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Design of a Near Zero Ultraflatten Dispersion Photonic Crystal Fiber for Communication System

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***Abstract*— The proposed photonic crystal fiber presents dispersion flattened optical fiber (DF-PCF) for tailoring near zero ultraflatten dispersion of 0.61 ps/nm/km for 1.26 µm to 1.64 µm wide wavelength range or 380 nm flat band as well as low confinement losses of near 10-5 dB/km. The finite difference time domain (FDTD) method with transparent boundary condition (TBC) is employed to investigate the guiding properties. Through the simulation result it has been observed that it is possible to achieve near zero ultraflatten dispersion of 0.61 ps/nm/km for 1.26 µm to 1.64 µm with low confinement losses of the order less than 10-5 dB/km for second and third optical window.**

***Index Terms*— Ultraflatten Dispersion, Confinement Loss, Finite Difference Time Domain (FDTD), Photonic Crystal Fiber (PCF).**

I. INTRODUCTION

The index guiding photonic crystal fiber or solid core photonic crystal fiber [1] generally contain a hexagonal collection of microscopic air holes channels running along length of the silica based fiber surrounding a solid silica core. Chromatic dispersion as well as modal properties can be managed considerably through varying air holes diameter, number of holes as well as positions of air holes [1]-[6]. Accordingly, dispersion flatten fiber demonstrate a number of exceptional properties including wide range single mode operation [7]-[8], zero dispersion for wide wavelengths range [1], [3]-[6], high as well as low nonlinearities [9], high birefringence [2], [8]-[12] and ultraflatten dispersion [5]-[6] . Thus, dispersion flatten fiber are so striking in managing application specific dispersion and modal properties [1], [3]-[6]. Chromatic dispersion control is essential for practical applications of optical fiber communication systems such as dispersion compensation [9] and nonlinear optics [9]. In addition, in cladding region there is a finite number of air holes, guided modes of high frequency are basically leaky, hence control of confinement losses [4], [6] are also essential.

Through modulating of air holes parameters of the cladding region, it is potential to design application specific guiding properties. Such as, very high as well as very low nonlinearity [9], dispersion flatten fiber for wide wavelength range [1], [3]-[6] high birefringence [2], [8]-[12], endlessly single mode guiding [7] and many more. In the broadband communications systems, fiber dispersion as well as confinement loss plays significant roles. Such as, in the wavelength division multiplexing (WDM) systems it is necessary to sustain a consistent response in different wavelength channels so that this is exactingly realized through make sure of ultraflatten dispersion characteristics of fibers [1], [3]-[6]. This new property facilitates in tuning transmission characteristics such as dispersion, nonlinearity as well as confinement loss.

The proposed PCF structure with 450 nm flat bandwidth dispersion which is an optimized model of the dispersion flattened reported through Sharafat Ali et al [3], a 350 nm flat bandwidth dispersion with five rings optimized model of the dispersion flattened reported through Chowdhury et al [6]. A novel five ring PCF structure with near zero ultraflatten dispersion in 1.26 µm to 1.64 µm wide wavelength range is proposed. The proposed design can manage effectively as a single mode fiber with ultraflatten chromatic dispersion of 0.61 ps/nm/km (380 nm bandwidth) as well as low confinement loss near about 10^{-5} dB/km.

II. DESIGN METHODOLOGY

Here Fig. 1 demonstrates a simple geometry for the dispersion flattened PCF [6] with 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 (∧). The refractive index of the air hole is 1.0 while and fiber silica refractive index is 1.4457.

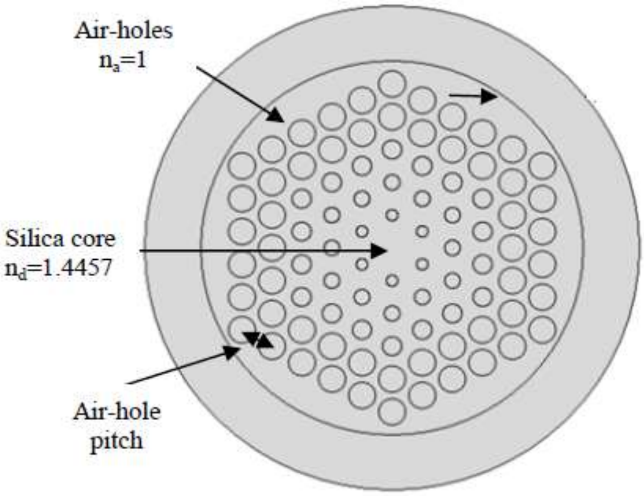

Fig. 1 Geometry of proposed five-ring [6]

As shown in Fig. 1, for managing the dispersion the five ring have four degrees of freedom for controlling dispersion behavior of four ring 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 reserved larger for better field confinement.

Numerically show that it is possibility to propose a comparatively simple PCF structure with fewer parameters for the telecommunication window without distorting the dispersion flatness as well as low confinement loss.

