# Design and Analysis of Honeycomb PCF for Ultra Flatten Dispersion for Broadband Communication

**Kailashika Rajee, Rahul Jain**

***Abstract*— The proposed Photonic Crystal Fiber (PCF) contains the high index core region enclosed with air holes of different diameters in a hexagonal structure. The proposed PCFs structure has been simulated via finite difference time domain (FDTD) technique with transparent boundary condition. For the proposed design geometrical parameters like air hole diameters and pitch are manipulated to obtain the nearly zero ultra flatten dispersion, low confinement loss as well as endlessly single mode fiber PCF. The proposed structure of index guided Honeycomb PCF has almost zero ultra flatten dispersion of 0±0.12 ps/(nm.km) in 1.37 µm to 1.715 µm wavelength range and confinement loss of the order of 10-5dB/m at third telecom window.**

***Index Terms*— Finite difference time domain (FDTD), Effective Refractive Index (neff), Photonic Crystal Fiber (PCF), Transparent Boundary Condition (TBC).**

## I. INTRODUCTION

The Photonic crystal fibers (PCFs) have been a center of attraction in recent time due to its exceptional propagation properties since 1992 [1]. The dispersion property of the PCFs is different from the conventional optical fibers because of the unnatural periodic cladding arrangement of air holes with micrometer diameter. These flexible air hole diameters permit the flexible tailoring of dispersion curves. The chromatic dispersion management is very significant for designing nonlinear systems [1], the optical communication systems [2] and dispersion controllers [3]. The Index guiding PCFs [1], [2], [4]-[6] also recognized as holey fibers (HFs) in which periodically arranged air holes around the solid core offer extraordinary properties like wide single mode wavelength range [2], great controllability in chromatic dispersion [2], [4], [5], [7]-[10], effective mode area [1], [2], [9] high birefringence [1], low confinement loss [1]-[5], [7]-[10] and many more . As a result of these unusual fiber properties, PCFs are supposed to be recognized as novel kind of functional devices.

The designing of PCFs is different as compared to conventional PCFs. To design PCFs, a finite number of air holes in the cladding region is managed. In the index guided PCFs, varying the diameter of each air hole ring and air hole pitch in the cladding structure it is possible to manage both dispersion as well as confinement loss in the broad wavelength range.

A number of designs have been investigated for the PCFs to achieve nearly zero ultra flatten chromatic dispersion properties. In the Conventional PCFs air holes are managed in a regular triangular lattice with all the air holes having same diameter [4], air holes with two defected core PCFs [11], PCF with triangular lattice with different types of air holes diameter [1], [4], [9]-[11], hexagonal PCFs with modified elliptical air holes [4] as shown in Fig. 1, square lattice PCFs [9] as shown in Fig. 2 and honeycomb PCF with different diameter [2].

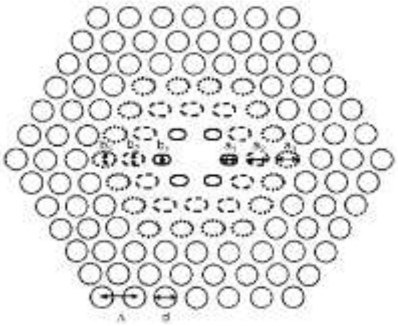

**Fig. 1 Hexagonal PCF with Elliptical Air Holes [4]**

There are different PCF [5], [7], [8] structures based on a different number of air holes rings and their arrangement. The design process becomes difficult as it requires four or five rings of different air hole diameters for each ring as well as single pitch to get nearly zero ultra flatten dispersion.

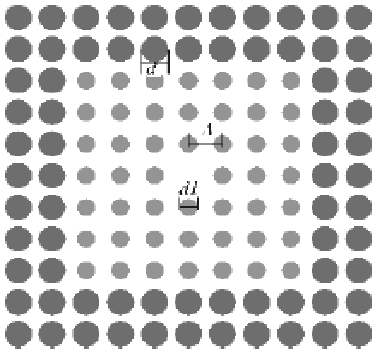

**Fig.2 Schematic Cross Section of Square Lattice PCF [9]**

In the previous work the proposed PCFs demonstrated ultra-flattened chromatic dispersion [2], [4], [5], [7]-[12], low confinement loss [1]-[5], [7]-[10] and endlessly single mode fiber [6].

