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Research paper

Analysis of Hexagonal Photonic Crystal Fiber Using the Golden Ratio

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Abstract

In this research, the proposed hexagonal photonic crystal fibers design is modelled using the principle of golden ratio; fixing the proportion of pitch to diameter of the air holes constant. Finite element method with perfectly matched layer boundary is used for numerical simulation of different properties. It is shown that the proposed design has lower effective area of below 9 µm2, low chromatic dispersion value of below 57 ps/(km.nm) and confinement loss of less than 0.01 dB/km at 1.55 µm wavelength. The proposed hexagonal photonic crystal fiber is applicable for data transmission systems.

Keywords: *Photonic crystal fiber; golden ratio; chromatic dispersion; confinement loss.*

1. Introduction

Since the introduction of photonic crystal fiber (PCF) in 1996, its rapid development has lead to an increase in its popularity; due to its design flexibility over the conventional optical fiber [1]. The microstructure of photonic crystal fiber follows periodic arrangement of air holes; causing the movement of photons within the PCF identical to the motion of electrons within ionic lattice solid. Photonic crystal fiber can either be hollow or concrete [2], [3]; referred to as photonic bandgap guiding and index-guiding, respectively. Index-guiding fiber has a core made of a single material such as silicon dioxide, also known as silica material; surrounded by air holes running along the fiber. It has advantages over the conventional optical fiber; with numerous attractive properties such as wide single mode range [4], [5]; large effective area [6]; large negative dispersion [7], [8]; high nonlinear coefficient [9], [10]; wide bandwidth [11]; birefringence [12], [13;] near zero and flattened dispersion [14], [15]; low attenuation [16] and so on.

Various designs for photonic crystal fiber have been introduced in the literatures [14], [15]. Photonic quasicrystal fiber with twelve fold symmetry and three cores, is introduced in [14]; exhibiting low chromatic dispersion of between 22.1 and 23.01 ps/km.nm, but with no mention of confinement loss. In [15], ultra-flattened near zero dispersion is obtainable; albeit with high confinement loss, from the hexagonal PCF design with varying air holes diameter. Complex designs are used in both PCFs [14], [15]; making fabrication processes difficult.

The principle of golden ratio may be used to make the fibre structurally stronger. A hexagonal photonic crystal fiber is introduced [9] using the principle of the golden ratio; keeping the ratio of pitch to air hole diameter equal to 1.618, utilising six rings of air holes. However, result has shown that the designed PCF achieves steep chromatic dispersion throughout the telecommunication wavelengths. In [12], golden spiral photonic crystal fiber design is introduced, with air holes arranged in a spiral pattern using the principle of golden ratio. Result demonstrates that the PCF achieves a number of zero dispersions at selected telecommunication wavelengths; adjustable by varying the diameters of the air holes of the design. However, both references [9], [12] do not analyse confinement loss; making its applicability in communication still questionable. Furthermore, fabrication of spiral structures [12] is relatively difficult; limiting its practical application even further. In this research, the principle of golden ratio shall be used in designing a hexagonal photonic crystal fiber. Finite element method with an absorbing perfectly matched layer is used to derive properties of the proposed photonics crystal fibers [17]. Results show low chromatic dispersion, small effective area and low confinement loss; making the proposed hexagonal photonic crystal fiber suitable for long distance optical data transmission system.

2. Proposed Design

Figure 1 shows the geometry of the proposed PCF design with air hole rings of identical diameters. The hexagonal photonic crystal fiber design is constructed by first arranging three air holes in equilateral triangular pattern; whilst keeping the ratio of pitch to diameter of the air holes constant following the golden ratio value of 1.618 i.e. $\Lambda/d=1.618$. This is done by varying pitch Λ between 0.8 µm and 1.2 µm, consequently changing the diameter of the air holes. The design is then duplicated to form hexagonal pattern with nine air hole rings, before eliminating the inner most hexagon ring, to obtain our finalized hexagonal photonic crystal fibre (PCF) design with eight air hole rings and a single core.

