Design and Analysis of Photonic Crystal Fiber with Nearly Zero Ultra Flattened Chromatic Dispersion

Rupayali Swaroop, Himanshu Joshi, Ramesh Bharti

Abstract— **A simple index-guiding hexagonal-lattice photonic crystal fiber is presented in this paper for almost Zero Ultra Flattened Chromatic Dispersion with extremely low confinement loss. In this type of PCF, finite-difference time-domain (FDTD) method with the perfectly matched layers boundary conditions has been used. The proposed holey fiber presents dispersion flattened optical fiber (DF-PCF) for tailoring near zero ultra-flatten dispersion of 0.58 ps /nm/km for 1.265 µm to 1.64 µm wide wavelength range or 375 nm flat band as well as low confinement losses of near 10-5 dB/km. By simulation result it is possible to achieve near zero ultra-flatten dispersion of 0.58 ps/nm/km for 1.265 µm to 1.64 µm with low confinement losses of the order less than 10-5 dB/km for second and third optical window which can be properly utilized in broadband optical transmission applications.**

Index Terms— **Ultra-flatten Dispersion, Confinement Loss, Finite Difference Time Domain (FDTD), Dispersion Flattened Optical Fiber (DF-PCF), Photonic Crystal Fiber (PCF).**

I. INTRODUCTION

The microstructure optical fiber (MOFs) [1] or index guiding photonic crystal fiber [1] generally contains a hexagonal collection of microscopic air channels running along the length of the silica based fiber surrounding a solid silica core. It is interesting to note that their Chromatic dispersion as well as modal properties can be managed considerably through varying air holes size, number of holes and their positions [1]-[5]. Hence, dispersion flatten fiber demonstrate a number of extraordinary properties including wide range single mode operation [6]-[8], zero dispersion for wide wavelengths range [1], [3]-[5], high as well as low nonlinearities [8], high birefringence [6], [4]-[7] and ultra-flatten dispersion [3]-[5],[7] . As a result, dispersion flatten fiber are so unusual in managing application specific dispersion and modal properties [1], [3]-[5]. The chromatic dispersion control is vital for practical applications of optical fiber communication systems such as dispersion compensation [8] and nonlinear optics [8]. Additionally, in cladding region there is a finite number of air holes, guided modes of high frequency are basically leaky, hence control of confinement losses [9], [7] are also essential. By modulating of air holes parameters of the cladding region, it is likely to design application specific guiding properties. For instance, a very high or very low nonlinearity [8], dispersion flatten fiber for wide wavelength range [1], [2]-[4] high birefringence [2]-[7], endlessly single mode guiding [10] and many more. Largely in broad band communication systems, fiber dispersion and confinement loss plays significant roles.

For instance, in the wavelength division multiplexing (WDM) systems it is required to maintain a regular response in different wavelength channels[1], [2]-[5].

As a result, this new property enables in tuning transmission characteristics such as dispersion, nonlinearity and confinement loss. The proposed PCF structure with 1550 nm flat bandwidth dispersion which is an optimized model of the dispersion flattened reported through Sumaiya Kabir et al [3], a 350 nm flat bandwidth dispersion with five rings optimized model of the dispersion flattened reported through Chowdhury et al [5].

A novel five ring PCF structure with near zero ultra-flatten dispersion in 1.265 µm to 1.64 µm wide wavelength range is proposed. The proposed design can manage effectively as a single mode fiber with ultra-flatten chromatic dispersion of 0.58 ps/nm/km (375 nm bandwidth) as well as low confinement loss near about 10^{-5} dB/km.

II. DESIGN METHODOLOGY

Fig. 1 illustrates the simple structure of the proposed PCF design [5] with refractive index of the air hole is 1.0 while material is fiber silica. The five ring structured dispersion flattened PCF circular air hole diameters d_1, d_2 and pitch (^). The air hole diameters on the first ring, second ring and third ring is d_1, d_2, d_3 while air hole diameters on the 4^{th} to 5^{th} ring is same d_4 and pitch (^).

