# Optimum Design of Photonic Crystal Fiber and its Propagation Properties

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***Abstract*— In this paper we have shown a comparison of two proposed hexagonal geometries of Photonic Crystal Fiber (PCF). These geometries are different with respect to the area of circular air holes. The area of circular air holes of the structure proposed in Fig. 1(a) is kept fixed. The area of circular air holes is kept increasing with increase in number of rings for another structure. Both structure considered consists of seven rings. At a wavelength of $0.85\mu m$ one of the PCF structure with increasing area of circular air hole report the most negative dispersion and before that almost zero dispersion. The birefringence of PCF structure with equal area of circular air hole is high compare to that of other proposed PCF structure. The confinement Loss reported is of the order of $10^{-5}$ for the PCF structure with equal area of circular air holes. The confinement factor was reported to be uniform for all the structures in this paper. The mode field pattern for both the structures appears to be a flower like shape with entire field being concentrated in the core and without leakage to cladding. The far field pattern (FFP) is also observed for both the structures.**

***Keywords*— *Birefringence, confinement loss, dispersion, total internal reflection, transparent boundary condition.***

## I. Introduction

Photonic Crystal Fibers (PCFs) have been a point of attraction for the researchers since last decade. As a result many interesting facts have been discovered. PCFs are having pure silica background and cladding containing tiny air-holes [1] . This cladding concept has resulted numerous investigation for designing PCFs. Air-holes in the cladding creates sufficient index difference between the core and the cladding to guide light by total internal reflection mechanism [2-3] . PCFs can realize flexible chromatic dispersion over a wide wavelength range. Control over chromatic dispersion is a very important for optical communications [4]. The confinement loss and birefringence are other important parameters considered during designing of PCFs [5]. The parameters that affect the dispersion, birefringence confinement loss and other linear and non-linear properties of the PCFs include its profile shape, number of air holes, diameter of the air holes and distance between the centre of two air holes [6-7]. Numerous designs have been investigated by varying the above mentioned parameters. Various index guiding PCFs with remarkable dispersion and leakage properties also have been reported [8-9]. PCFs with different air hole diameters have also been proposed [10]. A PCF structure whose dimensions are derived from Pascal's triangle and Dolph Tschebyscheff polynomials has been investigated and was found showing negligible dispersion for a wide range of wavelength [11-12]. For other structures of PCF one can refer [13-14] and the reference therein.

In this paper we have reported a comparative study of two proposed hexagonal PCF structure with difference in their area of circular air holes. The structures studied in this paper consists of seven rings of air holes. One of the structure presented consists of circular air holes of equal area. The other structure consists of circular air holes having increasing area with increase in number of rings. The proposed structure is analyzed with full vector mode solver using FDTD method. The simulations are carried out using OptiFDTD simulator. It is found that the structure with variation in area of air-holes shows very low dispersion compare to the other structures. However other structure shows comparatively low confinement loss and high birefringence. Hence both the structures are good candidates for applications like high data rate data transfer and optical communications.

The rest of the paper is organized in three more section. In section II we present some new structures for the index guided PCFs. The simulation results of these structures are shown in section III. At last in section IV we conclude our work.

## II. Proposed Structure

In this section we proposed two index guided photonic crystal fiber structures. The proposed index guided PCF structure as shown in Fig. 1(a) is an hexagonal structure. The hexagonal shaped proposed PCF structure consists of seven rings of circular air holes. The other proposed structure is compared with hexagonal structure PCF shown in Fig. 1(a). The proposed hexagonal PCF structure as shown in Fig. 1(b) also consists of seven rings of circular air holes. The proposed structure as shown in Fig. 1(a) consists of circular air holes of equal radius. The proposed hexagonal PCF structure as shown in Fig. 1(b) consists of circular air holes of different radius. The radius of inner most ring of the hexagonal proposed PCF structure is $0.5\mu m$ as shown in Fig. 1(b). Similarly the radius of the $2^{nd}$ , $3^{rd}$, $4^{th}$, $5^{th}$, $6^{th}$ and $7^{th}$ ring are $0.55\mu m, 0.6\mu m, 0.65\mu m, 0.7\mu m, 0.75\mu m$ and $0.8\mu m$ respectively as shown in Fig. 1(b). The radius of circular air holes of all rings of proposed hexagonal PCF structure is $0.6\mu m$ as shown in Fig. 1(a). The motivation for choosing the variation in the radius of the circular air holes is to compare the results of hexagonal PCF structure having equal area of circular air holes with that of hexagonal PCF structure having increasing area of circular air holes. Hence it would be interesting to compare and study the dispersion behavior, confinement loss, birefringence and other propagation characteristics of the proposed PCF structures.

