Design of Elliptical Air Hole PCF with Hybrid Square Lattice for High Birefringence and a Lower Zero Dispersion Wavelength

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***Abstract**: In this paper a hybrid square-lattice PCF with circular and elliptical air holes has been designed and the numerical investigation shows its high birefringence and shifting of zero dispersion wavelengths toward lower wavelength range with the increase in the ellipticity of air holes. A full-vector TE, FDTD method is used.*

***Keywords:** Photonic Crystal Fiber (PCF), Total internal reflection (TIR), Effective Refractive index (neff), high birefringence (Hi-Bi), Finite Difference Time Domain(FDTD),Transparent boundary condition(TBC).*

1. Introduction

The Photonic crystal fibers (PCFs) are made from single material such as silica glass, with an array of microscopic air channels running along its length [1–6]. In this a defect can be created by removing the central air-hole with glass to guide light by total internal reflection (TIR) between the solid core and the cladding region. These index-guiding PCFs are also called m-TIR PCFs. Another PCFs that use a perfectly periodic structure exhibits photonic band gap (PBG) effect and these PBG–PCFs guide light in a low-index core region [1,7,8]. In recent years, photonic crystal fibers are attracting much attention because of their unique properties, such as dispersion and polarization properties, which cannot be realized in conventional optical fibers. In this paper, we will focus on index-guiding PCFs.

The polarization and dispersive properties of elliptical air hole PCFs (EHPCF) were investigated using full-vector TE FDTD method and compared with circular air hole PCF, keeping the area of air filling fraction same in both the cases. High level of birefringence in fiber optics is required to maintain the linear polarization state by reducing polarization mode dispersion. Recently, due to the large index contrast of photonic crystal fibers (PCFs) compared to the conventional fiber, Hi-Bi PCFs have been reported by researchers by breaking the circular symmetry, implementing asymmetric defect structures such as dissimilar air hole diameters along the two orthogonal axes [9-10], designing an air hole lattice or a microstructure lattice with inherent anisotropic properties such as the elliptical-hole PCF [11-12]. Modal birefringence in these Hi-Bi PCFs has been reported to have values of the order of 10^{-3} or 10^{-2} higher than that of the conventional High Birefringence fibers (10^{-4}) [13]. According to the Symmetry theory, the rectangular lattice is potentially more anisotropic than the triangular and honeycomb lattices [16]. The values of birefringence for basic rectangular lattice PCF depicted in [16] are of the order of 10^{-3}. By making a combination of the elliptical- air hole and rectangular lattice, the birefringence increases to an order of10^{-2} [14-15]. However, elliptical air holes are very difficult to control during the fabrication process. The dispersion properties of square-lattice PCF have been reported by Soan Kim [17] where a hybrid square lattice PCF is proposed which exhibits birefringence of the order of $10^{-3.}$

In this paper, the PCF structure is designed and analyzed by well-established method: FDTD (Finite difference time domain). A full vector TE mode is used to perform the modal analysis which generates the effective refractive index, which is further used to calculate the waveguide dispersion and Birefringence. A Hybrid Square -lattice PCF with circular air holes (Fig.1) is referred [17] and compared with elliptical air holes which exhibits high birefringence and lower dispersion. Also Zero dispersion wavelength gets shifted towards lower wavelength range.

2. Analysis of dispersion and Birefringence-

Theory basis—

The most interesting aspects of the work on PCFs are their propagation properties with respect to their possible application in modern fibers optical communication systems, such as dispersion and Birefringence [18].Some polarization maintaining fibers (PMFs) contains elliptical air holes in the cladding to produce a high birefringence, which is elliptical photonic crystal fiber (EPCF).The birefringence is defined as $|n^x_{eff} - n^y_{eff}|$ where n^x_{eff} and

n^{y}_{eff} are the effective indices of x-polarized mode and y-polarized mode, respectively.

The effective refractive index of the base mode is given as $n_{eff} = \beta/K_0$, where β is the propagation constant, $k_0=2\pi/\lambda$ is the free-space wave number. First the modal effective indexes n_{eff} are solved, and then the dispersion parameter D can be obtained [19]

$$D(\lambda) = -(\lambda/c)\,(d^2 n_{eff}/d\lambda^2) \tag{1}$$

Where c is the velocity of the light in a vacuum and λ is the operating wavelength [19, 20].

The waveguide dispersion is strongly related to the design parameters of the PCFs and therefore can be optimized to achieve desired dispersion properties.

3. Design parameter and Simulation results

The cross section of a hybrid square-lattice PCF (using OPTI FDTD Simulator version 8) with circular air holes is shown in Fig.1. .