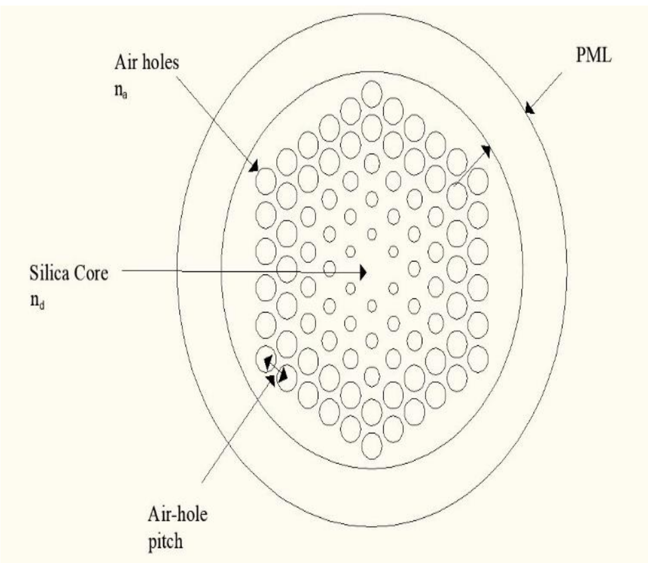

Fig. 1 Geometry of proposed five-ring

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Fig. 1, shows for managing the dispersion these five rings have four degrees of freedom to control dispersion behavior such as d_1, d_2, d_3, d_4 and pitch (^) to shape dispersion property whereas diameter of air holes on outer rings are kept larger for better field confinement. It is possible to show numerically a design which is comparatively simple PCF structure with fewer parameters for the telecommunication window without distorting the dispersion flatness as well as low confinement loss.

III. SIMULATION METHODOLOGY

In this holey fiber the Opti-FDTD software 8.0 version is used for investigating the guiding properties . The finite difference time domain (FDTD) method with transparent boundary condition (TBC) is used to calculate effective refractive index, chromatic dispersion, confinement loss and endlessly single mode fiber of proposed structure. The FDTD reliably solves the Maxwell equations to the best approximate value of the effective refractive index. Chromatic dispersion can be achieved using the following relation [1], [3]-[7]:

$$D = -\frac{\lambda}{c}\frac{d^2 \mathrm{Re}(n_{eff})}{d\lambda^2} \qquad \text{Eq. 1}$$

Where $\mathrm{Re}(n_{eff})$ is the real part of effective refractive index, n_{eff}, c is the velocity of light in vacuum ,λ is the wavelength,.

The material dispersion given by Sellmeier formula and can be calculated through [11].

$$n = \sqrt{1 + \frac{A_1\lambda^2}{\lambda^2 - \lambda_1^2} + \frac{A_2\lambda^2}{\lambda^2 - \lambda_2^2} + \frac{A_3\lambda^2}{\lambda^2 - \lambda_3^2}} \qquad \text{Eq. 2}$$

Where λ = Operating wavelength in µm and A_1, A_2, A_3, λ_1, λ_2, λ_3 are the Sellmeier constant for silica.

The total dispersion depends upon the calculation of sum of the geometrical dispersion (or waveguide dispersion) and the material dispersion obtained as [1], [12]:

$$D(\lambda) = (\lambda) + Dm(\lambda) \qquad \text{Eq. 3}$$

The confinement loss is obtained from the imaginary part of n_{eff} as follows [2]-[3]:

$$\text{Confinement Loss (dB/m)} = 8.686\ \mathrm{Im}[k0^* \, n\ eff] \qquad \text{Eq. 4}$$

where $[n_{eff}]$ is the imaginary part of the refractive index,

$k_0 = \frac{2\pi\rho}{\lambda}$ is the wave number in the free space.

