

Spiral Shaped Solid Core Photonic Crystal Fiber with Highly Nonlinear and Low Confinement Loss

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Abstract

Photonic crystal fibres (PCFs) is attracting more attention nowadays as a promising platform for communication chemical sensing and measurements. A spiral PCF structure is made of silica material is proposed where the core is defined as solid. Utilizing the finite element method (FEM) has numerically investigated waveguide properties. The PCF characteristics such as normalized frequency, mode field diameter, effective area, nonlinearity, and confinement loss are investigated. The ultra-low confinement loss is achieved at a $1.55\mu\text{m}$ wavelength. The high nonlinearity 7W-1km-1 at $1.55\mu\text{m}$ wavelength is achieved. The ultra-high birefringence 0.84065×10^{-2} is achieved at a $1.5\mu\text{m}$ wavelength.

Keywords— *Photonic crystal fibre, confinement loss, nonlinear coefficient, effective area, normalized frequency.*

INTRODUCTION

Photonic Crystal Fiber (PCF) is a microstructure arrangement of low and high refractive index material. PCF is a periodic arrangement of microscopic air holes with a defect that affects the motion of photons. The improved features provide several new applications such as fibre lasers, sensors, nonlinear fibre optics, and supercontinuum generation [1]. PCF has many similar applications, such as optical signal processing optical fibre with high nonlinearity and birefringence. The refractive index of silica (SiO_2) is 1.444 at a $1.55\mu\text{m}$ wavelength. PCF provides a high degree of freedom in structural parameter designs, which provides different features. This feature is not practicable for conventional fibre. Knight et al. [2],[3] proposed the first hexagonal PCF structure. Further until now, a lot of PCF design and progress of fabrication technology is proposed. The hexagonal, square, octagonal, circular, spiral, and honeycomb PCF [4]–[12].

The spiral structure is proposed in [9]–[12]. In [9], the spiral structure is designed in which all the lattice air holes are the same, and the core is three-layer circular air holes. The PCF characteristic is compared concerning the d/Λ ratio. The structure is designed for gas sensing applications in [9]. In [10], the ultra-high birefringence up to 10⁻¹ order and highly nonlinear coefficient 10³ order W-1m-1

is proposed. In [11], high birefringence is proposed for the biosensing application. In [12], gold material is used as the active plasmonic material in the outer layer of the structure. The active plasmonic material is used to improve the sensing resolution.

In this paper, confinement loss [4], normalized frequency [4], effective area [5], nonlinear coefficient [6], and numerical aperture are shown for different fluids. The proposed design consists of a hexagonal core with a spiral cladding structure. The background material is silica having a refractive index of 1.45. This paper is organized as follows: Section II proposes a four-layer spiral base photonic crystal fibre. In section III, simulation results of PCF characteristics and mathematical analysis such as confinement loss, normalized frequency, effective area, and nonlinear coefficient are proposed—further, the concluding remarks for this Spiral PCF in Section IV.

STRUCTURE DESIGN OF SPIRAL PCF

The proposed hexagonal core structure and the spiral cladding structure having air holes are depicted in Fig.1. The proposed structure has four air holes comprising red-coloured water and blue air bubbles—the blue and red colours indicate the spiral design with 60-degree shift positions. The diameter is increasing by 160 nm linearly. The

diameter (d1) of six lattice air holes is 360nm, designed by the first hexagonal structure. The diameter of d2 air holes is 160nm more than d1 air holes.

Similarly, d3 is more than d2, and d4 is more than d3. Silica is used for background material. The simulation is done for different values of diameter and pitch of the holes, and accordingly, the different extent of confinement is observed. Later on, based on the values of the effective refractive index obtained through the simulation is used to calculate various other parameters like confinement loss, mode field diameter, normalized frequency, etc. Rsoft FEMSIM software is used to simulate this proposed spiral structure, a graphical user interface and can also interface with third-party tools. The depicted figure shows the wavelength dependence of the effective refractive index of the proposed PCF for a given PCF structure.

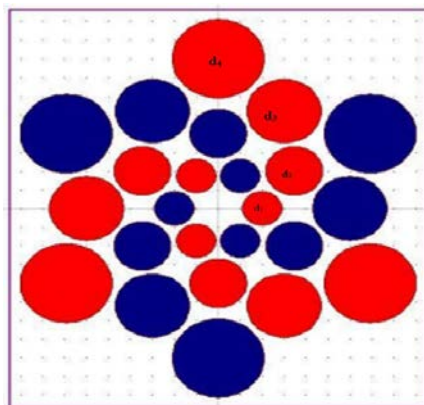


Figure: - 1 Cross-section view of the spiral based photonic crystal fiber

Considering the wavelength λ to be $1.55\mu\text{m}$ and varying the air bubble diameter as a spiral structure with varying radius, we obtained extents of confinement in Fig. 2.