The waveguide dispersion at different wavelength for the structures is calculated using the formula [12]:

$$D = -\frac{\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2} \quad (1)$$

where $D$ is the dispersion in ps/(nm-km), $n_{eff}$ is the effective modal index number and is the wavelength in $\mu m$. and c is the velocity of light in free space. The $n_{eff}$ effective modal index is obtained from the simulations as a function of the wavelength and its second order derivative is computed using the three point difference formula for approximating the derivative. The birefringence of the structures proposed are calculated by using the formula [12]:

$$B = \langle n_x - n_y \rangle \quad (2)$$

where B is the birefringence, $n_x$ and $n_y$ are the effective refractive indices of two fundamental polarization mode $(HE_{11}^{x})$ and $(HE_{11}^{y})$.The confinement loss of all the structure is calculated by using the formula [12]:

$$L_c = 8.686\,\mathrm{Im}[k_0 n_{eff}] \quad (3)$$

where $k_0$ is the free space number and is equal to $\frac{2\pi}{\lambda}$ , $\lambda$ is the corresponding wavelength, $\mathrm{Im}[n_{eff}]$ is the imaginary part of (effective modal index number). The normalised wavelength is defined as the ratio of the wavelength to that of the pitch factor $(\wedge)$. The confinement factor can be considered as a new quantity which relates the gain and the field distribution in a dielectric waveguide with complex refractive index. It is valid for any guided mode of waveguide with an arbitrary cross section. The shape of the far field pattern (FFP) of power distribution at the output of optical fiber determined by fiber modal distribution, which depends on fiber length, launching condition and coupling strength.

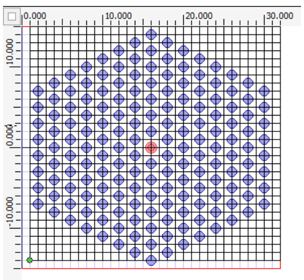

Fig. 1(a) The PCF structure with equal radius of circular air hole.

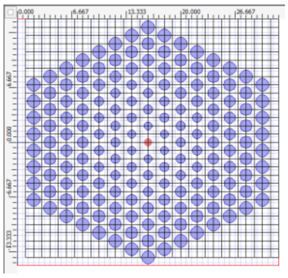

Fig. 1(b) The PCF structure with increasing radius of circular air holes.

## III. Simulation Results

In this section we present the simulation results of the proposed structures carried out in the OptiFDTD software. The area of circular air hole of the structure shown in Fig. 1(a) is kept same. For the structures shown in Fig. 1(b) the area of circular air hole increases with increase in number of each ring. The pitch factor $(\wedge)$ which is centre to centre spacing between the two nearest air hole , gives the characteristics of lattice of the PCF. The pitch factor $(\wedge)$ for both the structures proposed is chosen as $\wedge = 1.0\mu m$. The wafer is chosen of pure silica and is set to be of refractive index $n = 1.46$ and that of the air holes is $n = 1$. The boundary condition chosen is Transparent Boundary Condition (TBC). The mesh size for the finite difference time domain (FDTD) simulations is $\Delta x = \Delta z = 0.106\mu m$. The wafer length chosen for the structures proposed in Fig. 1(a) and Fig. 1(b) is $32\mu m$ whereas the width taken is also $30\mu m$. The diameter chosen of the circular air holes for the structure as shown in Fig. 1(a) is $1.2\mu m$. The diameter for the structure as shown in Fig. 1(b) has kept on increasing with a difference of $0.1\mu m$.

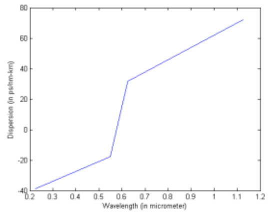

Fig. 2(a) The relation between dispersion and wavelength of the PCF structure proposed in Fig. 1(a).

We calculated the waveguide dispersion for the proposed structures at different wavelengths using (1) and the corresponding result have been shown in Fig. 2(a) and Fig. 2(b) respectively. It can be observed from Fig. 2(a), the negative dispersion was reported up to $0.6\mu m$ whereas maximum positive dispersion was reported at $1.15\mu m$.