All These researches have been mainly concerned with creating designs for the purpose to offer flat dispersion as well as low confinement loss and no concern about the fabrication accuracy is required in order to obtain the desired.

In this proposed work, a honeycomb PCF with different air holes and one pitch is designed as well as numerically examined. Through the analysis, it is observed that nearly zero ultra flatten dispersion can be achieved by a honeycomb PCF for different optical windows with the help of different air hole diameters and pitch. In addition, the proposed honeycomb PCF also shows low confinement losses and endlessly single mode operation in different applications. For the simulation purpose finite difference time domain (FDTD) method [9], [10], [12] is used with transparent boundary

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condition (TBC) to analyze the various properties of PCF. From the investigated results, it is found that the proposed honeycomb PCF offers nearly zero ultra flattened chromatic dispersion of 0±0.12 ps/(nm.km) in the optical window with confinement loss of the order of $10^{-5}$ dB/m. These are found to be more flat and wider than those of reported triangular, square PCFs and honeycomb structures [1], [2], [4],[9]-[12].

## II. Transmission Window of PCFs

PCF offers various advantages over the conventional optical fiber. In optical transmission window, PCF offers zero dispersion and uniform response in the different wavelength range. Due to various unique properties PCFs are widely used in fiber sensors application [1], supercontinuum generation [12], nonlinear optics [1], [5], [7], medical instrumentations [2], [12] which are not achievable in conventional optical fiber.

There are different optical wavelength bands or windows as (see Table I)

**Table I Optical Transmission Windows [14]**

| Band Description | Wavelength Range |
|---|---|
| Original Band (O band) | 1.26 to 1.36 µm |
| Extended band (E band) | 1.36 to 1.46 µm |
| Short wavelengths band (S-band) | 1.46 to 1.53 µm |
| Conventional Wavelength band (C-band) | 1.53 to 1.565 µm |
| Long Wavelengths band (L-band) | 1.565 to 1.625 µm |
| Ultra long Wavelengths band (U-band) | 1.625 to 1.675 µm |

In the silica glass, minimum attenuation loss occurs at 1.55 µm wavelength and the minimum material dispersion is accounted for 1.312 µm wavelength. Basically, there are three optical windows; the first generation belongs to 0.87 µm wavelength, for this window attenuation as well as material dispersion is comparatively high. Most of the communication systems are operated in the second and third optical window [14].

## III. Honeycomb Structure

In Fig. 3, the schematic cross section view of the investigated honeycomb PCFs structure with seven rings is shown. The proposed PCF is designed with circular air holes in the cladding region in a triangle lattice arrangement, where pitch (^) is the center to center spacing of the air holes and d is the air hole diameter. Here Silica is used as background material with refractive index 1.45 and refractive index of air holes is 1.0.

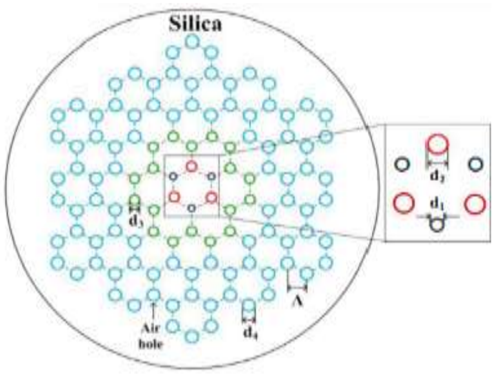


**Fig. 3 Schematic cross-section of honeycomb PCFs [2]**

The proposed honeycomb PCFs structure design is obtained by omitting some air holes in every ring. To design the proposed structure four different types of air holes diameter $d_1$, $d_2$, $d_3$, $d_4$ and single pitch (^) i.e. spacing between air holes are used. To achieve the nearly zero dispersion, suitable design according to these parameters is investigated. Through the analysis, it is obtained that the dispersion characteristics are dominantly influenced by the air hole sizes of the inner rings.

