Design of Single Mode Photonic Crystal Fiber with Outstanding Characteristics of Confinement Loss and Chromatic Dispersion over S to L Communication Band

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Abstract: In this article, a novel structure of photonic crystal fiber with nearly zero ultra-flattened chromatic dispersion and ultra-low confinement loss is presented. By replacing the circular air-holes of two first rings with the elliptical air-holes, a fiber with outstanding features of chromatic dispersion and confinement loss is designed. The proposed structure is optimized for operating in a wide wavelength range covering S, C, and L communications bands. Finite Difference Frequency Domain (FDFD) solver is applied to analyze the proposed fiber components. The designed fiber exhibits a chromatic dispersion of -0.12 ps/nm/km at 1.55 µm along with a slope of 0.002 ps/nm^2/km. Also, the other remarkable feature of this fiber is ultra-low confinement loss in order of 10^{-5} dB/km around λ = 1.55 µm.

Keywords: Chromatic Dispersion, Confinement Loss, Dispersion Slope, Photonic Crystal Fibers (PCFs).

1 Introduction

There is a growing interest in the new science of Photonic Crystal Fibers (PCFs) which are finding wide use in areas covering telecommunications, sensor technologies, spectroscopy, and medicine [1]. One of the most promising applications of these fibers is increasing the speed and bandwidth of advanced communication systems.

There are two different guiding mechanisms in PCFs. The first one, index-guiding PCF guides light by total internal reflection between a solid core and a cladding region with multiple air-holes. The second one uses a perfectly periodic structure exhibiting a Photonic Band-Gap (PBG) effect at the operating wavelength to guide light in a low index core-region [2-3].

These fibers have especially striking properties of great controllability in chromatic dispersion and confinement loss. All of these properties are related to the fiber structure such as; the air-holes diameter (d), the pitch (Λ) of the periodic array and the number of air-holes rings around the core (N) [4].

Conventional PCFs have the same uniform air holes and it is difficult to reduce confinement loss and dispersion characteristics, simultaneously [5]. In order to achieve ultra-flattened chromatic dispersion and low confinement loss, several designs have been proposed so far. Among these designs, it can be mentioned to a structurally-simple PCF with a defected-core along with adjusting the size of the central air-hole defect [6], a PCF with extra air holes inserted between the main air holes in the same ring [7], a PCF with different size of air holes in first ring and doped core [8] and dual concentric core PCF [4].

However some studies have concentrated on one issue; chromatic dispersion or confinement loss, while in broadband communication systems, these features both play important roles [9]. In [10], a PCF with 6 rings has been presented in which circular air-holes of two first ring have been replaced with elliptical air-holes, thus this PCF shows flattened dispersion characteristics. But however the confinement loss has not been studied in this work. So, it is required to optimize the fiber structure to achieve both of these features simultaneously.

The reported work in this paper shows that chromatic dispersion and confinement loss characteristics of Single Mode Photonic Crystal Fiber (SMPCF) will be improved by replacing the circular air-holes of two first rings with elliptical air-holes and controlling the other parameters. The effects of varying major and minor diameters of elliptical air-holes, and varying the pitch have been studied to find the trends of

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the dispersion and confinement loss variations. Then, the optimized parameters of structure have been achieved to design an ultra-low, ultra-flattened chromatic dispersion and Ultra low confinement loss PCF over a wide wavelength range which covers S, C and L telecommunication wavelength bands.

This paper is organized as follows: Section 2 focuses on the fundamental properties of PCFs such as confinement loss and chromatic dispersion and also the influences of structural parameters variation on these features. In the next section, fiber geometry structures and then the numerical results are discussed. Finally, the paper sets out its conclusion in the last section, section4.

2 Fundamental Properties Concepts

In this section, two major issues of designing the PCFs (chromatic dispersion and confinement loss) will be described. Also the effect of structural parameters variation such as the pitch (Λ) of the periodic array, the shape of the air-holes, the air-holes diameter (*d*) and the number of air-holes rings around the core (*N*) are investigated.

