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Dispersion properties of the square-lattice elliptical-core PCFs

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Abstract: In this paper the dispersion properties of the elliptical core square-lattice PCF in a silica matrix have been studied. The dispersion curves for the fiber for different hole-to-hole spacing and air-hole diameter has been studies extensively. It has been shown that elliptical-core square lattice PCF with small hole to hole distance (Λ) and large-hole diameter (d) can be used for dispersion compensation. A comparison between Elliptical PCF with square and triangular PCF has been performed, taking into account the dispersion properties and the effective area. A final study on the two types of PCFs is carried out when they are single mode in the studied wavelength region.

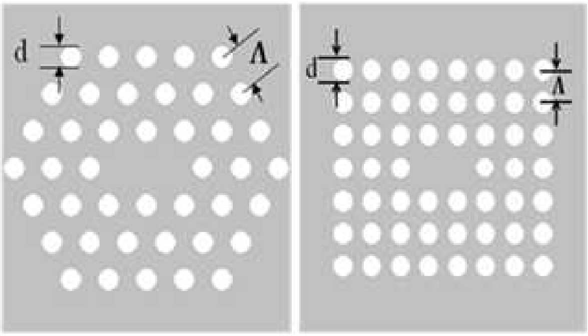
Keywords: Photonic Crystal Fibers (PCFs), Microstructured Optical Fibers (MOFs), Dispersion, Elliptical Core: Square-Lattice

1. Introduction

Photonic crystal fibers (PCFs) [1, 2] are made from regular lattices of air holes in the background of single material, usually un-doped silica. The large refractive index variation between the background material and the air holes in PCFs allows large dispersion over a wide wavelength region both in visible and near-IR region. PCFs posses the attractive properties of controlling the chromatic dispersion by varying the geometrical parameters like the hole diameter (d) and hole to hole spacing or pitch (Λ) of the air holes. Control of chromatic dispersion is essential for Wavelength Division Multiplexing (WDM) optical fiber networks as it limits the data transmission rate. PCFs with remarkable dispersion properties can be applied to practical applications like optical communication systems, dispersion compensation and nonlinear optics. PCFs with triangular arrangement of air-holes in the cladding can be used for shifting zero dispersion wavelengths to the visible and near-IR wavelengths [3, 4], an ultra-flattened chromatic dispersion [5-9], whereas PCFs with square lattice arrangement of air holes in the cladding can also compensate the dispersion [10] and can be useful for ultra-flat dispersion [11]. Another new types of PCFs where air-holes are arranged in circular pattern around the core can also be useful for different applications [12]. High birefringent PCFs or polarization maintaining PCFs can be realized using elliptical air-holes [13] and with asymmetric core [14] or different size of air holes in cladding [15]. PCFs with an elliptical-core can also compensate chromatic dispersion as reported in one of our earlier work [16].

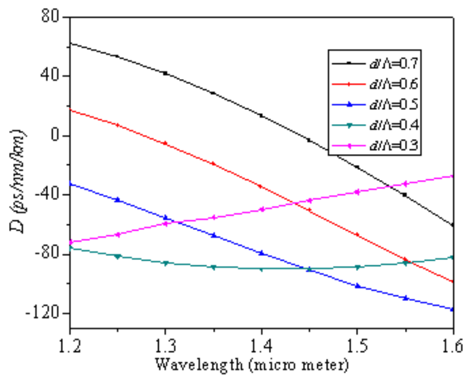
In this paper, the guiding and the dispersion properties of PCFs with an elliptical-core square-lattice has been studied in detail. It is of some interest to study the properties of elliptical-core PCF specially the square-lattice one and how they differ than their triangular counterpart. It has already been shown that the guiding properties differ drastically for the square one than the triangular one [16] as square-lattice PCF is single-mode for better range than the triangular one [16]. Square-lattice PCF has been realized and its property has been studied both theoretically and experimentally [17].

