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Modeling of Elliptical Air Hole PCF for Lower Dispersion

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Abstract

In this paper, the dispersion properties of index guided two dimensional Photonic Crystal Fibres with hexagonal layout and solid core has been investigated using Full Vector TE, FDTD method. The modal analysis is done to obtain the complex effective refractive index for: (i) Hexagonal lattice with five rings of elliptical air holes (ii) Hexagonal lattice with alternate rings of vertical and horizontal polarized elliptical air holes. The modal analysis which generates the effective refractive index is further used to calculate the waveguide dispersion. By varying the two parameters, the diameter of the air holes and pitch, PCF with different properties can be obtained. The model with large negative chromatic dispersion D (ps/km-nm) is considered.

Keywords: Photonic Crystal Fibers (PCFs), Effective Refractive index (neff), Chromatic Dispersion (D), Finite Difference Time Domain (FDTD).

1. Introduction

A new generation of optical fibers, called Photonic crystal fibers (PCFs) is a kind of two dimension photonic crystals, consisting of a central defect region surrounded by multiple air-holes that run along the fiber length. The core of the PCF is made of solid silica and the cladding consists of multiple layers of air holes separated by narrow silica bridges. PCFs are divided into two different kinds' of guiding mechanism. The first one is index guided PCF, guiding light by TIR between a solid core and a cladding region with multiple air-holes. Here refractive index is higher than the average refractive index of the cladding. The second one uses a perfectly periodic structure exhibiting a photonic band-gap (PBG) effect at the operating wavelength to guide light in a low index core-region. The design of PCFs is very flexible. There are various parameters to design the fiber: lattice pitch (a), air hole shape (circular or elliptical) and diameter (d), refractive index of the wafer and type of lattice (rectangular, hexagonal). Freedom of design allows zero, low, or flattened dispersion in visible wavelength range. Advantage of using Photonic crystal fiber is that we can achieve very good properties in birefringence, dispersion, nonlinearity. Index-guiding PCFs, also called holey fibers or microstructure optical fibers, possess especially attractive property of great controllability in chromatic dispersion by varying the hole-diameter and hole-to-hole spacing or hole-pitch. Typically, in PCF air holes are arranged on the vertex of an equilateral triangle with six air holes in the first ring around the core, which is called the HPCF. Beside the hexagonal structure other structures such as, square lattice, cob web, honeycomb, octagonal and decagonal are proposed for the design of PCF.

Photonic Crystal Fiber (PCF) can provide characteristics that ordinary optical fiber do not exhibit, such as: single mode operation from the UV to IR with large mode-field diameters, highly nonlinear performance for super continuum generation, numerical aperture (NA) values ranging from very low to about 0.9, optimized dispersion properties, and air core guidance, among others. Main difference between a PCF and the conventional one is the index profile of core/cladding. Applications for photonic crystal fibers include spectroscopy, metrology, biomedicine, imaging, telecommunication, industrial machining, and military, and the list keeps growing as the technology becomes a mainstream.

This paper is organised into various sections: firstly FDTD method is described along with the chromatic dispersion, next the designing of PCFs is mentioned and lastly the simulation results and analysis of dispersion.

2. FDTD Method

The finite difference time domain (FDTD) method is widely used for calculation of the evaluation of an electromagnetic field in depressive media. The wave propagation through the PCF structure is found by direct integration in the time domain of Maxwell's equations in a discrete form. Space and time is discrete in a regular grid. Evaluation of the electrical and magnetic field is calculated on a Yee cell. In addition the boundary conditions are added (absorbing or periodic ones). Most often uniaxial perfect matching layer (UPML) boundary conditions are used for PCF modeling. The method allows obtaining transmission and reflection coefficients, energy flow of propagation fields (Poynting vector). It allows the observation of a steady state field distribution as well as the temporary field distribution.

The FDTD method is universal, robust, and methodologically simple. The main drawback of this method is very high time and memory complexity of the algorithm. Since PCF are 3D structures with 2D refractive index distribution only short pieces of the fiber can be simulated with these methods. It can be successfully applied to model tapers, couplers, and double core coupling in the PCFs. Large volume simulations can be performed with computer clusters because the FDTD method can be relatively easily implemented as a parallel algorithm.