A parameter known as normalized frequency 'V' is utilized to investigate the number of guided modes in conventional step index fiber [8], [12];

$$V = \frac{2\pi\rho}{\lambda}\sqrt{(n_{core}^2 - n_{cladding}^2)} \qquad \text{Eq. 5}$$

Where ρ represents the pitch, n_{core} and $n_{cladding}$ represents the refractive index of the core as well as the cladding, respectively. By selecting proper air holes diameters and pitch (Λ) of the proposed PCF design it is achievable to keep value of V lower at cut-off normalized frequency in any wavelength range [11]- [12].

IV. PROPOSED DESIGNS AND SIMULATED RESULT

In this proposed study of PCF, a pure silica material is used. A PCF with ultra-flatten dispersion, low confinement loss and endlessly single mode fiber having wide wavelength range, can be developed as per Design-1 to Design-5. In this a total five hexagonal PCF designs are used with description of the circular air holes in rings. The structure of Hexagonal with solid core contain higher refractive index as compared to cladding region so that light will not propagate through the cladding which is characterized by different air holes diameters for the proposed structure is analyzed.

Elliptic waveguide is used to create circular air holes and elliptical holes by varying the distance between major axis and minor axis. All proposed hexagonal PCF design structures show the effect of varying the diameter of different circular rings on dispersion property while keeping the pitch between air holes constant.

The Design-1 refers to base paper design which offers ultraflatten dispersion and low confinement loss. It contains all the design parameter like d_1, d_2, d_3, d_4 and one pitch according to base paper. While Desgin-2 to Design-5 is the basic design to get better results as compared to base paper result. In these four proposed designs under study, elliptical air holes were introduced in all the rings one by one. The objective of these designs is to find out the effect of change in air holes diameter for all rings on dispersion, confinement loss and endlessly single mode fiber.

In all the above referred designs the total dispersion is calculated from addition of waveguide dispersion and material dispersion. The waveguide dispersion depends upon proposed structure configuration and changes in air holes diameter.The wafer size in all the below referred designs remains constant.

Design-1: This basically belongs to the base paper and in the base design all the design diameter are different with circular air holes. The air hole diameters are d_1= 0.5066 µm for first ring, d_2= 0.72116 µm for second, d_3= 0.8493 µm for third ring, d_4= 1.341 µm for fourth and fifth outer rings. The spacing between the adjacent air holes or pitch (Λ) is 1.49 µm.

Design-2: In this type of design the first ring has elliptical air holes but area of each elliptical air holes are same as area of each circular air holes so that over all area is constant. The air hole diameters are d_a = 0.611 µm major axis and d_b = 0.42 µm minor axis for first ring, d_2= 0.72116 µm for second, d_3= 0.8493 µm for third ring, d_4= 1.341 µm for fourth and fifth outer rings. The spacing between the adjacent air holes or pitch (Λ) is 1.49 µm.

Design-3: In this,the second ring has elliptical air holes and two air holes are tilde for better response but area of each elliptical air holes is same as area of each circular air holes so that over all area is constant. The air hole diameters are d_1= 0.5066 µm for first ring, d_a = 0.8 µm major axis and d_b = 0.65 µm minor axis for second ring, d_3= 0.8493 µm for third ring, d_4= 1.341 µm for fourth and fifth outer rings. The spacing between the adjacent air holes or pitch (Λ) is 1.49 µm as shown in Fig. 2.