In this paper, we have studied the asymmetric core PCFs with square lattice structure with C_2V symmetry; the PCFs consist of square lattice air holes with two adjacent central holes missing in a silica matrix background. Fig.1 (a) shows the cross section of an anisotropic core PCF, which contains square-lattice air-holes in the frequency dependent cladding. It is well known that a triangular lattice PCF is usually described by air-hole diameter *d* and pitch Λ as shown in Fig. 1 (b). Now, we use Λ as the hole to hole spacing in horizontal or vertical direction in the PCF with square-lattice air holes and d as the diameters of the air holes. We solve the guided modes of the present fiber by the CUDOS MOF Utilities [18] that simulate PCFs using the multipole method [19-20].



(a) (b)

Fig 1. *Cross section of the studied PCF, the gray area denotes pure silica; the white area denotes air holes. 1(a) triangular lattice PCF and (b) square lattice PCF.*



(b)

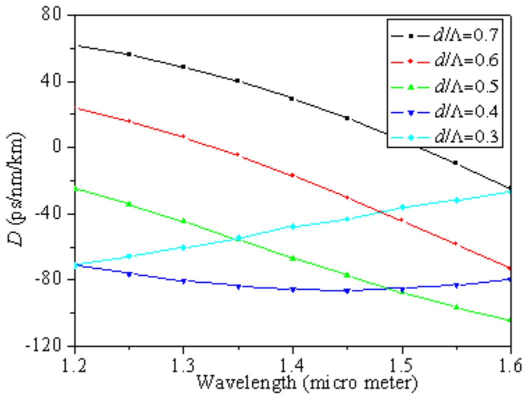
Fig 2. *Dispersion curves of the Elliptical core square-lattice PCFs with Λ=1μm and d/Λ from 0.3 to 0.7 for (a) x-polarized and (b) y-polarized component respectively.*

2. Dispersion Properties of the Elliptical Core Square-Lattice PCFs

The dispersion *D* for a PCF structure has been calculated from the n_{eff} values versus the wavelength through Eqn. (1), where 'c' is the speed of light in a vacuum and '*Re*' stands for the real part of the refractive index obtained from simulations. The chromatic dispersion of the background material silica has been taken into account through Sellmeier's equation. The influence of the geometric parameters d and Λ has been investigated considering the PCFs with three layers of air holes in the cladding. We have followed the same way Bouk *et el* [10] have done in their study of the dispersion properties of the square lattice PCFs. We have considered five values of hole to hole spacing which are 1 μm, 1.5 μm, 2 μm, 2.5 μm and 3 μm and *d*/Λ have been varied from 0.3 to 0.7 in the steps of 0.1.

$$D = -\frac{\lambda}{c}\frac{d^2\,\mathrm{Re}[n_{eff}]}{d\lambda^2} \qquad (1)$$

Figure 2 (a) and Fig. 2 (b) shows the dispersion parameter D of the elliptical-core square-lattice PCF for *x* and *y* polarized component respectively with different values of *d*/Λ values for Λ=1 μm for the wavelengths range between 1200 nm to 1600 nm.



(a)

From the figures (Fig. 2(a) and Fig. 2(b)) it is clear that for the lowest value of pitch of Λ=1 μm, the PCF all have the negative value dispersion parameter in the C band *i.e.* around 1550 nm. This is because of the fact that for smaller value of core diameter, the waveguide dispersion dominates the material one [6, 12, 21]. It is also clear from Fig. 2(a), that the dispersion parameter increases with the increase of air-hole diameter. So for *d*/Λ values of <0.5, that is with small values of air-hole diameter, the dispersion parameter is all negative in the wavelength range considered. For the smallest value of air holes *i.e.* for *d*/Λ=0.3, the dispersion values become minimum and then the slope of the dispersion increases. For *d*/Λ=0.4, the dispersion slope is always positive in the whole wavelength considered. The other elliptical core PCFs with *d*/Λ≥0.5 has negative dispersion slope, so they can be used as dispersion compensating fibers. When the pitch becomes larger, the effect of waveguide dispersion decreases and material dispersion dominates the dispersion for both regular triangular lattice PCFs [6, 21] and for square lattice PCF [10] and circular lattice PCFs [12]. The same is confirmed for the elliptical core square-lattice PCFs in Fig. 2(b) and Fig. 2(c) as we increase Λ values to 2 μm and 3 μm respectively. The dispersion parameters for these PCF all become positive, independent of the *d*/Λ values. It is also interesting to notice that, as we increase the value of pitch the dispersion slope of the curves all becomes more positive as that of the regular square-lattice PCFs. Moreover, a change of *d*/Λ values causes only a small difference for higher values of dispersion parameter for higher values of Λ=3 μm. It is also interesting to notice that, for smaller values of *d*/Λ, like *d*/Λ=0.3, 0.4 and 0.5, the dispersion curve is quite flat for the whole wavelength range considered for Λ=2 μm.

