Design of highly birefringent square lattice photonic crystal fiber with flattened dispersion and low confinement loss

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Abstract- **In this paper a square-lattice PCF with circular and elliptical air holes is proposed which is suitable for optical communication. The optimal structural parameters are used to achieve low and flattened dispersion, low confinement loss and high birefringence in wide wavelength range. At last, a design of triangular lattice PCF with same design parameters is proposed and result of this is compared with the result observed from the proposed square lattice PCF. Numerical investigation shows that value of chromatic dispersion for square lattice PCF and triangular lattice PCF are 10.66117ps/nm-km and 8.32956ps/nm-km respectively, confinement losses for these PCFs are 0.001128dB/km and 0.002473dB/km respectively at 1.5µm wavelength and maximum birefringence are 0.0012 and 0.0014 respectively. To analyse these PCFs, finite-difference time-domain (FDTD) is used.**

Keywords- **Birefringence, chromatic dispersion, confinement loss, photonic crystal fibers (PCFs), square lattice.**

I. INTRODUCTION

In recent years, several hundreds of Gbps based dense wavelength division multiplexing (WDM) optical transmission systems are successfully introduced in the field of optical communication [1]. So flexible dispersion or losses control in optical fibers at a desired spectral range have been become a major issue in high bit rate long haul wavelength division multiplexing optical communication systems [2]. The intersymbol interference (ISI) between successive bits in communication channel can occur by linearly accumulated chromatic dispersion along the transmission channel, which can significantly affects the communication quality [2]. Since in high speed optical communication, zero and flat dispersion slope with low losses are needed. Thus, in recent years, researchers and engineers focused on new fibers called photonic crystal fibers (PCFs) because of its unique features such as controllable dispersion, very low confinement loss, small bending radius and flexible design [3-8]. The photonic crystal fibers (PCFs) are new class of fibers which are also called microstructures fibers or holey fibers, their structures comprise a core and a cladding, but the cladding is two dimensional photonic crystal types consisting of air holes that run along the fiber length show unique properties [3]. Photonic crystals rely on regular morphological microstructure, incorporated into the material, which radically alters its optical properties [9]. Light guidance in PCFs are by total internal reflection (TIR) and photonic band gap (PBG) effect, depending on the core and cladding photonic crystal materials. In index-guiding PCFs [10], the refractive index difference between the core and cladding is always positive, by choosing a core material with a higher refractive index than the cladding refractive index. These fibers, also known as solid core PCFs that guide light through a form of total internal reflection (TIR). However, in fibers with air core, the refractive index of the cladding is higher than that of the core, TIR is not possible, so light guidance is attained by coherent Bragg scattering, where light at wavelengths within well-defined stop bands is prohibited from propagating in the photonic crystal cladding and is confined to a central defect [11]. Only certain wavelength bands are confined and guided down the fiber. Each band corresponds to the presence of a full two-dimensional PBG in the photonic crystal cladding. For this reason, these fibers are called photonic bandgap fibers (PBGFs) or hollow core fibers in which light is guided in a low-index core by the PBG effect. Due to limitations in choosing the wavelength of light in hollow core fibers, the proposed PCFs in this paper are of the solid-core type. Design parameters of the cladding, which offer the design flexibility in these fibers, include the air-holes dimensions (d), the spacing between two adjacent holes or pitch (Λ), number of rings (N), and arrangement of the holes. Through optimizing these design parameters, we can alter and improve the propagation characteristics in a PCF according to its application. One of the unique, most desirable features of PCF, which makes it a proper choice for optical communication applications, is that low flattened dispersion, low confinement loss and high birefringence in this paper is attainable at the same time.

Three main parameters investigated in this paper are dispersion, confinement loss and birefringence.

Chromatic dispersion [12-13] is the main contribute to the optical pulse broadening. Chromatic dispersion is caused by combined effects of material and waveguide dispersion. Control of the chromatic dispersion in PCFs is essential for practical applications in optical communication systems, dispersion compensation and linear/nonlinear optics. The chromatic dispersion is calculated as:

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

Where c is the velocity of light in vacuum, λ is light wavelength in term of μm and $\mathrm{Re}(n_{\mathrm{eff}})$ is the real part of the complex effective index n_{eff}, which is calculated from Maxwell's equation using FDTD tool.