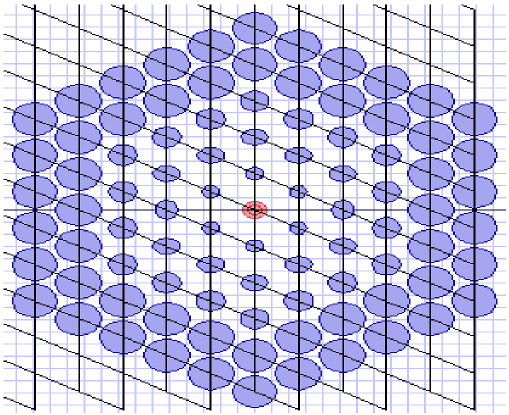

Fig. 2 Hexagonal PCF Structure of Proposed Design-3

-Design-4: In this type of design, the third ring has elliptical air holes but area of each elliptical air holes is same as area of each circular air holes so that over all area is constant. The air hole diameters are d_1= 0.5066 μm for first ring, d_2= 0.72116 μm for second ring, d_a = 0.88 μm major axis and d_b = 0.82 μm minor axis for third ring, d_4= 1.341 μm for fourth and fifth outer rings. The spacing between the adjacent air holes or pitch (Λ) is 1.49 μm .

Design-5: In Design-5,the fourth and fifth ring has elliptical air holes were introduced but area of each elliptical air holes is same as area of each circular air holes so that over all area is constant. The air hole diameters are d_1= 0.5066 μm for first ring, d_2= 0.72116 μm for second ring, d_3= 0.8493 μm for third ring, d_a = 1.36 μm major axis and d_b= 1.322 μm minor axis for fourth and fifth outer rings. The spacing between adjacent air holes or pitch (Λ) is 1.49 μm.

Below in Fig. 3 the value of chromatic dispersion changes by changing the diameter of air holes while keeping pitch constant. From 1.0 μm to 2.0 μm wavelength all design shows almost flatten dispersion as compare to initial wavelength range. As a result, it can be observed that dispersion is highly influenced by the inner rings diameter as compared to outer rings diameter.

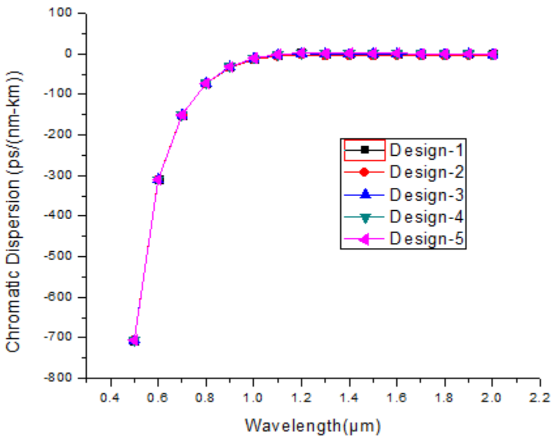

Fig. 3 Total Dispersion for Design-1 to Design-5

The Fig. 4 illustrates ultra-flatten dispersion characteristics of Design-3. It offers 0.58(ps/(nm-km)) ultra-flatten dispersion in 1.265 μm to 1.64 μm wide wavelength ranges or 375 nm flat band as compared to all the proposed designs.

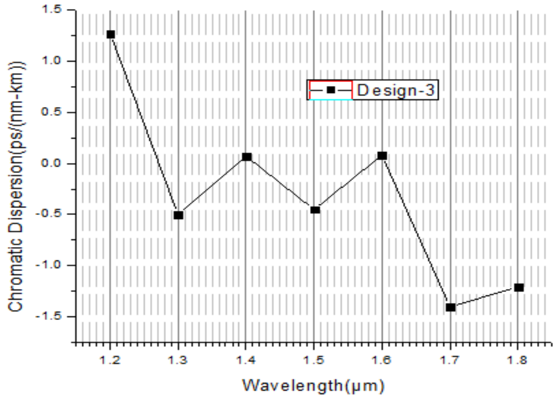

Fig. 4 Ultraflatten Dispersion Curve for Proposed Design-3

In Fig. 5, the value of confinement loss changes by changing the diameter of air holes, though pitch remains constant. Therefore by studying the fig.5 we can conclude that confinement loss is highly influenced by the air holes diameter of inner rings and less influenced by the air holes diameter of outer rings. The designs below shows minimum confinement loss for second and third optical window.