Figure 4 shows the variation of the dispersion parameter as we change the pitch values for a fixed value of *d*/Λ, which is taken to be 0.7 for our study, although the pattern are the same for all possible values of *d*/Λ studied. Most remarkable feature of the graph is when we change the Λ values from 1 μm to 1.5 μm the dispersion parameter changes significantly. The dispersion slope is negative for Λ=1μm whereas the dispersion slope becomes positive for the 2nd case for both the polarizations as shown in Fig. 4(a) and Fig. 4(b) respectively. For all values of Λ≥1.5, the slope of the dispersion curve is always positive. For Λ values of 3µm, the slope increases initially and then starts decreasing for higher wavelengths.

3. Comparison between the Square-Lattice Elliptical PCF with Triangular-Lattice Elliptical PCF

3.1. (A) Dispersion Properties

We have made a comparison between the elliptical-core square-lattice PCFs and Elliptical core triangular-lattice PCFs for the guiding and dispersion properties. For this purpose, we have taken three air-hole rings and the same value of Λ and *d*/Λ, which are 1 µm and 0.7 respectively for both the triangular-lattice and square-lattice PCFs. Both fibers can be used for dispersion compensating as shown in Fig. 5(a) and Fig. 5(b) respectively. As can be seen from the figure, the triangular-lattice PCFs have higher value of negative dispersion in comparison to the square-lattice PCFs. So, we need to have a longer length of square-lattice PCF than the triangular one to completely compensate the dispersion at any length, especially of the NZDF at 1550 nm. The most interesting fact is that the square-lattice PCFs can better compensate the positive dispersion of a NZDF in a wide wavelength range because of its lower value of dispersion slope around 1550nm.

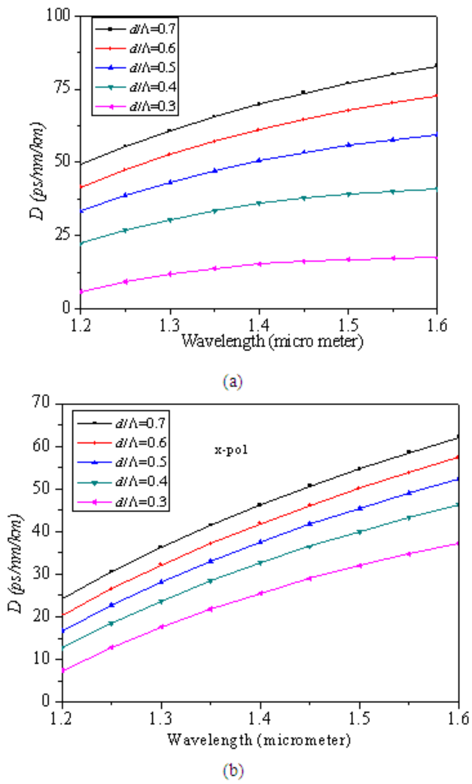


Fig 3. Dispersion parameter of the studied structure for (a) Λ=2µm and (b) Λ=3µm respectively for d/Λ values varies from 0.3 to 0.7.