3. Methodologies

In this research, various properties shall be investigated through numerical simulations and calculations such as effective refractive index n_{eff}, chromatic dispersion D, confinement loss L_c and effective area A_{eff} using the following equations [6, 17].

$$n_{\text{eff}} = \sqrt{1 + \left(\frac{B_1\lambda^2}{\lambda^2 - C_1^2}\right) + \left(\frac{B_2\lambda^2}{\lambda^2 - C_2^2}\right) + \left(\frac{B_3\lambda^2}{\lambda^2 - C_3^2}\right)} \quad (1)$$

Where,
λ is a wavelength
B_1, B_2, B_3, C_1, C_2 and C_3 are constants

$$A_{\text{eff}} = \frac{\left(\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|E|^2 dx\, dy\right)^2}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|E|^4 dx\, dy} \quad (2)$$

Where,
E is the electric field

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2 Re[n_{\text{eff}}]}{d\lambda^2} \quad (3)$$

Where,
D is the dispersion
$Re[n_{\text{eff}}]$ is the real part of effective refractive index

$$L_c = 8.686\, k_0 Im[n_{\text{eff}}] \quad (4)$$

Where,
$Im[n_{\text{eff}}]$ is the imaginary part of the effective refractive index
$k_0 = \frac{2\pi}{\lambda}$ is the free-space wavenumber

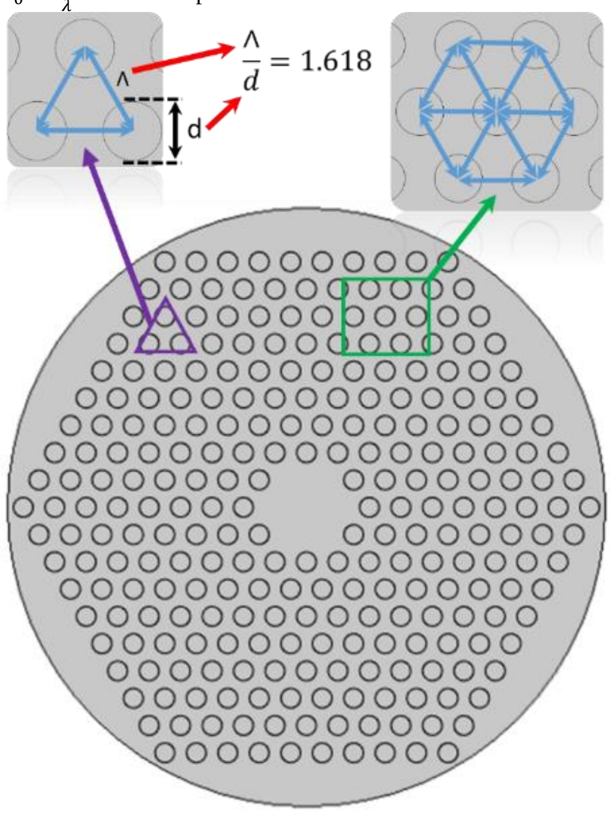
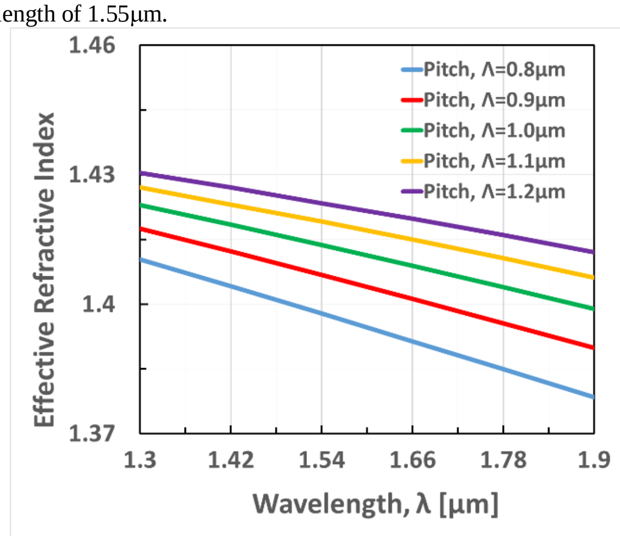