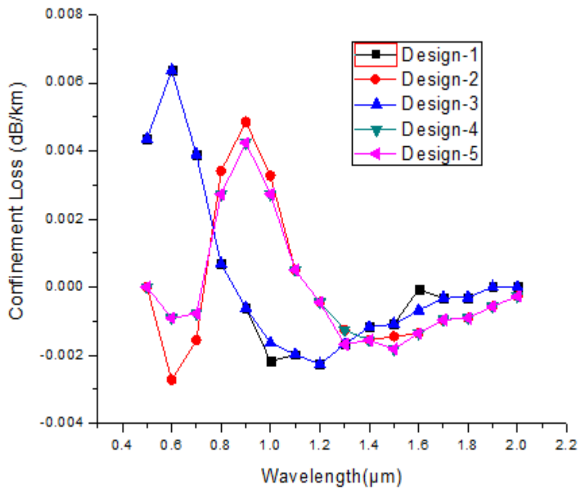

Fig. 5 Confinement Loss for Design-1 to Design-5

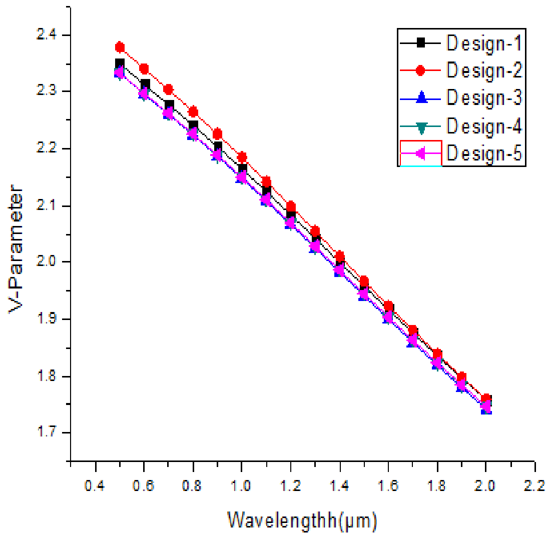

Fig. 6 V-Parameter for Design-1 to Design-5

In Fig. 6, the value of V-parameter changes by changing the diameter of air holes while keeping pitch among the air holes remains constant. The value of V-parameter should be less than or equal to 4.2 to full fill the requirement of the endlessly single mode fiber condition. The above hexagonal PCF Designs are continuously single mode fiber for wide wavelength and the value of V-parameter decreases when wavelength increase. Therefore it means that V-parameter is influenced by the change in air holes diameter for all the proposed designs.

Table I shows the results of the following table containing ultra-flatten dispersion, endlessly single mode fiber and low confinement loss property.

Table I Comparison between Proposed Design-3 and Reference Paper

Design	Wavelength (µm)	Chromatic Dispersion (ps/(nm-km))	V-parameter
Ref. [5]	1.25 µm to 1.60µm	0.65(ps/(nm-km))	NA
Proposed Design-3	1.265 µm to 1.64µm	0.58(ps/(nm-km))	Endlessly single mode fiber for 0.5 µm to 2.0 µm

The Design-3 shows more ultra flatten dispersion, flat band and endlessly single mode fiber as compare to reference.

V. Conclusion

In this study, a new DF-PCF is designed which also illustrates the variation effect of the diameters of the air holes and lattice constant on the dispersion and confinement loss characteristics. As a result nearly zero ultra-flatten dispersion PCF is developed which contains modest number of design parameters such as five rings, four types of air hole diameters with same pitch. In this the Hexagonal holey fiber allows an outstanding control of the dispersion properties of the fiber. Through numerical simulation technique this five ring dispersion PCF can offer nearly zero ultra-flatten dispersion of 0.58 ps/ nm/km in a 1.265 µm to 1.64 µm wavelength range or 375 nm flat band with low confinement losses. As a result with further optimization of the structure and better control of the fluctuations in fiber diameter, it is assumed that the dispersion values can be reduced further.

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