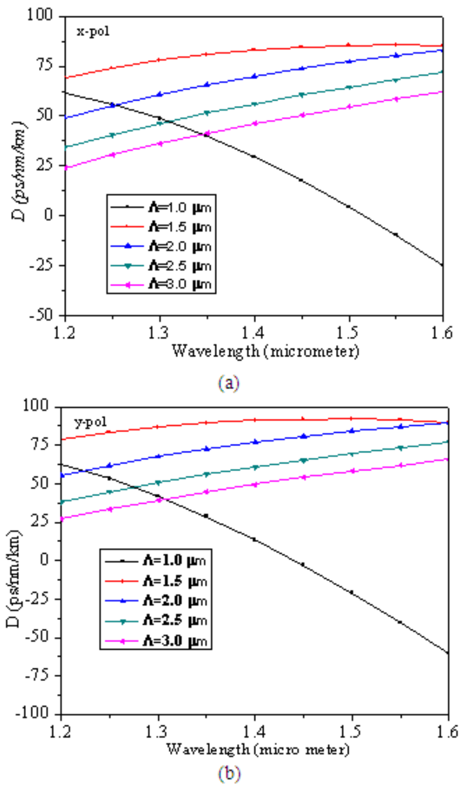


Fig 4. Dispersion curves of the elliptical-core square-lattice PCF with d/Λ 0.7 for different values of Λ (a) x-polarized component and (b) y-component respectively.

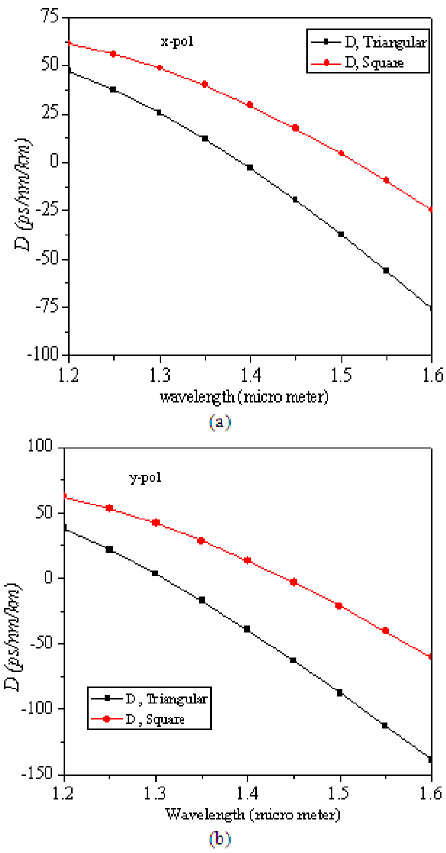


Fig 5. Comparison of the dispersion parameter for the square-lattice PCF with triangular-lattice PCF with d/Λ=0.7 and Λ=1µm.

3.2. (B) Effective Area Properties Comparison

The effective area for the elliptical core square-lattice PCFs are still small, being lower than 4 μm^2 in the entire whole wavelength considered for both polarizations as can be seen from Fig. 6 (a) and Fig. 6 (b) respectively. But this value is still higher than the triangular lattice one. For example the effective area for the square-lattice has a value approximately 22% greater than the triangular one for x polarized one and 21% for the y-polarized one at the wavelength of 1550nm.