Material dispersion refers to the wavelength dependence of the refractive index of material caused by the interaction between the optical mode and ions, molecules or electrons in the material which is directly included in the calculation given by Sellmeier's formula[14-15].

The confinement loss [16-17] due to the finite extent of cladding is calculated from the imaginary part (Im) of the complex effective index n_{eff} , using the following equation:

$$\mathrm{Conf.Loss} = \frac{40\pi}{\ln(10)\lambda}\mathrm{Im}(n_{\mathrm{eff}}) = 8.686k_0\mathrm{Im}(n_{\mathrm{eff}})\left[\frac{\mathrm{dB}}{\mathrm{m}}\right] \quad (2)$$

Birefringence [18-20] is defined as a difference between effective refractive indices of two fundamental polarization modes and can be written as

$$B = |n_x - n_y| \quad (3)$$

Where n_x and n_y are the effective refractive indices of each fundamental mode. The purpose of constructing birefringent fibers is to reduce the polarization coupling.

For the purpose of analyzing and simulating the propagation characteristics of the proposed photonic crystal fiber, finite-difference time-domain (FDTD) method has been employed.

II. DESIGN PARAMETER AND SIMULATION RESULT

According to their lattice structures, the photonic crystal fibers may be classified into two different types; triangular lattice and square lattice. The proposed PCFs in this paper are of the square-lattice type. Figure 1, shows the cross section view of such fiber. The proposed PCF comprises five air-hole rings with solid core. The dimension of air holes in inner three rings is considered to be elliptical with major axis = b and minor axis = a. Thus the dimension air holes of first inner ring is, major axis b=0.4μm and minor axis a=0.3μm, the air holes of second inner ring is with b=0.4μm and a=0.2μm, and the air holes of third ring is with b=0.8μm and a=0.3μm. Outer two rings are in circular shape with the diameter of 1.6μm. The spacing between adjacent air holes or pitch is 2.1μm.

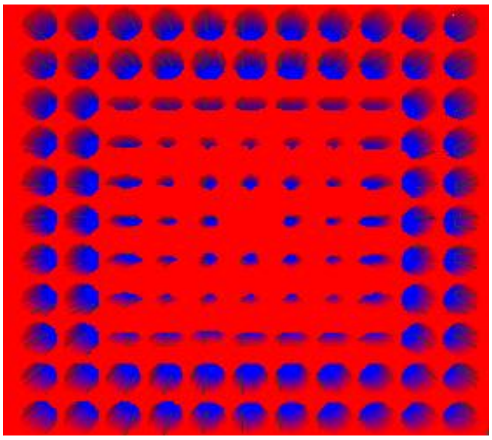

Figure 1, Cross section view of the proposed square lattice PCF with five air holes ring and pitch Λ=2.1μm

Figure 2, below shows the dependence of chromatic dispersion with the wavelength for both polarizations. Thus from this it can be observed that the value of chromatic dispersion for y-polarized mode is higher than the x-polarization mode. The value of chromatic dispersion for x-polarized mode is 10.661173ps/nm-km and for y-polarized mode is 18.741763ps/nm-km is observed at 1.5μm wavelength.

Figure 3, below shows the variation of confinement loss with wavelength for both polarization modes. Thus from this curve, it is observed that confinement loss for y-polarized mode is lower than the confinement loss of x-polarized mode. The value of confinement loss for x-polarized mode is 0.001128db/km and for y-polarized mode is -0.0012dB/km at 1.5μm wavelength.

Thus result observed from figure 2 and figure 3 shows that x-polarized mode shows lower chromatic dispersion but higher confinement loss compare to y-polarized mode.

Figure 4, shows the dependence of birefringence with wavelength for proposed PCF. Since birefringence is the effective index difference between these two polarization modes, thus it is observed that modal birefringence increases with increase in wavelength and it give maximum birefringence value is 0.00121985.