2.1 Chromatic Dispersion

PCFs have the attractive property of significant controllability in chromatic dispersion. The chromatic dispersion characteristics can be easily controlled by changing the shape and size of the air holes and the air holes pitch. Controllability of chromatic dispersion of PCFs is an important problem for practical applications to optical communication systems, dispersion compensation, and nonlinear optics [4]. So far, various PCFs with remarkable dispersion properties have been investigated numerically [7]. The chromatic dispersion D of a PCF is calculated from the effective index of the fundamental mode n_{eff} versus the wavelength using

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

where c is the speed of light in vacuum and n_{eff} is a function of wavelength and material dispersion ($n_m(\lambda)$), so that;

$$n_{eff} = \beta(\lambda, n_m(\lambda))/k_0 \qquad (2)$$

where β is the propagation constant and $k_0=2\pi/\lambda$ is the wave number of free space and $n_m(\lambda)$ can be estimated by using the Sellemeier's formula. The background material is Corning 7980 Silica whose refractive index can be estimated using the following Sellmeier's equation [11]:

$$n^2(\lambda) = 1 + \frac{0.6837\lambda^2}{\lambda^2 - 0.00460353} + \frac{0.420324\lambda^2}{\lambda^2 - 0.0133969} + \frac{0.585027\lambda^2}{\lambda^2 - 64.4933} \qquad (3)$$

When the pitch is large and the holes diameter to pitch ratio (*d*/Λ) is very small, the dispersion curve is close to the material dispersion of pure silica. As the air-hole diameter is increased, the influence of waveguide dispersion becomes stronger. In this article, we reduced chromatic dispersion by changing the shape of air holes and replacing them with elliptical air holes.

2.2 Confinement Loss

Confinement loss is an additional form of loss that happens in single-material fibers and it represents the light confinement ability within the core region. It should be mentioned that the number of layers of air-holes is finite and when the optical mode propagates in the core region, leaking light from the core to the cladding occurs through the region between air-holes and causes the confinement loss [4]. Confinement loss L_C (dB/km) is calculated as follows [7, 12, and 13]:

$$L_C = \frac{\left(\frac{20}{\ln 10}\right) 2\pi \,\mathrm{Im}(n_{eff})}{\lambda} = 8.686\frac{2\pi}{\lambda}\mathrm{Im}(n_{eff}) \qquad (4)$$

where Im[n_{eff}] is the imaginary part of the refractive index, $k_0 = 2\pi/\lambda$ is the wave number in the free space [13]. This confinement loss can be decreased exponentially by increasing the number of air-holes rings surrounding the solid core, and is determined by the geometry of the structure.

3 Design Principle and Simulation Results

As mentioned above, by adjusting the structural parameters of PCFs, we can achieve a PCF with excellent features; nearly zero ultra-flattened chromatic dispersion along with ultra-low confinement loss. These fibers typically consist only of a single material (usually silica), containing very small air holes with diameters of about 1 to a few micrometers. The structural parameters are chosen so that the proposed PCF is single mode over S to L communication band and the fiber nonlinearity effect is weak. Fig. 1(a) shows the cross section of the proposed PCF in which the circular air-holes of two first rings are replaced with elliptical air-holes. This PCF is a triangular PCF with 5 rings described by air-hole diameter *d*, holes pitch Λ; the major and minor diameters of elliptical air-holes; *a* and *b*, respectively.

Finite difference frequency domain method is popular and appealing for numerical electromagnetic simulation due to its many merits [14]. So, we used Mode Solution software as a simulation tool in which Perfectly Matched Layer (PML) for the boundary treatment and an efficient compact two dimensional finite-difference time-domain (2-D FDFD) method are combined to analyze PCF numerically.

Fig. 1(b) demonstrates the field intensity distribution of the fundamental mode of the PCF which evidently has very well characteristics from the viewpoint of fundamental mode confinement. In the following, we will investigate the chromatic dispersion and confinement loss characteristics of the designed PCF. Also the effects of varying the structural parameter on these characteristics will be studied in order to reach to an optimized structure with the desirable features.

The air-holes belonging to the inner rings, which surround the silica core, have a strong influence on the PCF dispersion properties, since the guided mode field is strictly confined in the central region of the PCF cross section.

In order to investigate the influence of the replacing the circular air-holes of two first rings with the elliptical air-holes on the dispersion, we firstly present chromatic dispersion curve of a single mode PCF with all circular air holes in which Λ = 1.68 μm and d = 1.4 μm (Fig. 2). As shown in this figure, the level of the dispersion is high and the dispersion slope is not flat at all.

Fig. 3 shows dispersion curve of a PCF in which the air-holes of the first ring is replaced by elliptical air holes with different size. As shown in this figure, chromatic dispersion is decreased by this technique and when the value of a_1/b_1 decreases, the level of dispersion increases and its slope decreases. Therefore, in order to achieve nearly zero and ultra-flattened chromatic dispersion, we replace the air holes of the second ring with elliptical air-holes as well.