2.1 Chromatic Dispersion

PCFs possess the attractive property of great controllability in chromatic dispersion. The chromatic dispersion profile can be easily controlled by varying the hole-diameter and the hole-pitch. Controllability of chromatic dispersion in PCFs is a very important problem for practical applications to optical communication systems, dispersion compensation, and nonlinear optics. So far, various PCFs with remarkable dispersion properties have been investigated numerically.

The chromatic dispersion D of a PCF is easily calculated from the effective index of the fundamental mode n_{eff} versus the wavelength λ using

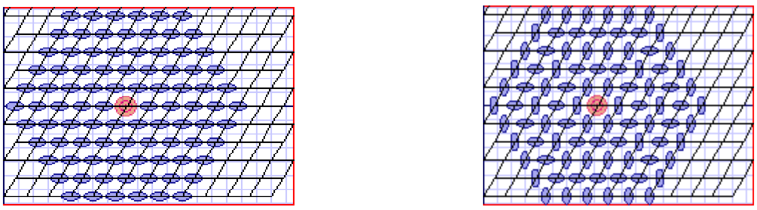
$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2 n_{eff}(\lambda)}{d\lambda^2}$$

where c is the velocity of light in a vacuum. When the hole-diameter to pitch ratio is very small and the hole pitch is large, the dispersion curve is close to the material dispersion of pure silica. As the air-hole diameter is increased, the influence of waveguide dispersion becomes stronger.

As mentioned above, the dispersion coefficient D is proportional to the second derivative of the modal effective index with respect to the wavelength λ. For this reason, we have to calculate the dependence of modal effective index n_{eff} with respect to the wavelength λ firstly.

3. Design Parameter & Simulaton Results

The cross section of hexagonal lattice PCF (using OPTI FDTD simulator) with elliptical air holes is shown in Fig.1



(a) (b)

Figure 1, 2: The cross section of PCF with a (a) regular elliptical air-hole array (b) alternate elliptical air-hole (at 0° and 90°) array.

The wafer chosen is of pure (non dispersive) silica with refractive index 1.45 and the refractive index of air holes is 1. The wafer is designed for length = 13*□ µm and width=11*b µm, where □ is the pitch and b is the height of triangle cell, ensuring high degree simulation accuracy. The major and minor diameters of the elliptical air holes are d_M and d_m respectively. The pitch (Λ) which is center to center spacing between two nearest air holes gives the characteristics of a hexagonal-lattice PCF. The boundary conditions chosen are TBC. The mesh size is $\Delta x = \Delta z = 0.08$ μm for both direction.

In this paper, a hexagonal-lattice PCF is investigated with (i) five rings of elliptical air holes as shown in fig.1 (ii) alternate rings of elliptical air holes (at 0° and 90°) as shown in fig.2, in order to control chromatic dispersion properties. By varying the two parameters, the diameter of the air holes and pitch, PCF with different properties is designed.

Here various configuration of PCF are considered:

The PCF layout with hexagonal lattice has configured for two cases:

1) Five rings of elliptical air holes.
2) Alternate rings of elliptical air holes at 90° and elliptical air holes at 0°. Major diameter of elliptical air holes at 90° is equal to the minor diameter of elliptical air holes at 0° and minor diameter of elliptical air holes at 90° is equal to the major diameter of elliptical air holes at 0°.

Configuration1: When pitch is constant and diameter is varied.

a) Lattice constant, □=1.5 μm, major diameter, d_M=1.1μm and minor diameter, d_m=0.6μm.
b) Lattice constant, □=1.5 μm, major diameter, d_M=1.2μm and minor diameter, d_m=0.6μm.
c) Lattice constant, □=1.5 μm, major diameter, d_M=1.3μm and minor diameter, d_m=0.6μm.

