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Improvement of Optical Properties in Hexagonal Index-Guiding Photonic Crystal Fiber for Optical Communications

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Abstract

Waveguides with low confinement loss, low chromatic dispersion, and low nonlinear effects are used in optical communication systems. Optical fibers can also be employed in such systems. Besides optical fibers, photonic crystal fibers are also highly suitable transmission media for optical communication systems. In this paper, we introduce two new designs of index-guiding photonic crystal fiber (IGPCF) with characteristics appropriate for optical communications. In the first proposed design with a hexagonal structure having a defect at the center, the chromatic dispersion at the wavelength of 1550 nm is less than 1 ps/(nm.km). In the second design with a hexagonal structure having air holes with unequal diameters, nearly zero dispersion at the wavelength range of 1370 to 1380 nm is achieved. At the same time, for the latter design, at the wavelength of 1550 nm, the chromatic dispersion slope is 1 ps/(km.nm), the confinement loss is less than 10^{-9} dB/km, and the nonlinear coefficient reaches 3.690 $W^{-1}.km^{-1}$.

Keywords: Hexagonal, index-guiding, chromatic dispersion, confinement loss, photonic crystal fiber, nonlinear coefficient.

2010 Mathematics Subject Classification: Primary 74E15; Secondary 91D10.

1. Introduction

Over the last decade, photonic crystal fibers (PCFs) have attracted much attention amongst various research groups. PCFs with large effective mode area can strongly confine light in their hollow cores [2, 9, 24]. PCFs with nearly zero and flat dispersion over a wide range of wavelengths are suitable media for applications

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in wavelength-division-multiplexing (WDM) systems [6, 8, 13, 22]. It is imperative to maintain a uniform response at different wavelength channels which requires that transmission happens within both very low chromatic dispersion and confinement loss regions. Thus, PCFs perform very well in both telecom and non-telecom applications [3, 7, 26]. In optical communications, chromatic dispersion plays an important role as it determines the information carrying capacity of the PCFs. Therefore, it becomes important to study the chromatic dispersion properties of PCF. In other hands, control of chromatic dispersion in PCFs is a crucial issue for practical applications in optical communication systems, dispersion compensation, and nonlinear optics [22].

Usually, PCFs are constructed from silica glass which contains very tiny air holes. The air holes running through the length of the structure act as the cladding of the fiber and a defect in the center (done by removing the hole at the center of the structure) acts as the core [6]. Since the average refractive index of the area surrounding core is lower than that of the core in the index photonic crystal fiber (IGPCF), the transmission in this type of PCFs is due to the total internal reflection (TIR) [4, 11, 14].

Until now, several designs for PCFs have been proposed to achieve a very low chromatic dispersion and low confinement loss. Hansen proposed a PCF structure with three-fold symmetry, low dispersion, and low dispersion slope. However, the confinement loss was about 10^{-3} dB/km [8]. Nejad et al. presented a new PCF structure with controlled chromatic dispersion. But, the confinement loss was 10^{-4} dB/km [13]. In 2011, an ultra-flattened dispersion photonic crystal fiber with low confinement loss was proposed by Olyaee et al. [15, 16].

Optical parameters such as a chromatic dispersion, confinement loss, and nonlinear effects are highly important to design PCFs. However, by tuning physical parameters including the diameter of the air holes, the shape of the holes, the defect at the center of the fiber or surrounding the core, the number of hole rings in the area surrounding the core and the spacing between the adjacent air holes, one could have PCFs with desired properties [20].

In this paper, we introduce and simulate two IGPCFs with improved optical parameters. In the first proposed design with a hexagonal structure having a defect at the center, the chromatic dispersion at the wavelength of 1550 nm is less than 1 ps/(nm.km). In the second design with a hexagonal structure having air holes with unequal diameters, nearly zero dispersion, low nonlinearity and very low confinement loss are obtained.

2. PCF Characteristics

PCFs have some important optical parameters and each of which is crucial for high-speed optical communications. Important parameters in PCFs are as follows:

2.1 Chromatic Dispersion

An important parameter for designing PCFs is the total dispersion. The chromatic dispersion, D(λ), is the sum of the material and waveguide dispersions. Unlike conventional fibers, both the material dispersion and confinement loss are controllable via suitable design of the cladding, core, and their air-holes. The chromatic dispersion of PCF is computed from the real part of the effective mode index, n_{eff}, by using the following equation [18]:

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2 Re[n_{eff}]}{d\lambda^2} \tag{1}$$

where, the operating wavelength, λ, is expressed in units of μm, c is the velocity of light in free space, and $Re[n_{eff}]$ is the real part of the n_{eff}. Therefore, the unit of chromatic dispersion is ps/(nm.km). For a given wavelength, the effective mode index of a guided mode is obtained by solving the MaxwellâĂŹs equations [8], using the FDTD method as explained in Eq. (2) [1, 10, 23, 27]:

$$n_{eff} = \frac{\beta}{k_0} \tag{2}$$

where, β and k_0 are the propagation constant and the free space wave number, respectively.