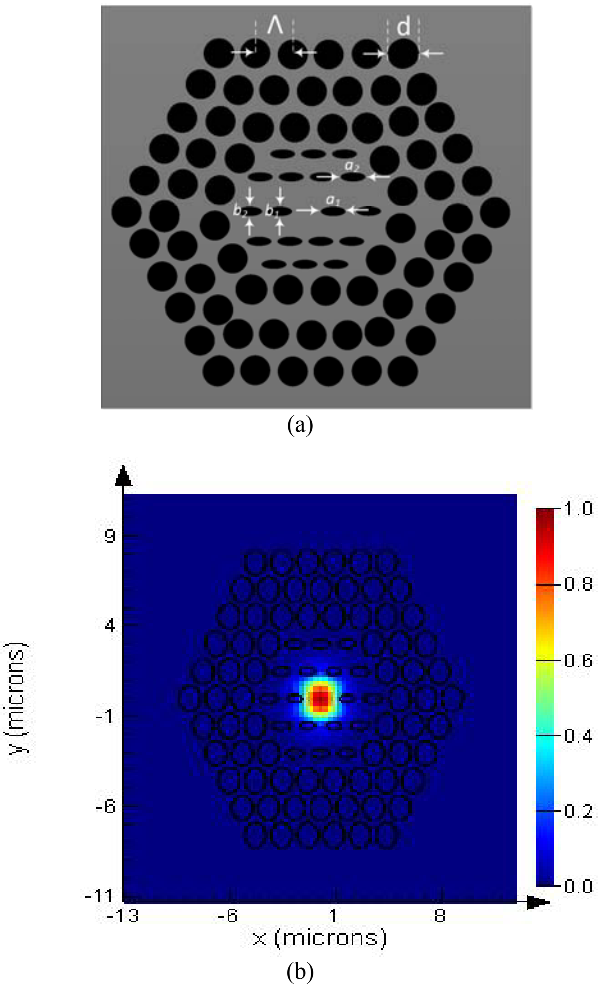

Fig. 1 (a) Cross section of the proposed PCF (b) Transversal field intensity distribution at a wavelength of 1.55 μm for the fundamental guiding mode.

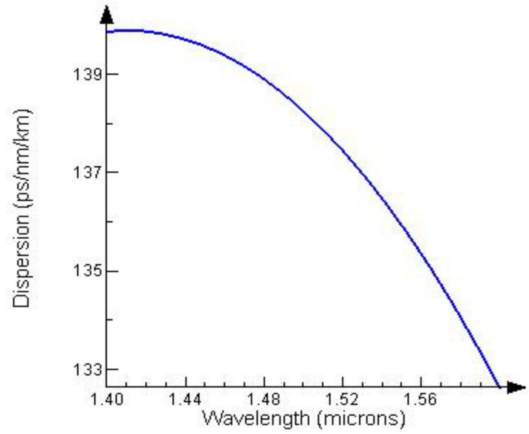

Fig. 2 Chromatic dispersion for a conventional PCF with Λ=1.68 μm, d=1.4 μm.

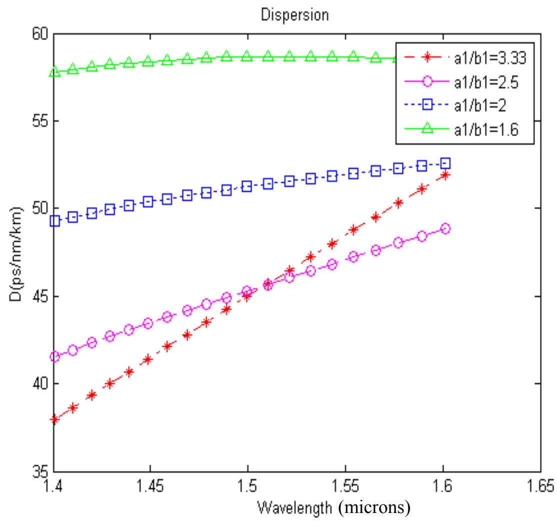

Fig. 3 Chromatic dispersion for the proposed design with Λ=1.68 μm, d=1.4 μm and different value of a_1/b_1.

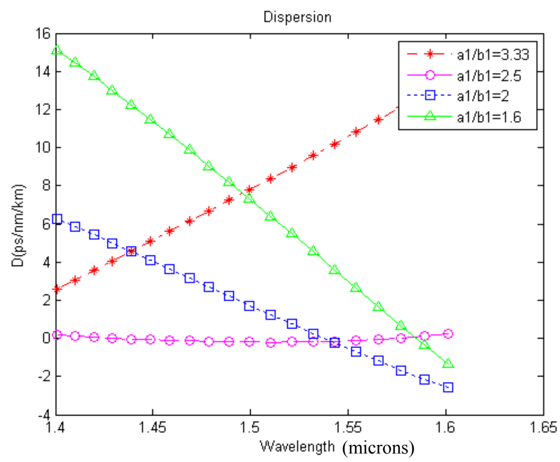

Fig. 4 Chromatic dispersion for the proposed design with Λ=1.68 μm, d=1.4 μm, a_2=1.2 μm, b_2=0.5 μm and different value of a_1/b_1.

