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Analysis of nonlinear PCF for birefringence application using FDTD method

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ABSTRACT

The effect of ellipticity on birefringence in a hexagonal photonic crystal fiber having elliptical air holes with Kerr nonlinearity is investigated, with and without defect using finite difference time domain (FDTD) simulations. It is found that the birefringence increases with the increase of ellipticity. Further this analysis is extended to a double defect structure, where two adjacent air holes are omitted horizontally from the hexagonal structure. This double defect structure is found to have more birefringence than the structure without defect. It is raveled that birefringence due to no defect is more for lower value of ellipticity; however at higher value of ellipticity, birefringence due to double defect is more than the one that could be due to no defect.

1. Introduction

Photonic crystal fiber (PCF) is a new class of optical fiber and it has been very popular in the field of fiber optic communication because of its confinement characteristics which is not possible in conventional optical fiber [1]. It is possible to obtain PCFs with diametrically opposite properties by changing the geometric characteristics of the air holes in the fiber cross-section, the main difference between PCF and conventional fiber is that photonic crystal fiber has air silica cross-section, whereas standard optical fiber has all glass cross-section [2]. It has been shown that PCF possess different types of unique properties that are unachievable by conventional optical fibers, such as endlessly, single mode propagation [3], highly configurable dispersion, tailorable modal area [4] and birefringence [5]. Several methods have been employed to study the characteristics of PCFs, including effective index method [6], the plane wave expansion method [7], the localized function method [8], the beam propagation method [9], the finite element method [10], and the finite difference time domain [11] or frequency domain method [12].

Among these techniques, the FDTD method using Yee's technique has been widely accepted as a very powerful computational technique for electromagnetic problem, and it is much easier to implement with comparable accuracy.

To maintain the linear polarization, high level of birefringence is required by reducing polarization mode dispersion. This is possible by breaking the circular symmetry and implementing asymmetric defect structure, such as dissimilar air hole diameter, varying the number of circular and elliptical air holes. Using these concepts a high birefringence PCF can be designed.

In this paper we have investigated how much linearity on birefringent property is obtained by comparing no defect and double defect (horizontal) in a hexagonal structure nonlinear PCF having silica as background material using FDTD method. This paper is organized as follows: Numerical analysis is presented in Section 2. In Section 3, hexagonal structure is designed. Simulations and discussions are shown in Section 4. Finally conclusions are drawn in Section 5.

2. Numerical analysis

For nonlinear, isotropic media, the time dependent Maxwell's equation can be written as

$$\nabla \times E = -\mu_{\mathrm{r}} \frac{\partial H}{\partial t} \tag{1}$$

$$\nabla \times H = \varepsilon_{\mathrm{r}} \frac{\partial E}{\partial t} + J \tag{2}$$

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where μ_r and ε_r are the relative permeability and permittivity respectively and J is the polarization current density in material, which is induced by electric field. In the FDTD, J can be expressed as $J(\omega) = i\omega P(\omega) = i\omega\varepsilon_r\chi(\omega)E(\omega)$, where P is the electric polarization density and χ is the frequency dependent susceptibility of the material.

Sellmeir equation gives the electric field dependence of the refractive index of the fused silica, which is given by

$$P = \varepsilon_0[\chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \cdots] \quad (3)$$

where linear, quadratic and cubic terms are a tensors describing the nonlinear susceptibilities of the medium. The magnitude of linear term decrease rapidly with increasing higher order terms, Quadratic term gives rise to second harmonic generation (SHG), sum and difference frequency mixing (SFG, DFG) and parametric generation. The cubic term is responsible for cubic nonlinear effects such as third generation (THG) and Kerr effect. So cubic term from Eq. (3) can be extracted as follows:

$$P = \varepsilon_0\chi E^3 \quad (4)$$

The basic relationship between polarization and electric field is

$$P = \varepsilon_0(\varepsilon_r - 1)E = \varepsilon_0\chi E^3 \quad (5)$$

Again the relation between relative permittivity and refractive index is given by

$$\varepsilon_r = n^2 \quad (6)$$

Using Eqs. (4)–(6), one can write

$$n = \sqrt{1 + \chi E^2} \quad (7)$$

Using Eq. (7), birefringence nature of PCF can be studied.