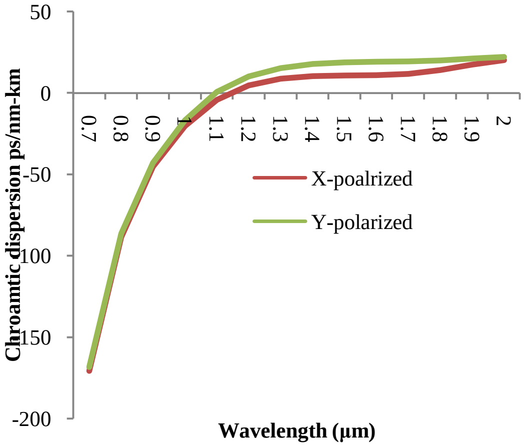

Figure 2, chromatic dispersion curve as a function of wavelength for proposed PCF

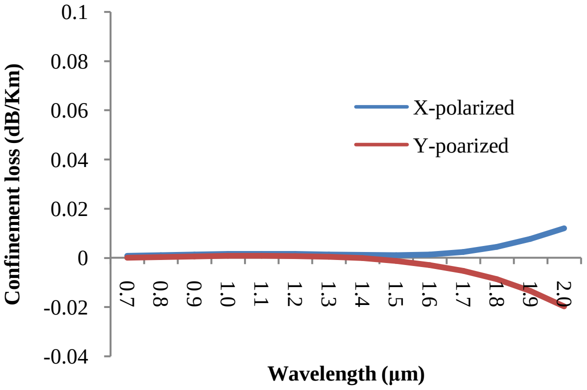

Figure 3, confinement loss curve as a function of wavelength for proposed PCF

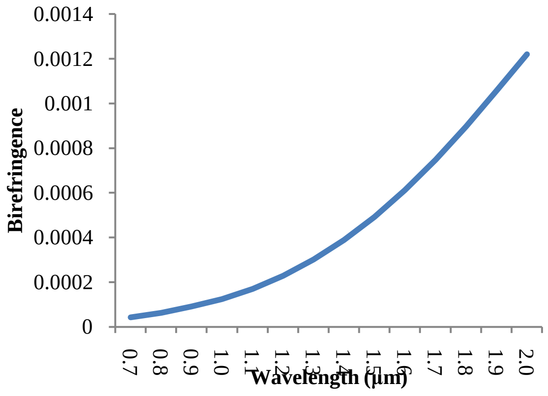

Figure 4, modal birefringence curve as a function of wavelength for proposed PCF

Thus from the study of proposed square lattice PCF, it is observed that, it gives a low and flattened dispersion, low confinement loss and considerable birefringence for polarization coupling in the wavelength rang 1.3µm to 2.0µm range.

III. COMPARISON BETWEEN SQUARE-LATTICE AND TRIANGULAR-LATTICE PCF

Figure 5, shows the cross-section view of a triangular-lattice PCF with identical design parameters those of the square-lattice PCF proposed above.

Figure 6, figure 7, and figure 8 show the chromatic dispersion, confinement loss and birefringence variations of square and triangular lattice PCF with wavelength for single polarization.

Thus from figure 6, it is observed that triangular lattice PCF offers low and more flattened dispersion characteristics compare to square lattice in wide wavelength range. Square lattice PCF shows more negative dispersion value for short wavelength. From this it is observed that the value of chromatic dispersion for triangular and square lattice is 8.32956ps/nm-km and 10.661173ps/nm-km respectively.

From figure 7, it is observe that in a low wavelength range, these two structures exhibit almost equal losses, however at the wavelength 1.5µm, which is the wavelength of choice in most telecom applications, the confinement losses in triangular and square-lattice structured PCFs are 0 .002473dB/km and 0.001128dB/km, respectively. Thus from figure it can be observed that square lattice PCF have low confinement loss compare to triangular lattice PCF at higher wavelength.