2.2 Confinement Loss

The confinement loss, L_c, is the light confinement ability within the core region. Increasing the number of air hole rings, strengthen the confinement of light in the core region. This in turn results in smaller losses than those with less air hole rings. The confinement loss is calculated as [12, 17, 19]:

$$L_c = \frac{(20 \times 10^6)}{(ln10)} k_0 Im[n_{eff}] \tag{3}$$

where, $Im[n_{eff}]$ is the imaginary part of the n_{eff} and the unit of L_c is dB/m.

2.3 Mode Effective Area

Mode effective area in PCFs, A_{eff}, in units of mm^2 is given by [25]:

$$A_{eff} = \frac{(\int\int \mid E \mid^2 dxdy)^2}{(\int\int \mid E \mid^4 dxdy)} \tag{4}$$

Here, $\mid E \mid$ the electric field distribution which derives from the eigenvalue problem drawn from Maxwell's equations [21]. By changing the geometric characteristics of the fiber-cross-section, such as large effective area, it is possible to obtain PCFs with various properties [5].

2.4 Nonlinearity Effects

If we choose the air hole diameter and lattice constant properly, the confinement loss in highly nonlinear PCFs can become lower than that in PCFs with low nonlinearity. However, such PCFs are not used in long-haul communications. Subsequently, nonlinearity in PCFs must be minimized. Large mode area of PCFs can prevent unwanted nonlinear impairments [21]. On the other hand, low confinement losses or small effective mode area is required for some special applications including nonlinear based phenomenon. The nonlinear effects can be written as:

$$\gamma = (\frac{2\pi . n_2}{\lambda A_{eff}}) \times 10^3 w^{-1} . km^{-1} \tag{5}$$

where, γ and n_2 are the nonlinear coefficient and nonlinear refractive index of PCFs, respectively [5].

3. Design and Simulation Results of the Proposed PCF

In this paper, to analyze the proposed PCFs, the finite-difference time-domain (FDTD) method with perfectly matched layer boundary conditions has been used. The first proposed IGPCF is made up of pure silica with a refractive index of 1.45. It has a triangular array of air holes formed along its length. This PCF consists of 5 air hole rings. The diameter of the holes in the PCF is chosen to be 780 nm. The lattice structure of the cladding is hexagonal and the pitch of the lattice, Λ (the spacing between the centers of two adjacent holes), is 2300 nm. At the center of the structure, we have a hole of doped silica with refractive index of 1.43. Diameter of the defected core is d_c=400 nm. We have a defected core at the center of the structure in order to enable us to control the chromatic dispersion. The transverse cross-section of the PCF is demonstrated in Figure 1.

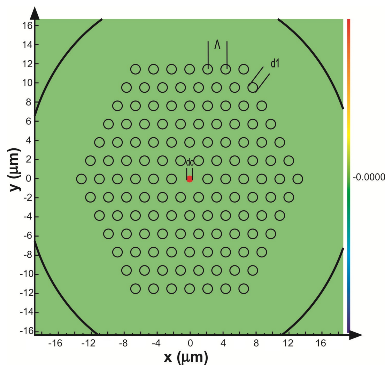

Figure 1: The cross section of the first proposed IGPCF with d_1=780 nm, Λ=2300 nm, and d_c=400 nm.

In this design, the pitch and diameter of holes are chosen to be constant, but diameter of the defected core is unequal with diameter of the other holes. The chromatic dispersion, confinement loss, and the nonlinearity change by either increasing or decreasing the $\frac{d}{\Lambda}$.

The chromatic dispersion curve of our first design is illustrated in Figure 2. The measured values of the chromatic dispersion over the wavelength range 1200-1600 nm are acceptable. The chromatic dispersion of the first proposed IGPCF is 1 ps/(nm.km), at the wavelength of 1550 nm. The minimum chromatic dispersion is related to the wavelength range of 1370 nm. In other ranges of wavelengths, the primary IGPCF has a less negative dispersion and in longer wavelengths, the positive dispersion increases. The best results are achieved with Λ=2300 nm.

The loss characteristic of the suggested IGPCF within the wavelength range of 1200-1600 nm is plotted in Figure 3. It can be seen from the figure, the loss of the designed PCF is 0.341 dB/cm at the wavelength of 1550 nm. In addition, the PCF shows the losses of 0.04 $\sim$ 0.34 dB/cm in the wavelength range of 1200-1600 nm and less than 0.35 dB/cm over other wavelength ranges. Figure 4 illustrates the variation of the neff with respect to the wavelength in the first proposed IGPCF. As shown in Figure 4, the effective index decreases with increasing wavelength.

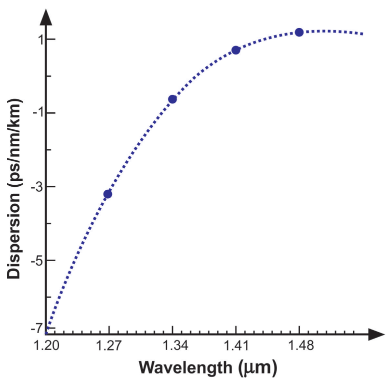

Figure 2: The chromatic dispersion curve of the first proposed IGPCF as a function of wavelength.