Fig. 4 shows the dispersion curves of PCF with different sizes of the elliptical air holes in the first central ring while all the other geometric characteristics of the PCF, that is the pitch Λ, hole diameter d and dimension of the elliptical air holes in the second ring a_2, b_2 are kept constant at Λ=1.68 µm, d=1.4 µm, a_2=1.2 µm and b_2=0.5 µm. As shown in Fig. 3, when the value of a_1/b_1 changes gradually from 3.33 to 1.6, (while a_1 is fixed at 1 µm) we have a dispersion curve with positive slope at a_1/b_1=3.33, then it gets more flattened at a_1/b_1=2 and slope of the dispersion curve is negative for a_1/b_1=1.6.

Fig. 5 shows the dispersion curves of PCF with different sizes of the elliptical air holes in the second central ring while all the other geometric characteristics of the PCF, that is the pitch Λ, hole diameter d and dimension of the ellipse air holes in the first ring a_1, b_1 are kept constant at Λ=1.68 µm, d=1.4 µm, a_1=1 µm and b_1=0.4 µm and the value of a_2/b_2 changes from 2 to 3 gradually (a_2 is fixed at 1.2 µm).

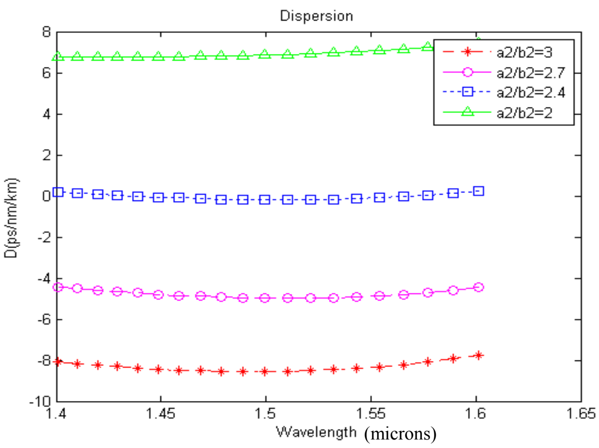

Fig. 5 Chromatic dispersion for the proposed design with Λ=1.68 µm, d=1.4 µm, a_1=1 µm, b_1=0.4 µm and different value of a_2/b_2.

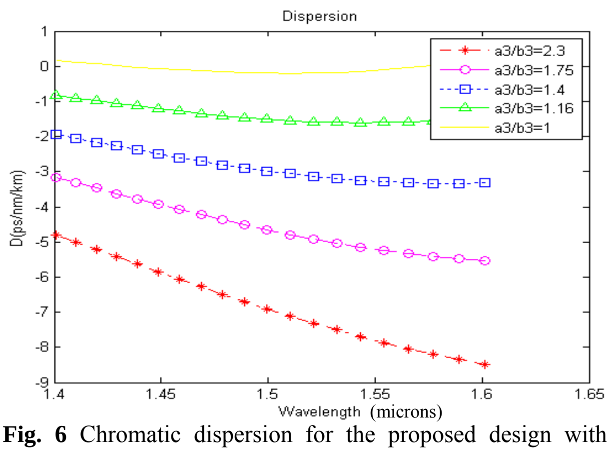

Fig. 6 Chromatic dispersion for the proposed design with Λ=1.68 µm, d=1.4 µm, a_1=1 µm, b_1=0.4 µm, a_2=1.2 µm, b_2=0.5 µm and different value of a_3/b_3.

As shown in Fig. 5, the level of dispersion decreases as a_2/b_2 decreases and we have nearly zero ultra-flattened chromatic dispersion at a_2/b_2=2.4.

If the circular air-holes of the third ring are also replaced with elliptical air-holes, the results depicted in Fig. 6 will be achieved. As illustrated in this figure, both dispersion value and its slope improve as a_3/b_3 decreases and for a_3/b_3=1, the best case is achieved with nearly zero ultra-flattened chromatic dispersion. Therefore replacing the circular air-holes of the third ring with elliptical air-holes is useless.

According to the simulation results, the optimized structural parameters for the proposed PCF with desirable dispersion characteristics are Λ=1.68 µm, d=1.4 µm, a_1=1 µm, b_1=0.4 µm, a_2=1.2 µm, b_2=0.5 µm.