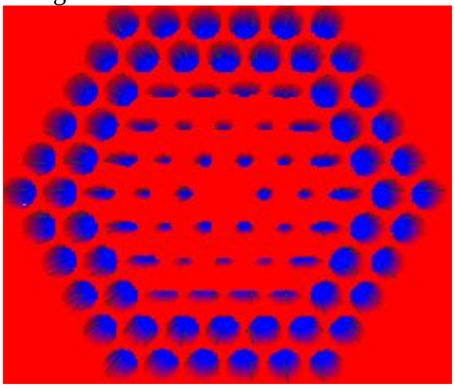

Figure5, cross section view of the triangular lattice PCF, design parameters are identical to proposed square lattice PCF

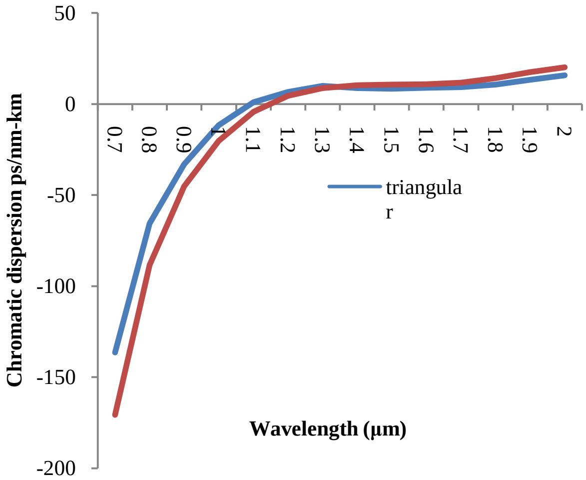

Figure 6, chromatic dispersion curve for square and triangular lattice PCF with same design parameters

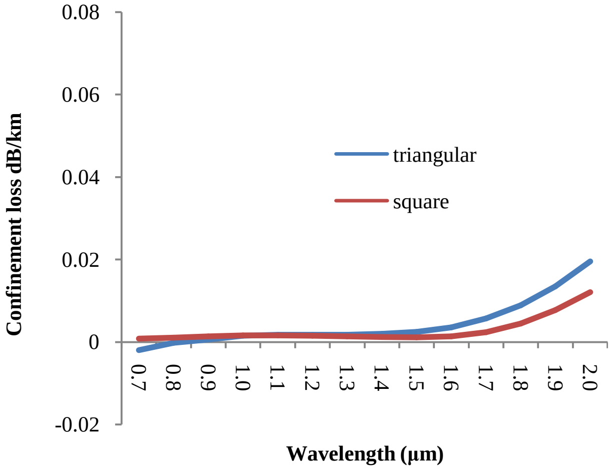

Figure 7, confinement loss curve for square and triangular lattice PCF with same design parameters

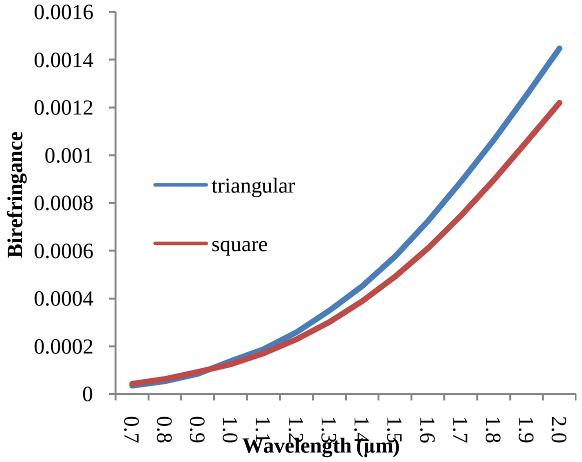

Figure 6, modal birefringence curve for square and triangular lattice PCF with same design parameters

From figure 8 above, it can be observed that triangular-lattice structure PCF shows more birefringence compare to square-lattice PCF in our proposed designs. Thus the maximum value of birefringence for square and triangular lattice is 0.001445 and 0.00122 at 2.0μm respectively.

IV. CONCLUSION

In this paper, a new design of photonic crystal fiber with square-lattice structure is proposed. The proposed design simultaneously has a low and flattened dispersion, low confinement loss and high birefringence for both polarizations in wide wavelength range. By comparing the both polarizations it is observed that x-polarized mode has better dispersion characteristic and y-polarized mode has better confinement loss characteristic. Finally dispersion, confinement loss, and birefringence of proposed square-lattice PCF is compared with triangular-lattice PCF with similar structure parameter, and it is observed that triangular-lattice PCF give a better dispersion and birefringence characteristics but poor confinement loss compare to square-lattice PCF and it is also observed that square lattice PCF show large negative dispersion value for short wavelength. Thus, both structured PCF provide a favourable transmission medium in 1.3μm to 2.0μm wavelength range.

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