Consequently, careful choice of inner ring air hole diameter plays an important role in achieving desired dispersion properties. To reduce the confinement loss, diameter of outer air hole rings is maintained outsized enough. In the optical communication system, dispersion plays a significant part because it finds out the information carrying capacity of the fiber. As a result, it becomes essential to consider the dispersion properties of PCF.

## IV. Proposed Structure and Simulated Result

For the proposed design; dispersion, confinement loss and endlessly single mode operation properties are analyzed. The dispersion (D) is related to the subsequent derivative of the effective refractive index ($\eta_{eff}$) with regard to the wavelength ($\lambda$) and can be calculated as [1]-[5], [7]-[12]:

$$D = -\left(\frac{\lambda}{c}\right)\frac{d^2}{d\lambda^2}\left[R_e\left(n_{eff}\right)\right] \qquad (1)$$

Where Re ($\eta_{eff}$) is the real part of $\eta_{eff}$, $\lambda$ is the wavelength, and c is the velocity of light in vacuum.

The total (chromatic) dispersion is the sum of the waveguide dispersion and the material dispersion and can be obtained as [1], [4], [11], [12]:

$$D(\lambda) = D_g(\lambda) + \Gamma D_m(\lambda) \qquad (2)$$

Here the confinement factor in material and its value is near to unity. $D_g(\lambda)$ and $D_m(\lambda)$ are waveguide and material dispersion. The waveguide dispersion is influenced by the different air holes diameter as well as the pitch of the structure. The material dispersion can be calculated by sellmeier equation as below [11], [12]

$$n = \sqrt{1 + \frac{A_1\lambda^2}{\lambda^2-\lambda_1^2} + \frac{A_2\lambda^2}{\lambda^2-\lambda_2^2} + \frac{A_3\lambda^2}{\lambda^2-\lambda_3^2}} \qquad (3)$$

Here $\lambda$ is the operating wavelength in µm and the Sellmeier coefficients for Fused silica (fluorine-doped silica 1 mole %) are:

$A_1$ = 0.696166300, $A_2$ =0.407942600, A3 = 0.897479400
$\lambda_1^2$= 4.67914826×$10^{-3}$µm$^2$, $\lambda_2^2$= 1.35120631×$10^{-2}$µm$^2$,
$\lambda_3^2$= 97.9340025 µm$^2$.

The Confinement or leakage loss originates from the finite width of the cladding structure. By selecting the parameters d and Λ properly in PCFs, confinement loss can be formulated minimum. The rise in the amount of air hole rings ends up in a supplementary reduced confinement loss. Confinement loss can be calculated by [2], [5], [7], [8]:

$$\text{Confinement Loss (dB/m)} = 8.686\ \text{Im}[k_0 * n_{eff}] \qquad (4)$$

Where $k_0 = \frac{2\pi}{\lambda}$ , $\lambda$ is the wavelength of light and $n_{eff}$ is the effective refractive index of the proposed structure.

PCF is proposed for endlessly single mode operation for a wide range of the infrared spectrum. A parameter known as normalized frequency 'V' is utilized to calculate the number of guided modes in conventional step index fiber [6];

$$V = \frac{2\pi\Lambda}{\lambda}\sqrt{\left(n_{core}^{2} - n_{cladding}^{2}\right)} \qquad (5)$$

Where $\Lambda$ is pitch, $n_{core}$ is the refractive index of core and $n_{cladding}$ is the refractive index of cladding.

To investigate the proposed honeycomb structure total five designs (Design-1 to Design-5) are analyzed for different properties of PCF. For this configuration, cladding contains lower refractive index as compared to the core.