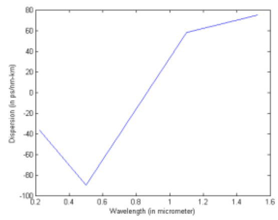

Fig. 2(b) The relation between dispersion and wavelength of the proposed PCF structure in Fig. 1(b).

As it can be seen from the Fig. 2(b) the structure shown in Fig. 1(b) has shown the maximum dispersive value at a wavelength of $1.55\mu m$. It is to be noted the structure shown in Fig. 1(a) shows the same maximum positive dispersion but at wavelength of $1.1\mu m$. The dispersion reported at wavelength of $0.85\mu m$ was zero . A negative dispersion is observed up to $0.85\mu m$. A comparison of dispersion for both the structures is shown in Fig. 2(c). It is also observed that the structure shown in Fig. 1(b) can propagates at higher wavelength maintaining the same dispersion .

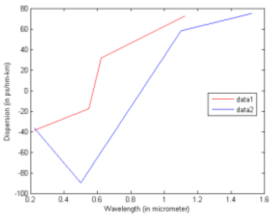


Fig. 2(c) A comparison of the relation between dispersion and wavelength of proposed PCF structure. Data1 and data2 shows the dispersion value of PCF structure proposed in Fig. 1(a) and Fig. 1(b) respectively.

The birefringence of the structure proposed in Fig. 1(a) and Fig.1(b) was calculating using (2) and the results were shown in Fig. 3(a) and Fig. 3(b) respectively. The birefringence reported for structure shown in Fig. 1(a) is of the order of $10^{-4}$.

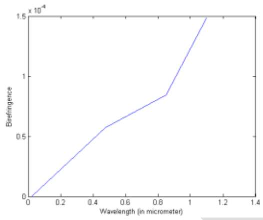


Fig. 3(a) The relation between birefringence and wavelength of proposed PCF structure in Fig. 1(a).

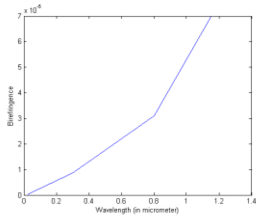


Fig. 3(b) The relation between birefringence and wavelength of PCF structure proposed in Fig. 1(b).

As it can be seen from the Fig. 3(b) the birefingence of the PCF structure shown in Fig. 1(b) is observed to be of the order of $10^{-5}$.

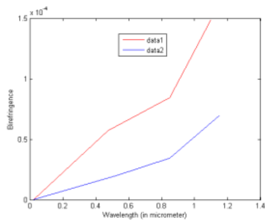


Fig. 3(c) A comparison of the relation between birefringence and wavelength of proposed PCF structure. Data1 and data2 shows the birefringence value of PCF structure proposed in Fig. 1(a) and Fig. 1(b) respectively.

A comparison is shown in Fig. 3(c) of birefringence and wavelength of the structures shown in Fig. 1(a) and Fig. 1(b). The data1 and data2 are showing the birefringence of structure shown in Fig. 1(a) and Fig. 1(b) respectively. As can be seen from Fig. 3(c) the birefringence of the structure reports to be higher for the same wavelength.

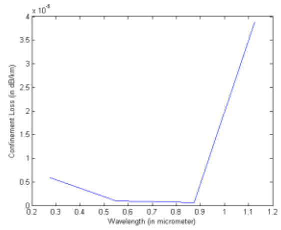


Fig. 4(a) The relation between confinement loss and wavelength of PCF structure proposed in Fig. 1(a).

The confinement loss of the structure proposed in Fig. 1(a) and Fig.1(b) was calculating using (3) and the results were shown in Fig. 4(a) and Fig. 4(b) respectively. The structure as shown in Fig. 1(a) reported a confinement loss of the order of $10^{-5}$. It can be seen from the Fig. 4(a) that the confinement loss was almost zero up to a wavelength of $1.2\mu m$.

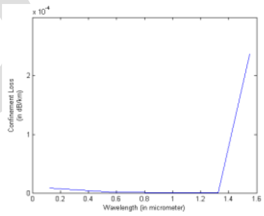


Fig. 4(b) The relation between confinement loss and wavelength of proposed PCF structure as shown in Fig. 1(b).