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III. Simulation Methodology

The Opti-FDTD software 8.0 version is employed as a simulation tool. The finite difference time domain (FDTD) method with transparent boundary condition (TBC) is employed to calculate effective refractive index, chromatic dispersion, confinement loss as well as endlessly single mode fiber of proposed structure. The FDTD unswervingly solves the Maxwell equations to best estimate the value of the effective refractive index.

Chromatic dispersion can be achieved using the following relation [1], [3]-[4], [6], [8]:

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

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

The material dispersion given by Sellmeier formula and can be calculated through [12].

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

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 is depends upon the calculation of sum of the geometrical dispersion (or waveguide dispersion) and the material dispersion obtained as [1], [8]:

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

The confinement loss is obtained from the imaginary part of n_{eff} as follows [3]-[4]:

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

where $[n_{eff}]$ is the imaginary part of the refractive index, $k_0=\frac{2\pi}{\lambda}$ 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 [8], [12].

IV. Proposed Designs and Simulated Result

In the proposed work, a pure silica material with refractive index 1.4457 is employed. To achieve ultraflatten dispersion, low confinement loss and endlessly single mode fiber for wide wavelength range, Design-1 to Design-5 total five hexagonal PCF designs were proposed. There is description of the circular air holes in rings which offers the ultraflatten dispersion in the proposed work.

In the proposed work, 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 designs (Design-1 to Design-5) structures show the effect of varying the diameter of different circular rings on dispersion property while keeping the pitch between air holes constant.

Here the PCFs Design-1 is basically belongs to base paper design which offers ultraflatten dispersion and low confinement loss. Design-1 contains all the design parameter such as d_1, d_2, d_3, d_4 and one pitch according to base paper. The proposed Desgin-2 to Design-5 is the basic design to get better results as compared to base paper result. In these four proposed design, elliptical air holes were introduced in all the rings one by one. The aim of investigation 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.

For all the designs the total dispersion is calculated from addition of waveguide dispersion and material dispersion. Waveguide dispersion depends upon proposed structure configuration and changes according to change in air holes diameter.

Design-1: The Design-1 is basically belong to base paper design in which four different types of air holes diameter and one pitch along with 5 rings was used. In the base design all the design diameter are 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 the proposed Design-2, in first ring 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_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 the proposed Design-3, in second ring elliptical air holes were introduced 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.

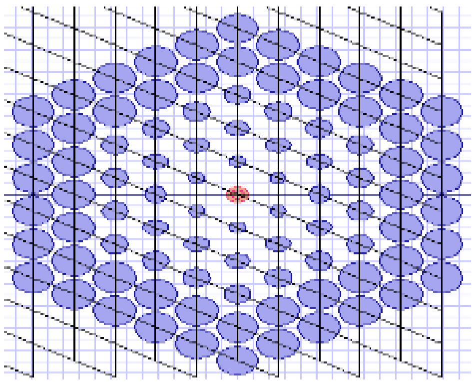

Fig. 2 Hexagonal PCF Structure of Proposed Design-3

Design-4: In the proposed Design-4, in third ring 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_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 the proposed Design-5, in fourth and fifth ring 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.

Fig. 3 shows, value of chromatic dispersion changes by changes in 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. From the above result, it can be conclude that dispersion is highly influenced by the inner rings diameter as compare to outer rings diameter.

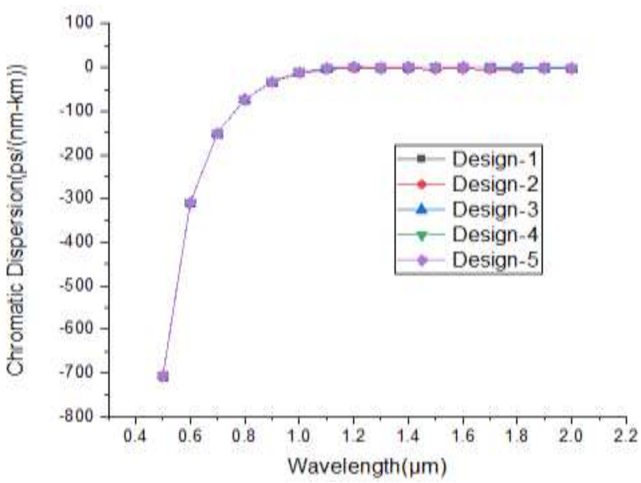

Fig. 3 Total Dispersion for Design-1 to Design-5

Here Fig. 4 shows ultraflatten dispersion characteristics of Design-3. Here it can be conclude that proposed Design-3 offers 0.61(ps/(nm-km)) ultraflatten dispersion in 1.26 µm to 1.64 µm wide wavelength ranges or 380 nm flat band as compared to all the proposed designs.