SIMULATION RESULTS OF PCF CHARACTERISTICS

The confinement loss of PCF measures the amount of power leakage from its core to the cladding. As the confinement loss decreases, the mode area also decreases, but due to a finite number of air holes present in the fibre structure, all the PCF guided modes are leaky. Confinement loss is the light ability within the core region. By proper selection of air hole diameter and pitch, the loss could be minimized as possible. The number of layers also plays an important role where the selection of a small pitch is impossible. The confinement loss [8] is obtained from the imaginary part of the effective refractive index (n_{eff}) as follows:

$$\text{Confinement loss} = 8.686 \times k_0 \times \text{Im}[n_{eff}] \quad (1)$$

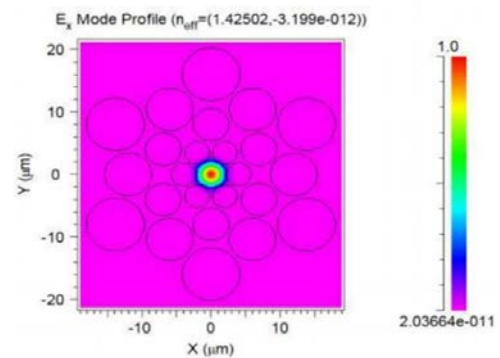


Figure: - 2 Confinement of Light the proposed Cross-section spiral PCF

where K_0 and $\text{Im}[n_{eff}]$ are free spaced wave number and imaginary value of an effective refractive index, respectively. The free space wavelength is $2\pi/\lambda$. Fig. 2 depicted confinement loss versus wavelength. The lowest confinement losses are achieved at a $1.55\mu\text{m}$ wavelength.

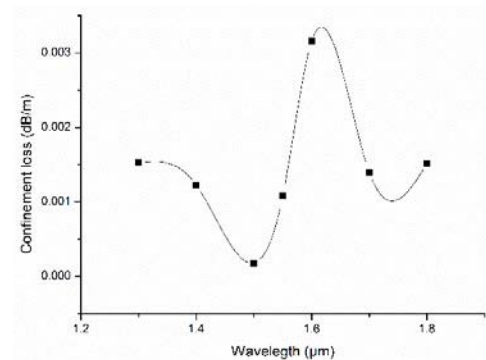


Figure: - 3 Confinement loss the proposed Cross-section spiral PCF

The Sellmeier equation calculates the background material refractive index. According to the Sellmeier equation, the refractive index is inversely proportional to wavelength. The Sellmeier equation [1] for the refractive index is:

$$n^2(\lambda) = A + \frac{B\lambda^2}{\lambda^2 - C} + \frac{D\lambda^2}{\lambda^2 - E} \quad (2)$$

Where λ represented for free-space wavelength and Sellmeier coefficient are represented as A, B, C, D, and E in Eq. 2. Fig. 4 depicted the relation between effective refractive index, which is a number quantifying the phase delay per unit length in a waveguide relative to the phase delay in vacuum and wavelength. As the wavelength increases, the effective index is decreased linearly, which is shown in Fig.4. At $1.55\mu\text{m}$ wavelength, the effective index is 1.425 is active for the spiral structure.

Fig. 5 depicts the graph properties of normalized frequency, which is the amount of energy in the

mode that lies in the solid core spiral PCF. The normalized frequency is also known as V-number. For step-index fibre, the effective normalized frequency should be less than 2.405. Similarly, for multimode, it should be greater than 2.405.

$$\text{Normalized frequency } (V_{\text{eff}}) = \left(\frac{2\pi a}{\lambda} \right) \sqrt{n_{\text{core}}^2 - n_{\text{eff}}^2} \quad (3)$$

The n_{core} and n_{eff} are the refractive index of core and effective refractive for the proposed structure, respectively. The diameter of the core is a . Fig. 5 depicted the relation between normalized frequencies versus wavelength. As wavelength increases, the normalized frequency decreases. So, the normalized frequency is inversely proportional to wavelength.

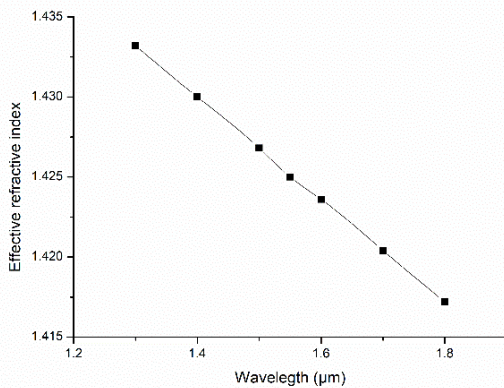


Figure: - 4 Effective refractive index the proposed Cross-section spiral PCF

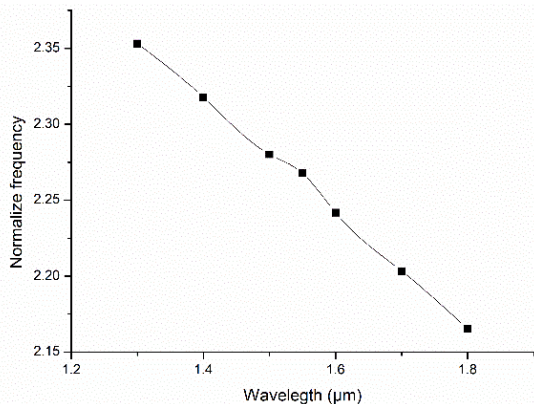


Figure:-5 Normalized frequency the proposed Cross-section spiral PCF

Mode field diameter (W_{PCF}) for photonic crystal fiber can be calculated by using Eq. 4,

