticed that for small air holes the fiber achieves stronger mode coupling i.e., shorter coupling length but birefringence is low for smaller air holes in the structure and also the confinement loss is larger. If the birefringence is small then the coupling length for x and y-polarized light is almost same and hence it would become difficult to split the light. But we can see from Fig. 4 that for 1.4 μm air hole diameter and 2 μm air hole pitch

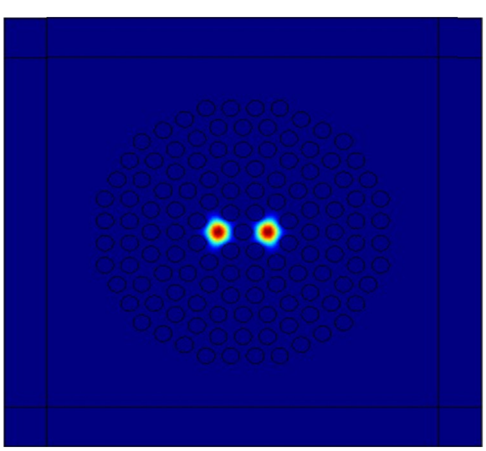

Fig. 2. Two-dimensional plot of the simulated structure.

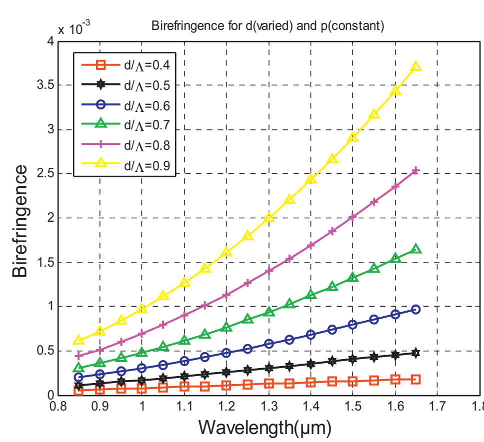

Fig. 4. Birefringence varying with wavelength for different d/Λ ratio.