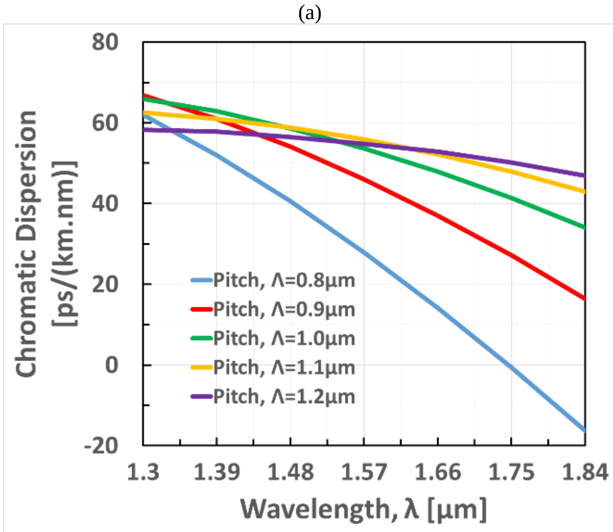
Fig. 1: Structure of the proposed hexagonal photonic crystal.

4. Results and Discussion

Figure 2(a)-2(b) show the wavelength dependence properties of effective refractive index n_{eff} and chromatic dispersion D, respectively for the hexagonal PCF in Figure 1, for different pitch values Λ between 0.8 μm-1.2 μm. In Figure 2(a), it can be observed that hexagonal PCFs with higher pitch values Λ have higher real effective refractive indexes over all wavelength. Furthermore, increasing wavelength λ results in reduction of effective refractive index n_{eff}; with the rate of decrease more prominent for smaller pitch value Λ. Plot of operating wavelength λ against chromatic dispersion D in Figure 2(b) illustrates that the proposed hexagonal PCF exhibits ultra-flattened chromatic dispersion D, particular for designs with high pitch values Λ. Chromatic dispersions of less than 57 ps/(km.nm) are achievable; with dispersion of less than 30 ps/(km.nm) for pitch value Λ of 0.8μm, at the operating wavelength of 1.55μm.



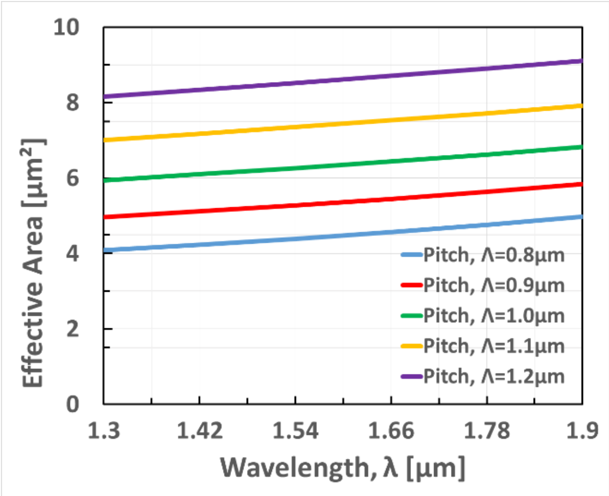
(a)