$$W_{PCF} = \frac{a}{2} \left[0.65 + 1.619V_{\text{eff}}^{-3/2} + 2.879V_{\text{eff}}^{-6} \right] \quad (4)$$

The effective area (A_{eff}) for PCF can be calculated by using Eq. 5,

$$A_{\text{eff}} = \pi [W_{PCF}]^2 \quad (5)$$

The importance of the effective area is introduced to measure non-linearity. For a high power density

for nonlinear effects, we need a low effective area. This is the total area where light confines in the PCF core region. The nonlinear coefficient [8] (γ) can be calculated by using Eq. 6,

$$\gamma = \frac{2\pi \times n_2}{\lambda \times A_{\text{eff}}} \quad (6)$$

where n_2 represents the nonlinear coefficient of background material. The nonlinear coefficient for silica is 2.33×10^{-20} .

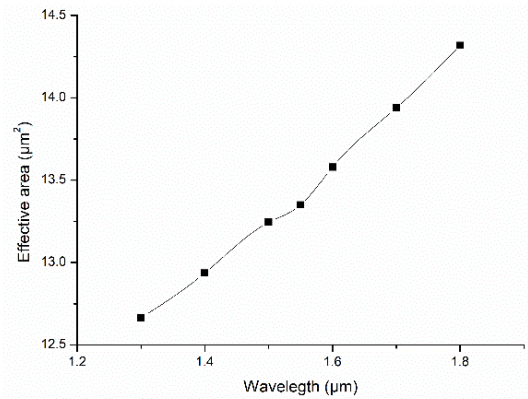


Figure: - 6 Effective area the proposed Cross-section spiral PCF

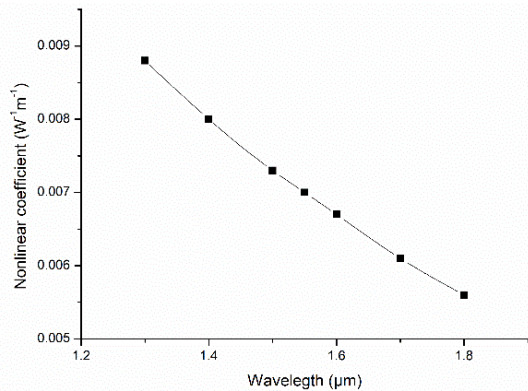


Figure:-7 Nonlinear coefficient the proposed Cross-section spiral PCF

Fig. 6 depicted the graph representation of the effective area of spiral PCF. With the increase of wavelength, the effective size is also increased for spiral PCF. At 1.55μm wavelength, the effective area is achieved 13.35 μm². Fig. 7 depicted the nonlinearity versus wavelength. As shown in Fig. 7 nonlinear coefficient is decreased as it increases with wavelength. At 1.55μm wavelength, the non-linearity is achieved by 0.0070 per watt per meter for spiral PCF.

Fig. 8 depicts the birefringence versus variable wavelength. The figure shows that till the 1.5 μm wavelength, birefringence increases gradually, then it starts decreasing. The highest birefringence is succeeded at 1.5 μm wavelength, which is 0.84065×10^{-2} .

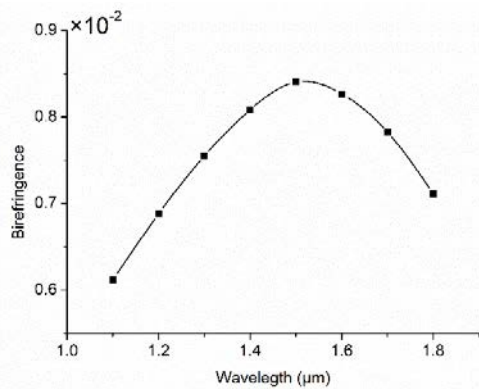


Figure - 8 Variation of Birefringence for spiral PCF as a function of wavelength.

CONCLUSION

The four-layer spiral based PCF is designed and analyzed with microstructure air holes and investigated its PCF properties. The FEM method is used for numerical investigation. Due to the small core, it offers low confinement loss and high nonlinearity. The highest birefringence is achieved at a $1.5\mu\text{m}$ wavelength. The ultra-low confinement loss, ultrahigh birefringence, and high nonlinearity it is used for remote sensing applications. Due to the small core, a highly nonlinear coefficient is 7W-1km-1 at $1.55\mu\text{m}$ wavelength and used for communication purposes.

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