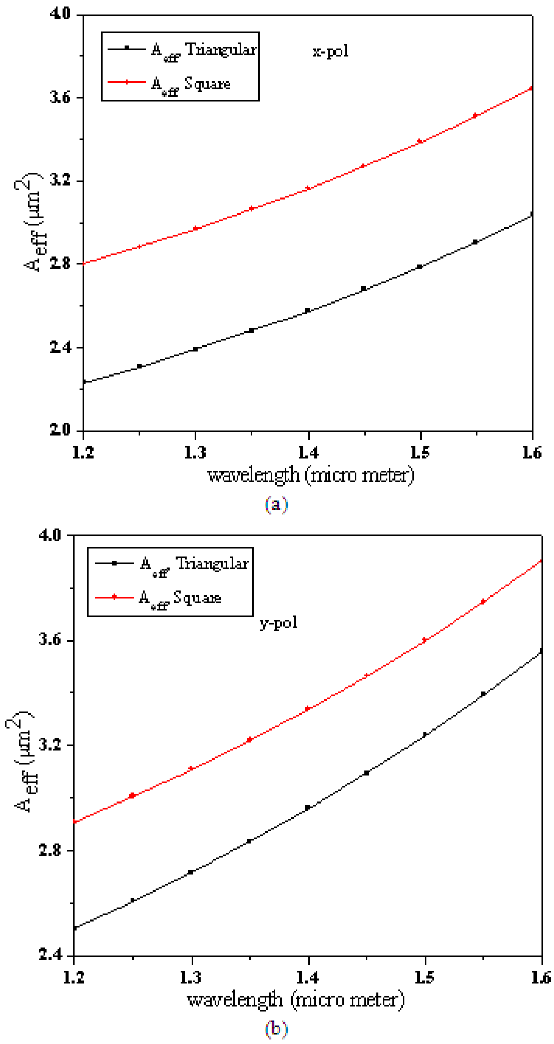


Fig 6. Comparison of the effective area of the (a) x-component and (b) y-component respectively for the square-lattice PCF with triangular-lattice PCF for d/Λ=0.7 and Λ=1μm.

The difference can be explained from the air-filling fraction $f_{\square} = (\pi d^2)/(4\Lambda^2) = 0.7854(d^2/\Lambda^2)$ for the square-lattice which is almost 86% than that of the triangular one whose $f_{\Delta} = (\pi d^2)/(2\sqrt{3}\Lambda^2) = 0.9069(d^2/\Lambda^2)$.

As a consequence of the filling fraction, the square-lattice PCFs provide higher values of average refractive index of the cladding that means a lower step index, which subsequently results in a lower field confinement.

3.3. (C) Single Mode Properties Comparison

A final analysis on the properties of both types of PCFs is reported in Fig. 7 and Fig. 8 for different values of Λ values namely 1 μm and 2 μm. We have taken d/Λ values to be 0.3 for our study such that both the elliptical core PCFs remains single-mode in the whole wavelength considered. A detail study of the single mode properties has been discussed in our previous work [16]. Elliptical core is single mode up-to a d/Λ value of 0.29; whereas the elliptical core triangular PCFs is single-mode for d/Λ value up-to 0.25. Cut-off normalized frequency (Λ/λ) for elliptical core triangular PCF and square–lattice PCF are 1.785 and 2.041 for d/Λ=0.3 respectively. An interesting fact can be seen from the figures (Fig. 7(a) and Fig. 7(b)) that square-lattice PCF has higher D values than triangular one for smaller values of Λ(*i.e.* 1 μm) and lower D values for larger values of Λ(*i.e.* 2 μm) before cross-off and vice versa after cross-off.

The dispersion slope has been affected with the geometrical characteristics of the lattice. With the increase of the Λ values to 2 μm, the slope almost vanishes as we move towards the higher wavelength ranges and the dispersion parameter is always positive in the whole wavelength range. PCFs with square-lattice always have higher effective area than triangular one for both pitches.The fundamental component of the electric field has been shown in Fig. 9. The tight confinement of the field for both type of the PCFs are clearly visible from the figures (Fig. 9 (a) and Fig. 9 (b)).