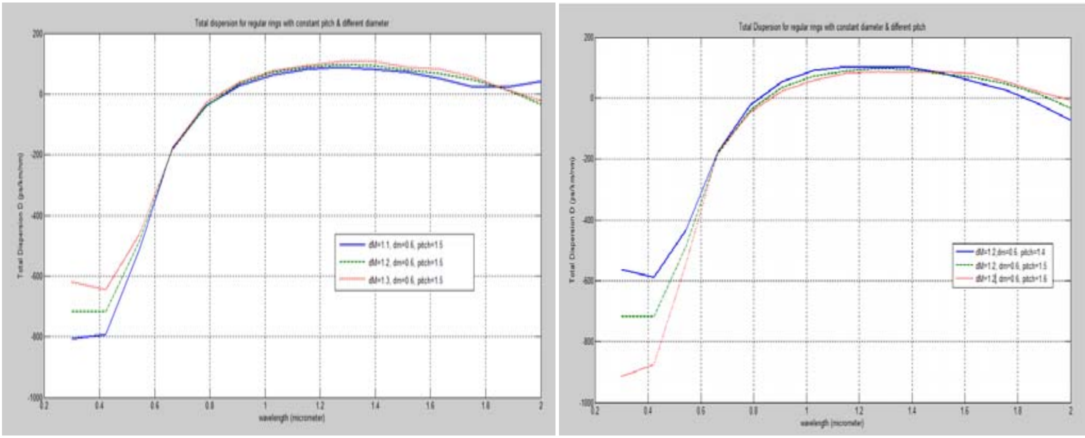
Configuration2: When diameter is contant and pitch is varied.

a) Lattice constant, □=1.4 μm, major diameter, d_M=1.2μm and minor diameter, d_m=0.6μm.
b) Lattice constant, □=1.5 μm, major diameter, d_M=1.2μm and minor diameter, d_m=0.6μm.
c) Lattice constant, □=1.6 μm, major diameter, d_M=1.2μm and minor diameter, d_m=0.6μm.

The various layouts designed and investigated using OPTIFDTD mode solver. The modal analysis which generates the effective refractive index is further used to calculate the waveguide dispersion by using the above mentioned formula.

The various plots obtained for dispersion are shown in figure 3,4,5,6. Five rings PCF having regular elliptical air holes and alternate elliptical air holes of hexagonal layouts are analyzed and compared.

Firstly, the dispersion is calculated for hexagonal layout with elliptical air holes having same major and minor diameter in each ring. Three different cases with constant pitch and different major and minor diameter are compared as shown in figure 3. The dispersion value obtained is for wavelength ranging from 0.3μm to 2.0μm. The dispersion observed at 1.55μm is 59.23ps/nm/km for the first design, 70.46ps/nm/km for the second design, and 82.61ps/nm/km for the third design. After comparison, the lowest dispersion observed at 1.55µm is for the first design. Within the wavelength range, the lowest dispersion observed at 0.3µm (-806.61ps/nm/km) is for the first design.

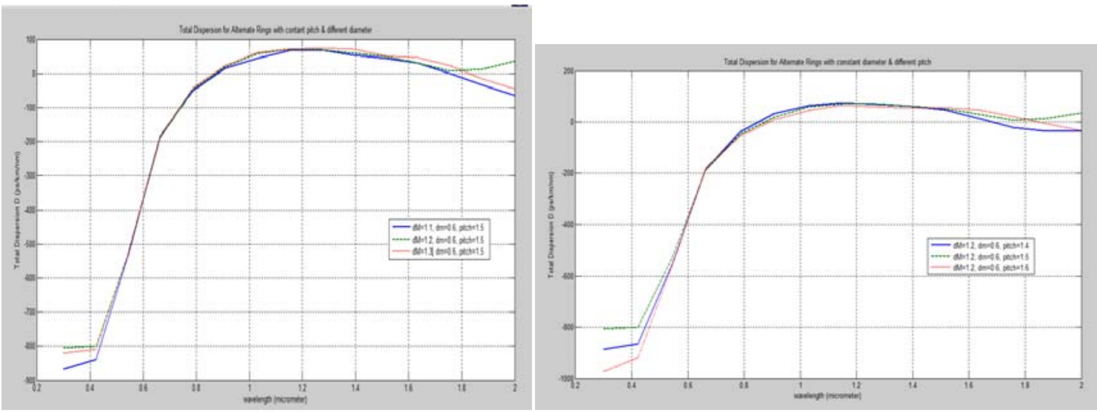


(a) **(b)**

Figure 3, 4: Comparison graph of total dispersion of regular rings for three different PCF layouts (a) with constant pitch and varying diameter (b) with constant diameter and varying pitch.

