Guiding Properties of a Decagonal Photonic Crystal Fiber

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Abstract—This paper describes guiding properties of a decagonal photonic crystal fiber (D-PCF) based on isosceles triangular unit lattices. A comparison between guiding properties of hexagonal PCFs (H-PCFs) and that of the D-PCF have also been performed. Simulation results show that the D-PCF has smaller effective area, lower confinement loss, more circular field distribution and wider single mode operation in comparison to H-PCFs.

Index Terms—Photonic crystal fiber, chromatic dispersion, confinement loss, effective area.

I. INTRODUCTION

Photonic crystal fibers (PCFs) or holey fibers [1] have a microscopic array of air channels running around the undoped silica core. In this way, light can be confined and guided through the fiber by mechanisms of either a total internal reflection (TIR) or a photonic band gap (PBG). In contrast to conventional fibers, PCFs have additional design parameters namely the pitch, number of rings, and air-hole diameters that offer design flexibility which is not possible in conventional fibers. As a result, PCFs have been reported with such attractive features as endlessly single mode operation, high nonlinearity, and ultra-flattened chromatic dispersion with a low confinement loss, and so on. Thus PCFs have owned many different potential applications [2].

Generally in PCF, six air-holes are placed on the first ring in a hexagonal symmetry which is known as the hexagonal PCF (H-PCF) or conventional PCF. This type of PCF has many attractive features mentioned earlier but still it is very difficult to design a simple H-PCF in order to obtain ultra-flattened dispersion over a wide range of wavelength keeping confinement loss to a minimum level. Therefore, besides the hexagonal arrangement of air-holes, other structures, such as square lattice, honeycomb, circular-ring and octagonal-lattice have been proposed as PCF designs [3]-[5]. Design of these non-hexagonal structures depict that exactly periodic arrangement of air-holes is not necessary to guide light based on the TIR mechanism. In spite of such diversity in PCF design, demand for a simple PCF structure with ultra-flattened dispersion and low confinement loss continues. Therefore, in pursuit of a novel structure for index guiding PCF, in this paper, investigations are made for the
guiding properties of a D-PCF with isosceles triangular unit-lattices. The final objective is to provide a rule of thumb to PCF designers regarding changes in propagation properties due to a change in PCF structure. As a part of the aforesaid work, this paper describes some basic properties of D-PCF.

It has been shown that the D-PCF can assume wider single mode operation, very low confinement loss, more circular field distribution and smaller effective area in comparison to a regular triangular lattice H-PCF.

II. GEOMETRY OF THE D-PCF

Figure 1 (a) shows geometry of the D-PCF with air-hole diameter, d and pitch, \( \Lambda \) between the adjacent air-hole rings. For simplicity only two air-hole rings are shown. The spacing between air-hole centers on the same ring is \( \Lambda_1 \) and is related to \( \Lambda \) by the relation \( \Lambda_1 \approx 0.615 \Lambda \). Therefore, the maximum diameter of an air-hole may have a value of 0.3075\( \Lambda \). The D-PCF is constructed by repeating the unit isosceles triangular lattice with vertex angle 36° around the core as shown in Fig. 1(b). The core diameter is 2\( a \), where ‘\( a \)’ equals \( \Lambda-d/2 \). Air-holes of diameter, d are located at each corner of the isosceles triangle. Since an isosceles triangular lattice contains more air-holes than a regular triangular lattice for a given number of rings, the former can assume lower refractive index around the core compared to the later. Therefore, it is expected that the D-PCF has strong light confinement ability.

![Fig.1. Geometry of the proposed D-PCF, (a) a structure with two air-hole rings and (b) an unit isosceles triangle-lattice of the D-PCF.](image)

The increased air-holes result in a lower confinement loss in comparison to H-PCFs. Using the definition of air-filling fraction, AFF [3]; it can easily be shown that the air-hole radius of a D-PCF can be around 18% smaller than that of an H-PCF for the same AFF and pitch values.

III. PROPERTIES OF THE D-PCF

The finite difference method (FDM) [6] with anisotropic perfectly matched boundary layer (PML) is used to analyze the chromatic dispersion, effective area, and confinement losses based on equations given in [7]. The effective area approach is used to investigate cut-off behaviors of the D-PCF.
Figure 2 (a) shows chromatic dispersion characteristics of the D-PCF for pitch $\Lambda = 2.0 \ \mu m$ and different air-hole diameters relative to the pitch. It was observed earlier that the characteristics of chromatic dispersion curves are similar to that of an H-PCF [8]. Figure 2 (b) shows a comparison of chromatic dispersion characteristics between the D-PCF and an H-PCF. For the purpose of comparison 5 rings and $d/\Lambda = 0.50$ are used for both the cases. It is seen that chromatic dispersion of the D-PCF is larger than that of the H-PCF. Moreover, it is expected that for the D-PCF there is possibility to shift zero dispersion wavelengths towards shorter wavelengths. For $\Lambda = 1.0 \ \mu m$ negative chromatic dispersion with more negative dispersion slope is obtained than that of the H-PCF for a 1.20 to 1.60 $\mu m$ wavelength range. This indicates that a D-PCF can be designed for a dispersion compensating fiber.

![Image](a)  
**Fig. 2** (a) Chromatic dispersion characteristics of the D-PCF with five rings and $\Lambda = 2.0 \ \mu m$ (b) a comparison of chromatic dispersion between the D-PCF and the H-PCF for five rings, three different pitches (black lines for $\Lambda = 2.0 \ \mu m$, red lines for $\Lambda = 1.5 \ \mu m$ and green lines for $\Lambda = 1.0 \ \mu m$), $d/\Lambda = 0.50$.