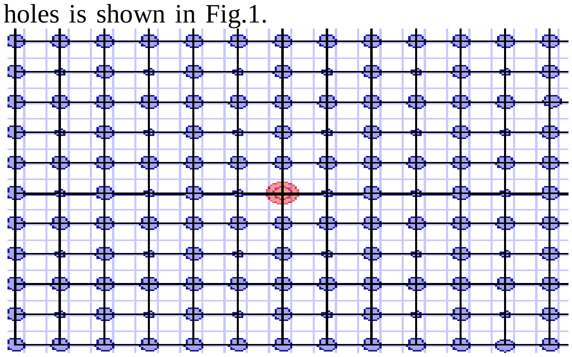

Fig1. A Hybrid Square -lattice PCF with circular air holes d_c/d =0.5 µm, pitch (Λ) =2 µm, d_c/Λ=0.2 [17].

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 = 26µm and width=22µm, ensuring high degree simulation accuracy. The diameters of the small and large air holes are d_c and d respectively. The pitch (Λ) which is center to center spacing between two nearest air holes gives the characteristics of a hybrid square-lattice PCF. The boundary conditions chosen are TBC. The mesh size is $\Delta x = \Delta z$ =0.106 µm for both direction.

In this paper, a hybrid square-lattice PCF is investigated with circular and elliptical air holes in order to control not only modal birefringence but also chromatic dispersion properties simultaneously. Taking reference of Fig 1(configuration I) with d_c/d =0.5 µm, pitch (Λ) =2 µm, dc/ Λ=0.2 ,the hybrid square lattice PCF with elliptical air holes structures were designed and are shown in Fig 2, 3, 4 respectively. Any stress or pressure intentionally or unintentionally may deform circular air hole to the elliptical shape. So the above investigation may be very applicable as far as fabrication is concerned. For elliptical air-holes the minor axis is defined as 'a' and major axis is defined as 'b' respectively. The ellipiticity is defined as the ratio of major axis and minor axis i.e. b/a. For the II, III, IV configuration the layout designs are shown in Fig. 2, 3, 4. For II configuration d_c=0.4µm, a=0.1µm, b=0.4µm for small air holes and a=0.3µm, b=0.533µm for large air holes and for III configuration a=0.1µm, b=0.4µm for small air holes and a=0.2 µm, b=0.8µm for large air holes, and for IV configuration a random distribution of circular and elliptical air holes are shown.

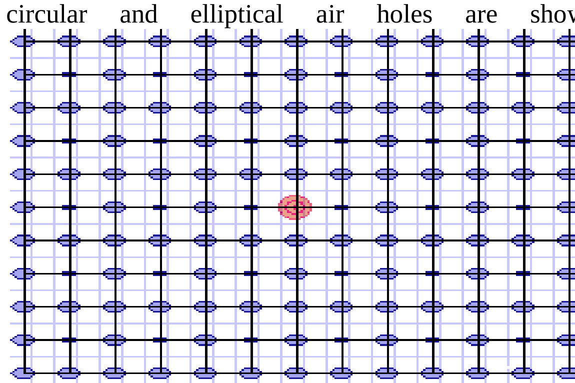

Fig 2 Layout design for a hybrid square lattice PCF with elliptical air holes, here a =0.1µm, b=0.4 µm for small air holes and a=0.3 µm, b=0.533 µm for large air holes

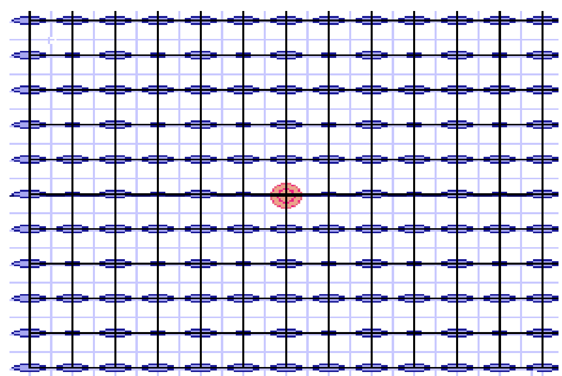

Fig 3 Layout design for a hybrid square lattice PCF with elliptical air holes, here a=0.1 µm, b=0.4 µm for small air holes and a=0.2 µm, b=0.8 µm for large air holes.

Table I - Dispersion in ps/nm.km

Wavelength	Dispersion (ps/nm.km) Conf I	Dispersion (ps/nm.km) Conf II	Dispersion (ps/nm.km) Conf III	Dispersion (ps/nm.km) Conf IV
(λ=1.5 µm)	10.42721	2.71813	-7.65905	12.40358

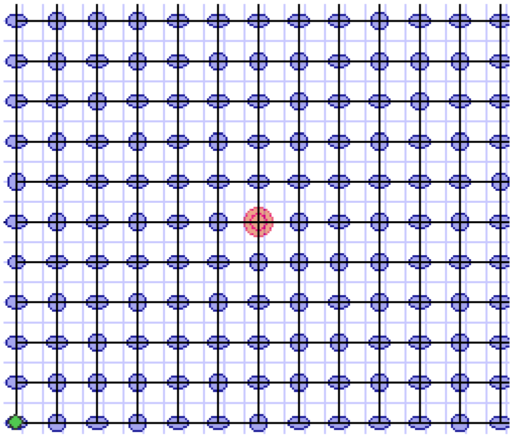

Fig 4 Layout design for a hybrid square-lattice PCF with a random distribution of circular and elliptical air holes.