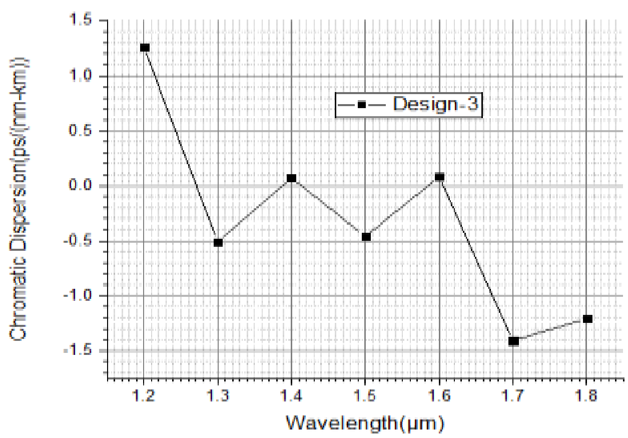

Fig. 4 Ultraflatten Dispersion Curve for Proposed Design-3

Here Fig. 5 show, the value of confinement loss changes by changes in the diameter of air holes while keeping pitch constant. From the above result, it can be conclude that confinement loss is highly influenced by the air holes diameter of inner rings and very small influenced by the air holes diameter of outer rings. Here all the designs show minimum confinement loss for second and third optical window.

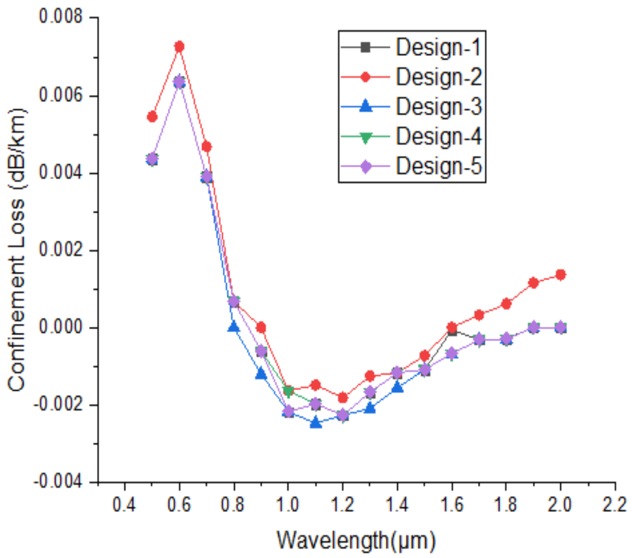

Fig. 5 Confinement Loss for Design-1 to Design-5

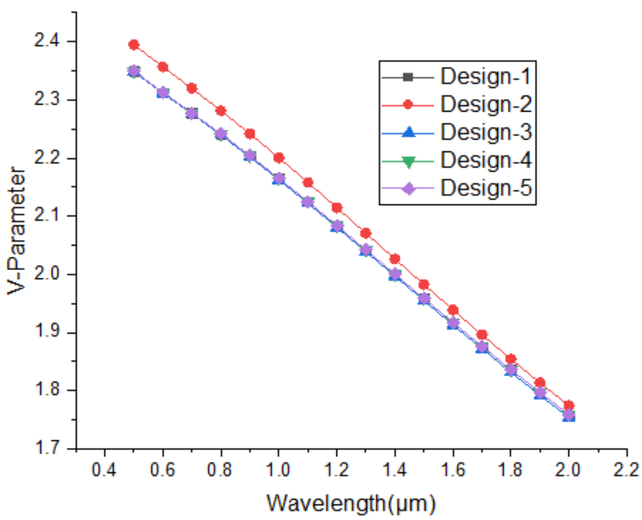

Fig. 6 V-Parameter for Design-1 to Design-5

Here Fig. 6 show, the value of V-parameter changes by changes in the diameter of air holes while keeping pitch among the air holes 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. It can be observed for above result that the entire proposed PCF Design-1 to Design-5 is endlessly single mode fiber for wide wavelength. From the above result, it can be conclude that the V-parameter is influenced by the change in air holes diameter for all the proposed designs.

Table I shows various optimized properties results of proposed Design-3. From the above discussed results the following table contains ultraflatten dispersion, endlessly single mode fiber and low confinement loss property.

Table I Comparison between Proposed Design-3 and Reference Paper

Design	Wavel -ength (μm)	Chromatic Dispersion (ps/(nm-km))	V-parameter
Ref. [6]	1.25 μm to 1.60 μm	0.65 (ps/(nm-km))	NA
Proposed Design-3	1.26 μm to 1.64 μm	0.61 (ps/(nm-km))	Endlessly single mode fiber for 0.5 μm to 2.0 μm range

Here it can be conclude that proposed Design-3 offers more ultra flatten dispersion, flat band and endlessly single mode fiber as compare to reference.

V. Conclusion

An exceptionally near zero ultraflatten dispersion PCF is proposed. This PCF contain modest number of design parameters such as five rings, four types of air hole diameters and single pitch. Here Hexagonal PCF allows an outstanding control of the dispersion properties of the fiber. Through numerical simulation technique this five ring dispersion PCF can offer near zero ultraflatten dispersion of 0.61 ps/ nm/km in a 1.26 μm to 1.64 μm wavelength range or 380 nm flat band with low confinement losses. With further optimization of the structure as well as better control of the fluctuations in fiber diameter, it can be assumed that dispersion values further can be reduced.

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