3. Hexagonal design

Hexagonal structure PCF design is known to be the best arrangement for obtaining high birefringence and comparatively low confinement loss. Here a highly birefringence hexagonal solid core PCFs with five rings has been modeled. The material used here is pure silica with refractive index 1.42 and lattice constant of 1.6 μm. The two different structures are designed and compared for various parameters. The first structure suggests a five ring elliptical air holes without any defect, whereas the second comprises five ring elliptical air holes with two adjacent missing air holes horizontally. The hexagonal structure having with and without defect is shown in Fig. 1(a) and (b). It is seen that elliptical air holes are periodically arranged throughout the crystal structure and we introduce here the nonlinearity in air holes of photonic crystal fiber.

4. Simulation result analysis

Choosing hexagonal PCF structure, mentioned in previous section, we have carried out simulation to verify the effect of nonlinearity on birefringence of said structures of no defect and double defect PCF using FDTD method. Here we initiated the excitation at the center of the structure in both the case. This birefringence PCF is formed by a regular hexagonal lattice of elliptical air holes on silica, however the first structure is no defect (without missing air holes) PCF and second one is double defect (adjacent missing air holes) PCF. The linearity in the birefringence versus wavelength plot in a PCF structure depends on the nature and configuration of the said structure, such as lattice constant (lattice pitch) Λ, refractive index 'n' and ellipticity ($\eta = a/b$) where a and b are the major and minor axes of elliptical holes are directed along x and y axes respectively. We have considered ellipticity in five different condition such as $\eta = 1$, $\eta = 2$, $\eta = 2.2$, $\eta = 2.5$ and $\eta = 3$ which correspond to $a = b = 0.6$; $a = 0.6$, $b = 0.3$; $a = 0.6$, $b = 0.272$; $a = 0.6$, $b = 0.24$; and $a = 0.6$, $b = 0.2$ respectively and effective index difference x and y polarized fundamental modes are simulated at wavelengths 0.5, 0.75, 1.0, 1.25, 1.50, 1.75, 2.0 μm. The simulation results are shown in Figs. 2–5.

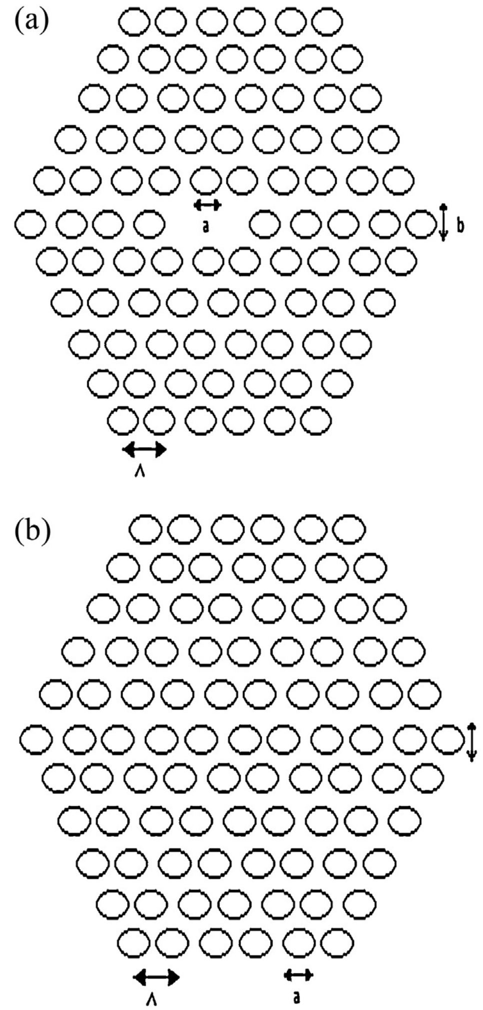

Fig. 1. (a) and (b) Hexagonal structure PCF with the core consisting of double defect and no defect.

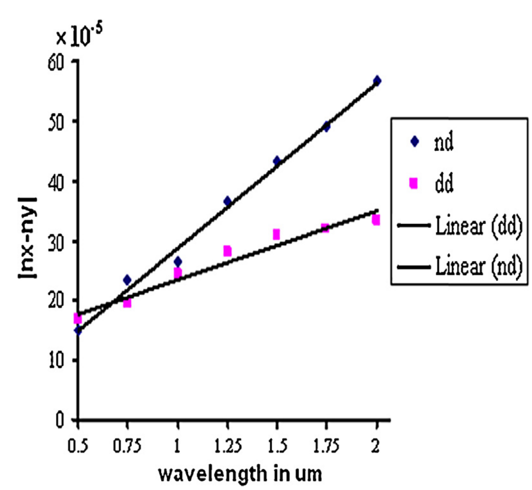

Fig. 2. Dependence of birefringence on wavelength for circular air hole PCFs with lattice constant = 1.6 μm and ellipticity 1 for both no defect and double defect.