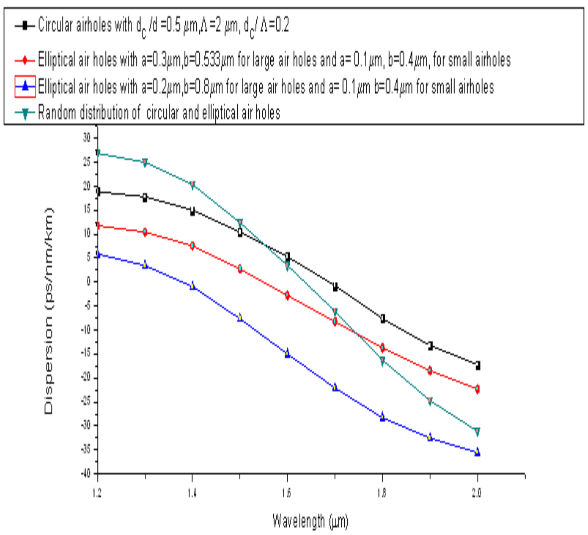

Fig 5 Waveguide dispersion of a hybrid square-lattice PCF varying ellipticity of air holes with $d_c/d = 0.5$,d_c/ Λ = 2µm, Λ=2 µm, a=0.1 µm(red, blue)0.2 µm (blue),0.3 µm (red)and b=0.4 µm(red, blue),0.533 µm(red),0.8 µm(blue)

The dispersion properties of square lattice PCFs with elliptical air holes has been compared with circular air holes keeping the dimensions of the square Lattice same in Fig 5.The plots shows that dispersion gets decreased to -7.65905 ps / (nm.km) with increase in the ellipticity of air holes over the wavelength range 1.2 µm to 2 µm(incorporating optical range). Also Zero dispersion wavelength is shifted towards lower wavelength range. Table I shows a comparison Of Dispersion values at 1.5µm for all the stated configurations.

Table II- Zero Dispersion Wavelength

	Conf I	Conf II	Conf III	Conf IV
Zero Dispersion Wavelength	1.69 µm	1.475 µm	1.38 µm	1.645 µm

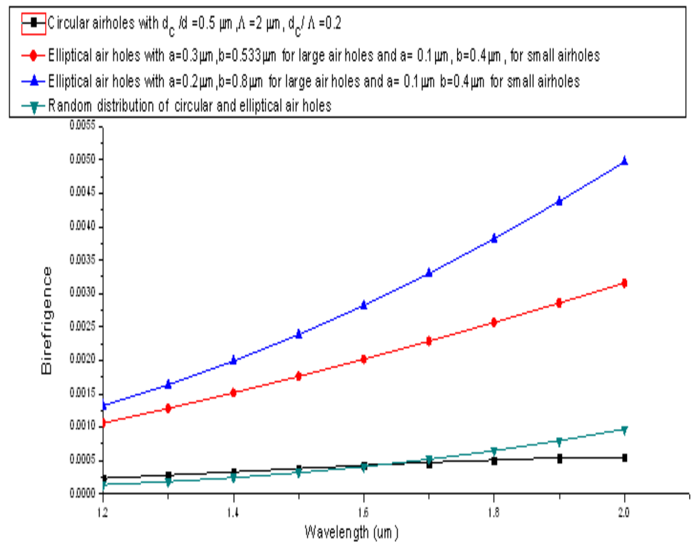

Fig 6 wavelength dependence of the modal birefringence of a hybrid square-lattice PCF Here with $d_c/d = 0.5$,d_c/ Λ = 2µm, Λ=2 µm, a=0.1 µm (red, blue), 0.2 µm (blue), 0.3 µm (red) and b=0.4 µm(red, blue), 0.533 µm (red), 0.8 µm(blue)

The modal birefringence of a hybrid square-lattice PCF of elliptical air holes with $d_c/d = 0.5$, d_c/ Λ = 2µm, Λ=2 µm, a=0.1 µm, b=0.4 µm for small air holes and a=0.2 µm, b=0.8 µm for large air holes as shown in Fig.6 increases to 4.9 x10^{-3}, comparing with the conventional square-lattice PCF with circular air holes 5.5 x 10^{-4}.

4. Conclusion

A Hybrid Square–lattice PCF with elliptical and circular air holes are compared and investigated for their dispersion and birefringence properties, with the design in fig 3(Conf III) , dispersion is decreased to -7.65905 ps / (nm.km) and zero dispersion wavelength gets shifted to 1.38 µm with the increase in the ellipticity of air holes. Thus the Zero dispersion wavelength is shifted towards lower wavelength range, the modal birefringence of a hybrid square-lattice PCF with elliptical air holes is investigated to be equal to 4.9 x10^{-3} at 2 µm wavelength which is very high as compared to circular air hole PCF. Therefore that the proposed Hybrid Square Lattice PCF with elliptical air hole can be used as high birefringence and low dispersion fibers.

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