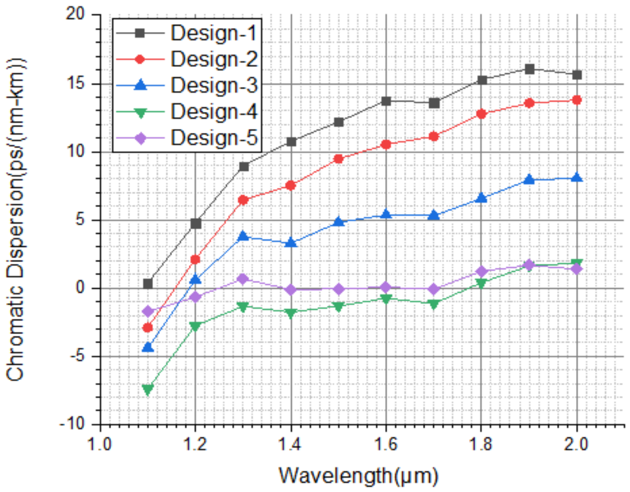


**Fig. 4 Effect on dispersion by changing pitch while keeping diameters of air holes constant**

Figure 4 shows the effect of changing pitch from Design-1 to Design-5 for dispersion property. In the proposed Desgin-1 to Design-5, air holes diameter $d_1$= 0.54 μm, $d_2$= 0.792 μm, $d_3$= 0.7812 μm, $d_4$= 1.415 μm are constant for all the proposed design and variable pitch 1.85 μm, 1.80 μm, 1.70 μm, 1.60 μm and 1.62 μm designed according to Fig. 3.

Here Fig. 4 shows the effect on the dispersion of change in pitch while air hole diameters are constant for all the proposed design. It can be observed that dispersion is highly influenced by the change in pitch. Design-5 shows the nearly ultra flatten dispersion for 1.37 μm to 1.715 μm wavelength range. Based on this result, it can be concluded from all the proposed design that Design-5 is best among all the proposed designs.

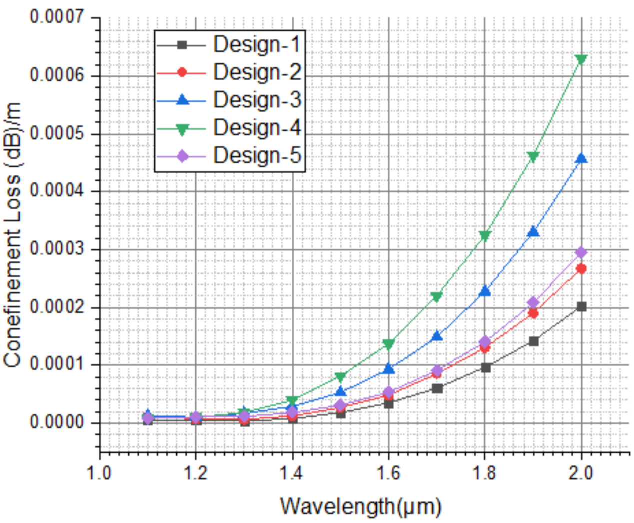


**Fig. 5 Effect on confinement loss by changing pitch while diameters of air holes are constant**

Fig. 5 shows the effect of changing pitch from Design-1 to Design-5 on confinement loss. Here Fig. 5 shows the effect on confinement loss of change in pitch while air hole diameters are constant for all the proposed designs. It can be observed that confinement loss is also influenced by the change in pitch. Design-1, Design-2 and Design-5 have almost same confinement loss for wide wavelength as that of Design-3 and Design-4.

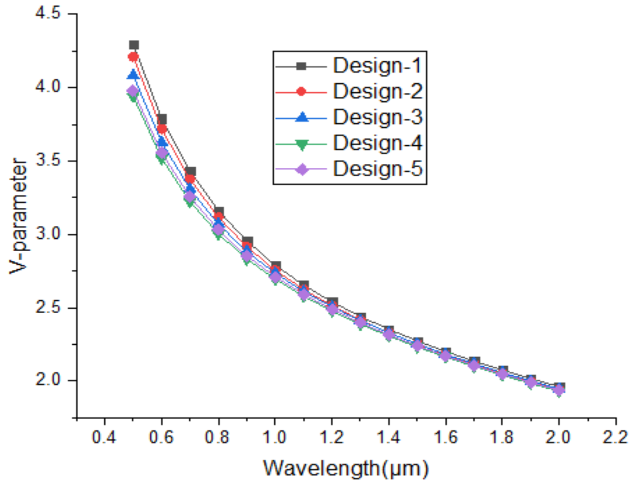


**Fig. 6 Effect on V-parameter by changing pitch while diameters of air holes are constant**

Fig. 6 shows the effect of changing pitch on V-parameter from Design-1 to Design-5. Here Fig. 6 shows the effect of changing pitch on V-parameter while keeping air hole diameters constant for all the proposed designs. It can be observed that V-parameter is also influenced by the change in pitch. All the proposed designs show endlessly single mode operation.