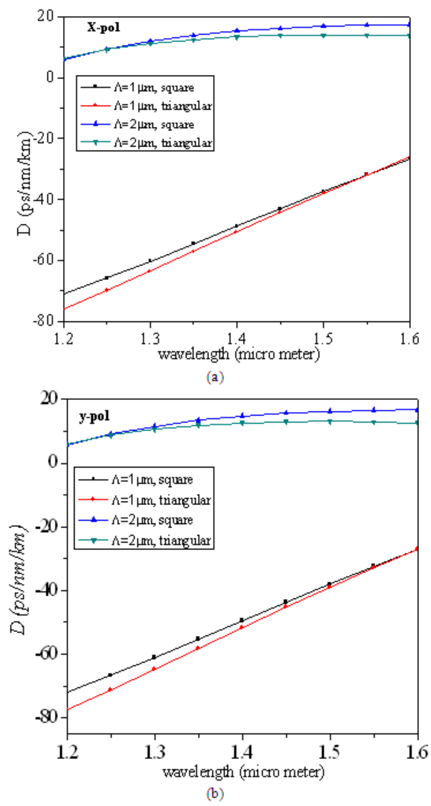
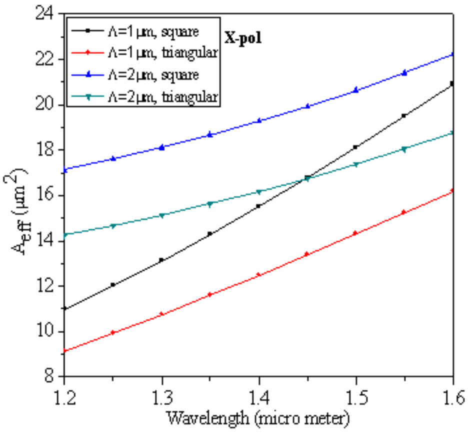
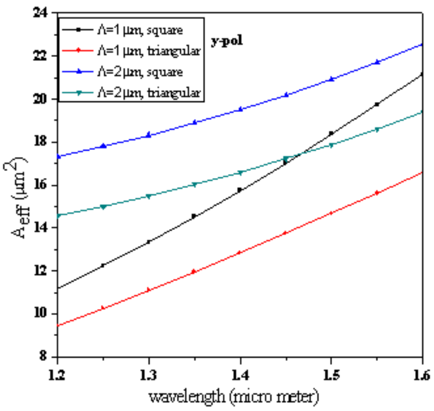


Fig 7. Comparison of the dispersion properties for the square-lattice PCFs with triangular-lattice PCF with d/Λ=0.3, for Λ=1μm and Λ=3μm.

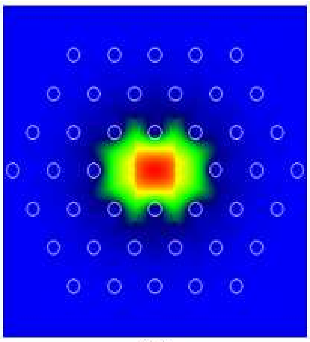


(a)



(b)

Fig 8. *Comparison of the effective area for the square-lattice PCFs with triangular-lattice PCF with d/Λ=0.3, for Λ=1μm and Λ=3μm.*


(a)

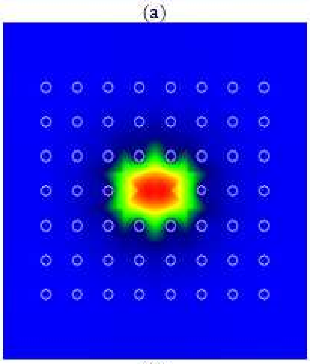

(b)

Fig 9. *Fundamental components of the Magnetic Field for (a) elliptical-core triangular-lattice PCF and (b) elliptical core square-lattice PCF.*

5. Conclusions and Discussions

We have made a detailed analysis of the guiding and dispersive properties of the elliptical-core square-lattice PCFs with silica background. Different values of hole-to-hole values and air-hole diameter has been considered, in order to show how the PCF properties are influenced by the geometric characteristics of the lattice. The properties of both the *x*-polarized component and the *y*-polarized component are discussed and it is shown that their properties are almost same for the aspects, namely dispersion and effective area, considered in the paper. It is shown that elliptical core square-lattice PCFs with smaller values of pitch Λ (1 μm) and high *d*/Λ (0.6 and 0.7) can be used as dispersion compensating fiber. For higher values of Λ, the dispersion parameter is always positive in the wavelength range considered. Dispersion parameter changes drastically if we increase the Λ values from 1 μm to 1.5 μm for a fixed value of *d*/Λ. A comparison has been performed between the triangular-lattice PCFs and square-lattice PCFs. A longer length of square-lattice PCF is required than the triangular-lattice PCF to compensate positive dispersion occurred in the normal fibers. A square-lattice PCF can better compensate the dispersion as it has lower dispersion slope around 1550 nm wavelength. Effective area for square-lattice PCF is always higher than that of the triangular-lattice PCF one. Finally, the fundamental component of the magnetic field for both type of the PCFs at 1550 nm wavelength for Λ=2 μm and *d*/Λ=0.3 are shown, which clearly indicates the tight confinement for both type of PCFs.

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