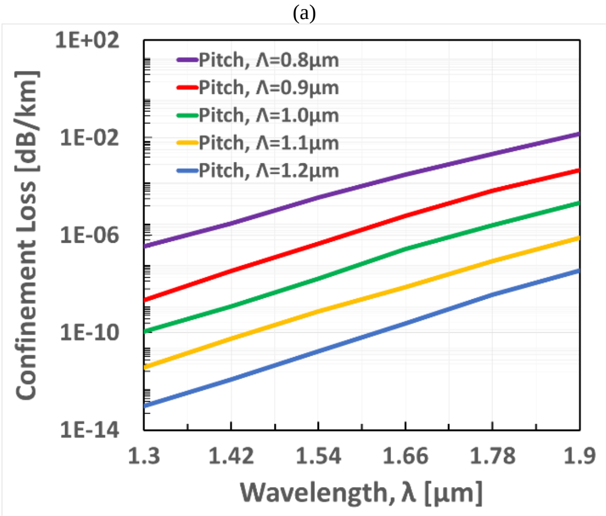
(b)

Fig. 2: (a) Effective refractive index and (b) Chromatic dispersion, as function of wavelength for the hexagonal PCF in Fig. 1.

For applicability in long distance communication systems, the PCF must also have a low effective area A_{eff} as well as low confinement loss L_c. Variation of effective area A_{eff} and confinement loss L_c, with wavelength λ are shown in Figure 3(a)-3(b) for different pitch values Λ. Generally, large pitch values Λ give large effective areas A_{eff}; with effective area A_{eff} of between 4.4 μm^2 and 8.5 μm^2 at the communication operating wavelength of 1.55μm. Furthermore, it is illustrated in Figure 3(b) that the proposed hexagonal PCFs experience confinement loss of less than 0.01 dB/km at operating wavelength of 1.55 μm for all pitch values Λ under consideration; with confinement loss smaller for larger pitch values. Confinement loss of 0.2 dB/km at 1.55μm represents the minimum value for applicability for data communication systems.
This is further supported in Figure 4, showing a strong confinement of light at the core of the hexagonal PCF.
From fabrication point of view, the proposed fiber in Figure 1 is relatively easier to fabricate as compared to the design in [12]; due to its simple symmetrical design.



(a)



(b)

Fig. 3: (a) Effective area and (b) Confinement loss, as function of wavelength for the hexagonal PCF in Fig. 1.

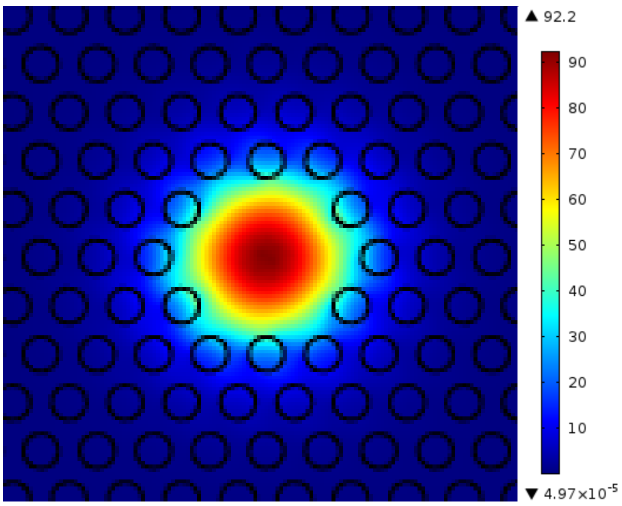


Fig. 4: Normalised electric field at wavelength of 1.55 μm.

5. Conclusion

Hexagonal photonic crystal fiber adhering to the golden ratio value has been proposed; exhibiting ultra-flattened chromatic dispersion, with dispersion value of below 57 ps/(nm.km) at the 1.55 µm wavelength. It has been shown that reducing pitch value reduces the chromatic dispersion; albeit with less flattened dispersion at wavelength ranges of interest, giving relatively smaller effective area and lower confinement loss. Unlike references [9], [12], confinement loss is shown to be less than 0.01 dB/km at 1.55 µm wavelength; thereby proving that the proposed design is applicable for long distance data transmission. Moreover, its uncomplicated design architecture simplifies its fabrication process without comprising on quality.

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