Secondly, the dispersion is calculated for hexagonal layout with elliptical air holes having same major and minor diameter in each ring. Three different cases with different pitch and constant major and minor diameter are compared as shown in figure 4. The dispersion value obtained is for wavelength ranging from 0.3µm to 2.0µm. The dispersion observed at 1.55µm is 66.34ps/nm/km for the first design, 70.46ps/nm/km for the second design, and 83.58ps/nm/km for the third design. After comparison, the lowest dispersion observed at 1.55µm is for the first design. Within the wavelength range, the lowest dispersion observed at 0.3µm (-914.47ps/nm/km) is for the third design.

Thirdly, the dispersion is calculated for hexagonal layout with alternate rings of elliptical air holes at 90° and elliptical air holes at 0°. Three different cases with constant pitch and different major and minor diameter are compared as shown in figure 5. The dispersion value obtained is for wavelength ranging from 0.3µm to 2.0µm. The dispersion value obtained is for wavelength ranging from 0.3µm to 2.0µm. The dispersion observed at 1.55µm is 35.82ps/nm/km for the first design, 39.034ps/nm/km for the second design, and 46.71ps/nm/km for the third design. After comparison, the lowest dispersion observed at 1.55µm is for the first design. Within the wavelength range, the lowest dispersion observed at 0.3µm (-867.80ps/nm/km) is for the first design.



(a) **(b)**

Figure 5, 6: Comparison graph of total dispersion of alternate rings for three different PCF layouts (a) with constant pitch and varying diameter (b) with constant diameter and varying pitch.

Lastly, the dispersion is calculated for hexagonal layout with alternate rings of elliptical air holes at 90° and elliptical air holes at 0°. Three different cases with different pitch and constant major and minor diameter are compared as shown in figure 6. The dispersion value obtained is for wavelength ranging from 0.3µm to 2.0µm. The dispersion value obtained is for wavelength ranging from 0.3µm to 2.0µm. The dispersion observed at 1.55µm is 28.07ps/nm/km for the first design, 39.034ps/nm/km for the second design and 48.85ps/nm/km for the third design. After comparison, the lowest dispersion observed at 1.55µm is for the first design. Within the wavelength range, the lowest dispersion observed at 0.3µm (-972.018ps/nm/km) is for the third design.

4. Conclusion

A hexagonal lattice PCF layout with regular elliptical air holes and alternate elliptical air holes has been investigated for their dispersion properties. Plots of the dispersion for various configurations are compared for the lowest dispersion. It has been noticed that the lowest dispersion for regular rings of elliptical air holes with constant pitch and variable diameter is 59.23ps/nm/km (Λ=1.5µm, d_M=1.1µm, d_m=0.6µm) and with constant diameter and variable pitch is 66.34ps/nm/km (Λ=1.4µm, d_M=1.2µm, d_m=0.6µm). It has been noticed that the lowest dispersion for alternate rings of elliptical air holes with constant pitch and variable diameter is 35.82ps/nm/km (Λ=1.5µm, d_M=1.1µm, d_m=0.6µm) and with constant diameter and variable pitch is 28.07ps/nm/km (Λ=1.4µm, d_M=1.2µm, d_m=0.6µm). The lowest dispersion for all the designs is noticed at 0.3µm wavelength for alternate rings of elliptical air holes with Λ=1.6µm, d_M=1.2µm, d_m=0.6µm is -972.0184ps/nm/km. It is concluded that when small diameter and small pitch is taken then we get lower dispersion and we can use that particular designs for making of PCF.

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