Fig. 7(a) demonstrated the dispersion characteristics of this fiber with more precision. As shown in this figure, the designed PCF has a chromatic dispersion of -0.12 ps/nm/km at 1.55 µm and a dispersion variation of ±0.2 ps/nm/km across a wide wavelength range from 1.4 µm to 1.6 µm. The proposed structure has better characteristics in compare to the other PCFs.

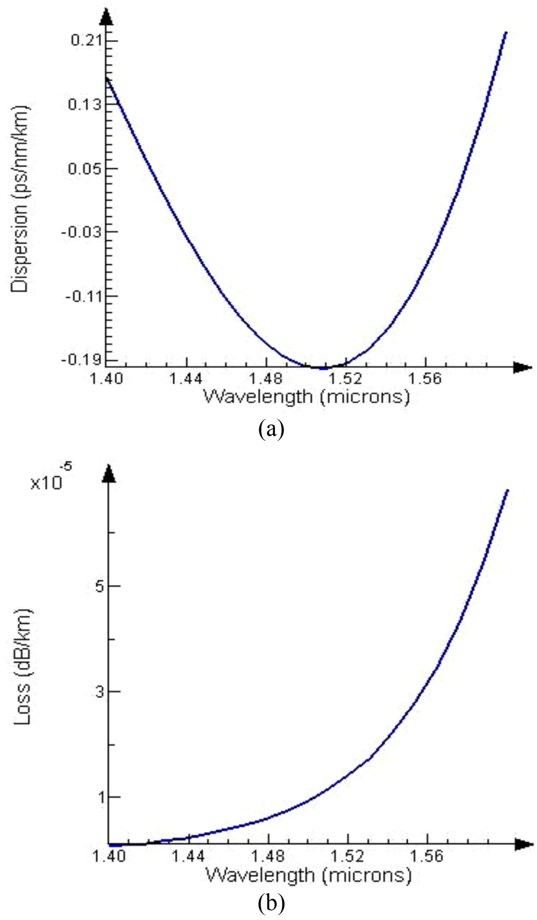

Fig.7 (a) Chromatic dispersion and (b) confinement loss as a function of wavelength for optimum structural parameters (Λ=1.68 µm, d=1.4 µm, a_1=1 µm, b_1=0.4 µm, a_2=1.2 µm, b_2=0.5 µm).

Table 1 Comparison of the results with results from other studies.

Reference	Design Complexity	Dispersion at 1.55 µm (ps/nm/km)	Dispersion Slope $ps/nm^2/km$	Confinement Loss dB/km
[4]	High	1	-7.828×10^{-4}	3.06×10^{-4}
[7]	Medium	-6	0.02	
[8]	High	-0.5		0.306411
[10]	Medium	0	0.0035	
[14]	High	0.35	0.0014	10^{-4}
[16]	High	0.06	0.0015	1.728
[17]	High	0.23	0.0027	0.01
Proposed PCF	Medium	-0.12	0.002	2.6×10^{-5}

Table 1 presents the results comparison between the other structures referred in related works and the proposed design. It should be mentioned that the wavelength range of analysis, reported in some of these studies, is less and about 100nm [8]. Also, the confinement loss has not been studied in some of these works [7, 10] and some of them have many rings to reduce the confinement loss [4, 16] or has more design complexity [4, 8, 14, 16, and 17].

In addition, Fig. 7(b) shows the confinement loss of the proposed PCF. It is obvious that our design has low confinement loss in the order of 10^{-5}dB/km across a wide wavelength range which covers S to L telecommunication wavelength bands (from 1.4µm to 1.6µm) and the value of this parameter is 2.6×10^{-5} dB/km at $\lambda = 1.55$ µm.

Therefore, as it can be seen, the proposed PCF has ultra-low-flattened chromatic dispersion and ultra-low confinement loss across a wide wavelength range from 1.4 µm to 1.6 µm, so in overall, it has more better features than that of the other PCFs.

4. Conclusion

This article presents a novel index-guiding Photonic Crystal Fiber (PCF) in which the circular air-holes of the first and the second rings are replaced by the elliptical air-holes. The simulation of the proposed design was carried out using FDFD method. The results revealed that low confinement loss and nearly zero-flattened chromatic dispersion can be obtained by varying the elliptical air-holes diameters. In this work, a PCF with nearly zero and ultra-flattened dispersion (-0.12 ps/nm/km & 0.002 $ps/nm^2/km$) low confinement loss in order of 10^{-5} dB/km over a wide wavelength range from 1400 to 1600 nm is designed.

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