Here Fig. 7 shows the chromatic dispersion curve for proposed Design-5. Design-5 shows the nearly ultra flatten dispersion for 1.37 μm to 1.715 μm wavelength range. Based on this result it can be concluded that from the all proposed designs, Design-5 is best.

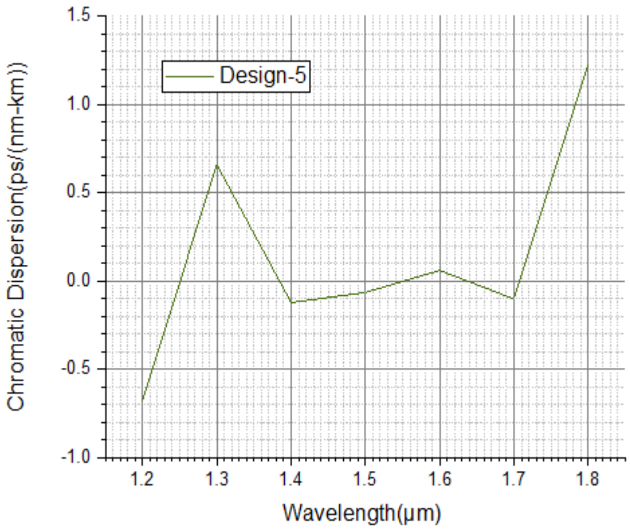


**Fig. 7 Chromatic Dispersion for Proposed Design-5**

Table II shows the comparison of those fibers having flat dispersion, wavelength range and the number of design parameters including the number of rings ($N_r$), number of pitch ($N_\Lambda$) and number of different diameter of holes ($N_d$) which are used in PCF designs.

**Table II Comparisons of Reference Papers with Proposed Design-5**

| PCF | Comparison of Properties | | | |
|---|---|---|---|---|
| | **Wavelength Range** | **Dispersion ps/ (km-nm)** | **Flat Band (nm)** | **Nr, $N_{\Lambda}$, $N_d$** |
| Ref. [4] | 1.315 µm to 1.855 µm | 0.5 ps/nm/km | 540 | 6,1,4 |
| Ref. [5] | 1.44 µm to 2.0 µm | 0±0.25 ps/nm/km | 560 | 5,1,2 |
| Ref. [9] | 1.375 µm to 1.605 µm | 0±0.06 ps/nm/km | 230 | 5,1,2 |
| Ref. [7] | 1.25 µm to 1.70 µm | 0 ± 1.20 ps/nm/km | 450 | 6,1,3 |
| Ref. [2] | 1.39 µm to 1.70 µm | 0±0.2 ps/nm/km | 310 | 7,1,4 |
| Proposed Design-5 | 1.37 µm to 1.715 µm | 0±0.12 ps/nm/km | 345 | 7,1,4 |

From the above Table II, it can be concluded that the proposed Design-5 has flattened dispersion as compared to previously proposed designs.

## V. Conclusion

Honeycomb PCF structure is proposed as well as numerically analyzed that contains a high index core enclosed by air holes with different air hole diameters. For the designing purpose, few geometrical parameters like $d_1$, $d_2$, $d_3$, $d_4$ and pitch (^) are optimized and with the help of these optimized parameters nearly ultra flatten zero dispersion over a wide wavelength range is efficiently achieved. Moreover, the proposed PCF also offers low confinement losses and endlessly single mode operation. In comparison with several proposed designs of previous research works, it offers flattened dispersion. The proposed design also offers advantage easy fabrication due to less number of air holes. It has been shown that the proposed index guided honeycomb PCF has nearly zero ultra flatten chromatic dispersion of 0±0.12 ps/(nm-km) in the third optical window. The final conclusion of the proposed research work is that the honeycomb PCF could be appropriate for chromatic dispersion management applications like chromatic dispersion controller, dispersion compensator as well as nonlinear optical application.

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