The confinement loss at different wavelength of the PCF structure as shown in Fig. 1(b) can be seen in Fig. 4(b). It is seen that the confinement loss reported is of the order of $10^{-4}$. It is to be noted that the confinement loss reported is zero up to a wavelength of $1.3\mu m$. Comparing the result as shown in Fig. 4(a) and Fig. 4(b) it can be concluded that the structure shown in Fig. 1(a) reports low confinement loss for the same wavelength.

We also show the effective modal index number versus normalised wavelength curve in for all the structures proposed in this paper. The normalised wavelength as defined earlier is the ratio of wavelength and the pitch factor $\lambda / \wedge$. As seen from Fig. 5 the value of modal index number decreases with increasing value of normalised wavelength showing good agreement from theory [13-14].

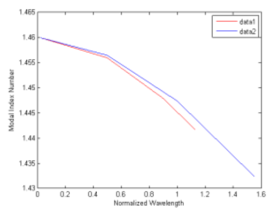


Fig. 5 The relation between modal index number and normalized wavelength of the proposed structure.

The confinement factor which shows a relation between gain and field distribution is also calculated. The Fig. 6(a) and Fig. 6(b) shows the realation between confinement factor and the corresponding wavelength of the structures proposed in Fig. 1(a) and Fig. 1(b). respectively. It is observed that both PCF structure shows an uniform relationship. The confinement factor is decreasing with the increase in wavelength.

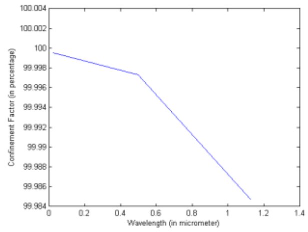


Fig. 6(a) The relation between confinement factor and wavelength of the proposed structure as shown in Fig 1(a).

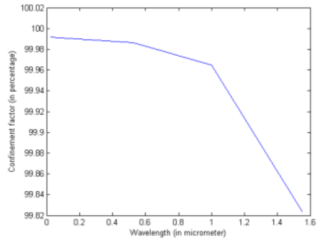


Fig. 6(b) The relation between confinement factor and wavelength of the PCF structure proposed in Fig. 1(b).

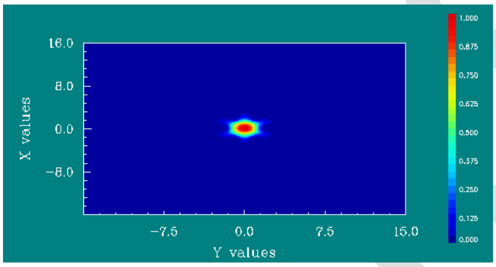


Fig. 7(a) Mode field pattern at wavelength $1.0\mu m.$ of the structure shown in Fig. 1(a).

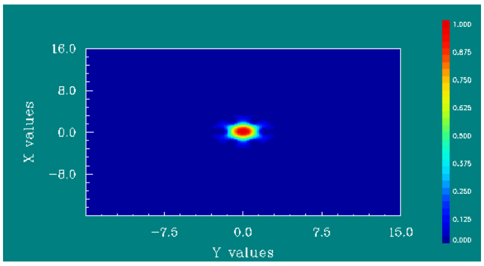


Fig. 7(b) Mode field pattern at wavelength $1.0\mu m.$ of the structure shown in Fig. 1(b).

The mode Field pattern for both the structures is also observed as shown in Fig. 7(a) and Fig. 7(b). The mode field pattern for both the structures appears to be a flower like shape with entire field being concentrated in the core and without leakage to cladding.

## CONCLUSION

In this paper we have shown a comparison of two hexagonal geometries of Photonic Crystal Fibers (PCFs). These geometries are different with respect to the area of circular air holes. It was found that structure with uniform area of air holes shows good results excluding dispersion. At a wavelength of $0.85\mu m$ one of the PCF structure with increasing area of circular air hole report the most negative dispersion and before that almost zero dispersion. The birefringence of PCF structure with equal area of circular air hole is high compare to that of other proposed PCF structure. The confinement Loss reported is of the order of $10^{-5}$ for the PCF structure with equal area of circular air holes. The confinement factor was reported to be uniform for all the structures in this paper. Thus both the structures are good candidates for applications like high data rate data transfer and optical communications.

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