Figure 3 (a) shows a comparison between effective areas of the D-PCF and that of the H-PCF for three pitches, five rings, $2a = 3.0 \ \mu m$, and $d/\Lambda = 0.50$. In each of the three pitch values ($\Lambda = 1.0 \ \mu m$, $\Lambda = 1.5 \ \mu m$, and $\Lambda = 2.0 \ \mu m$), effective areas of the D-PCF are less than that of the H-PCF. Figure 3(b) and (c) shows effective areas of the two types of PCF at 1.55 $\mu m$ for five rings as a function of pitch (1.0 to 2 $\mu m$) and relative air-hole size, $d/\Lambda$ (0.30 to 0.70) respectively. These results indicate that the D-PCF has inherently high nonlinearity and it can be explored in designing highly nonlinear PCFs for efficient supercontinuum generation in the telecommunication windows. Figure 4 (a) shows wavelength dependence of confinement losses of the D-PCF for $\Lambda = 2.0 \ \mu m$, $2a = 3.0 \ \mu m$ and $d/\Lambda = 0.50$. Number of rings is indicated on the figure with number of air-holes inside brackets. It is clear that the confinement loss of the D-PCF is less than 1.0 dB/m for less than or equal two-rings of air-holes in contrast to four-rings for H-PCFs [2]. A comparison of confinement losses between the fibers are shown in Fig. 4 (b). Fig. 4(c) and (d) shows the confinement losses at 1.55 $\mu m$ of the two PCFs for five rings as a function of pitch and AFF respectively. These results clearly indicate that the D-PCF possesses lower confinement loss than that of the H-PCF.
Fig. 3 (a) Comparison of effective area between the D-PCF and the H-PCF for three pitches (black lines for $\Lambda = 2.0 \ \mu m$, red lines for $\Lambda = 1.5 \ \mu m$ and green lines for $\Lambda = 1.0 \ \mu m$), $d/\Lambda =0.50$; (b) effective area of the two types of PCF at 1.55 $\mu m$ as a function of pitch for five rings and $d/\Lambda =0.50$; (c) effective area of the two types of PCF as a function of $d/\Lambda$ at 1.55 $\mu m$ for five rings.

Figure 5 (a) shows a phase diagram between single-mode and multi-mode region of operation of the two types of PCFs. The phase diagram is constructed by finding out the cut-off wavelengths for different AFF. The $\lambda/\Lambda$ values for AFF values less than 0.3 are obtained by curve fitting techniques. In both cases four-rings and $\Lambda = 1.0 \ \mu m$ pitch is used. It is known that at shorter wavelength the effective area is almost constant, but at longer wavelengths the mode field spread to the cladding region and the effective area increases significantly [3]. Therefore, crossing of a tangent line with the horizontal axis drawn at rising portion of the effective area curve indicate cut-off wavelength. Cut-off wavelengths obtained for the H-PCF are almost the same as calculated by J-S. Cheng et al. [3]. Dot marks on the same figure show the Kuhlmey et al. boundary [9]. Although the effective area approach is an approximate method, closeness of results in both cases prove validity of the effective area (approximate approach) approach. Following the same process, it can be shown that the H-PCF has a shorter cut-off wavelength for the fundamental mode and a longer cut-off wavelength for the higher order modes than that of the D-PCF. This indicates that under the same AFF and pitch condition, the D-PCF can support wider single mode operation than the H-PCF does. In other words,
the D-PCF can offer relatively wider wavelength range for single mode operation than the H-PCF under same AFF and pitch values.

Fig. 4(a) confinement loss of the D-PCF for \( \Lambda = 2.0 \, \mu m \), \( d/\Lambda = 0.50 \); (b) comparison of confinement losses (solid lines for D-PCF and dashed lines for H-PCF) with five rings, three pitches (black lines for \( \Lambda = 2.0 \, \mu m \), red lines for \( \Lambda = 1.5 \, \mu m \) and green lines for \( \Lambda = 1.0 \, \mu m \) ) and \( d/\Lambda = 0.50 \); (c) confinement loss at 1.55 \( \mu m \) of the two PCFs as a function of pitch for five rings, \( d/\Lambda = 0.50 \); (d) confinement loss versus AFF of the two PCFs at 1.55 \( \mu m \).

Fig. 5 A Phase diagram between single mode and multi-mode operation of the D-PCF and H-PCF with four rings and pitch \( \Lambda = 1.0 \, \mu m \).

Fig. 6(a) shows the fundamental mode field distribution at 1.55 \( \mu m \) wavelength of the D-PCF and Fig. 6(b) shows the same of the H-PCF for five rings, \( 2a = 3.0 \, \mu m , \Lambda = 2.0 \, \mu m \) and \( d/\Lambda = 0.50 \). It is seen that the D-PCF’s field nature is almost circular. From the above simulation results it can be
concluded that the D-PCF has wider single mode wavelength response, smaller effective area, more circular field distribution and lower confinement losses in comparison to conventional H-PCFs. The only point worthy of consideration is the fabrication issue. The well known stack and draw method can be changed to fabricate the D-PCF [10].

![Fig. 6. Fundamental mode field distribution of (a) the D-PCF and (b) the H-PCF for five rings, \( \Lambda = 2.0 \mu m \), and \( d/\Lambda = 0.50 \)](image)

IV. CONCLUSION

The propagation characteristics of a decagonal PCF (D-PCF) have been numerically investigated using the FDM method. It has been shown through numerical simulation results that the D-PCF has lower confinement loss, more circular field distribution and high non-linearity in comparison to H-PCFs. Moreover, the D-PCF operates a single mode in a wider wavelength range than H-PCFs do for the same AFF and pitch values.

REFERENCES