In the suggested design, a strong confinement of light is obtained in the core. The mode field is mainly distributed and guided in the silica core region. The light is well trapped at the center of the structure and the mode effective area of 26.34 μm^2 is achieved at 1.55 μm. In order to visualize and confirm our results, we then calculated the nonlinear coefficient of our first design which is a relatively large value of 4.6125 $w^{-1}.km^{-1}$, as shown in Figure 5.

The effective mode area of about 26.34 μm^2 is calculated at 1.55 μm wavelength. Because of the obtained mode field distribution, the maximum optical power is at the center of the IGPCF core. In addition, a PCF with small effective

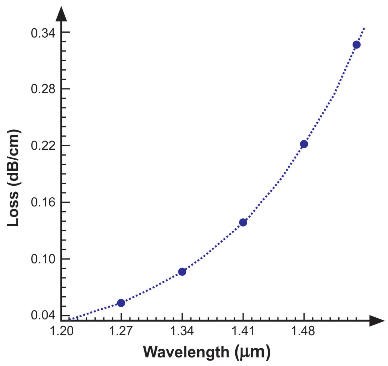

Figure 3: The confinement loss curve of the first proposed IGPCF as a function of wavelength.

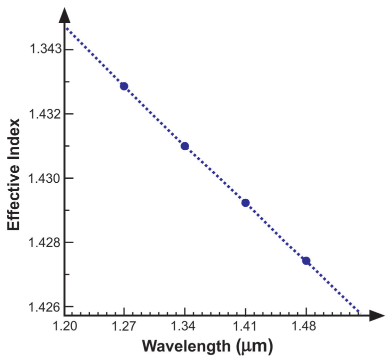

Figure 4: The effective index curve of the first proposed IGPCF as a function of wavelength.

mode area is useful for nonlinear optical applications. It is appropriate to couple the proposed PCF to an index guiding fiber. Generally, this IGPCF is more useful in optical telecommunication systems because it has approximately low dispersion, low confinement loss, and an appropriate effective mode area. This structure due to its symmetry is simple and easy to fabricate.

4. Design and Simulation Results of the Improved PCF

In IGPCF with hexagonal structure, the holes that are closer to the core have a stronger impact on dispersion, although their effects on confinement loss are quite negligible. To improve the characteristics of our first IGPCF structure; we designed the second IGPCF as shown in Figure 6. The air hole diameter-to-pitch ratio, (d/Λ), plays a critical role in the design of IGPCF. By decreasing the d/Λ value in the cladding, the chromatic dispersion reduces. On the other hand, increasing the d/Λ results in the reduction of the confinement loss. To better control the chromatic dispersion, the confinement loss, and nonlinearity, unequal diameters for air holes can be selected. Hence, a larger diameter for the holes in outer rings is necessary. In order to have both low dispersion and low confinement loss, the diameter of outer rings is chosen to be bigger. Therefore, the diameters of holes in the internal rings are selected to be smaller, whereas the diameters of holes in the external rings are chosen to be larger, as shown in Figure 6.

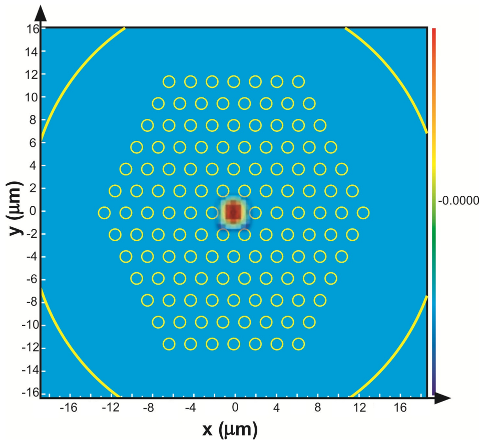

Figure 5: The field distribution of the first-order mode for the first proposed IGPCF at λ=1.55μm.

In this design, the PCF consists of 9 air hole rings. The diameters of the holes in the first three inner rings are chosen to be 780 nm, for the fourth, fifth, and sixth rings are selected to be 1300 nm and finally for the three outer rings are chosen to be 1800 nm. The lattice structure of the cladding is hexagonal and the

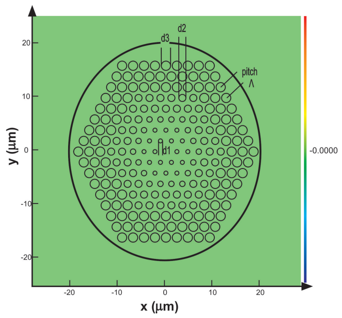

Figure 6: The cross section of the second proposed IGPCF with d_1=780 nm, d_2=1300 nm, d_3=1800 nm, and Λ=2300 nm.

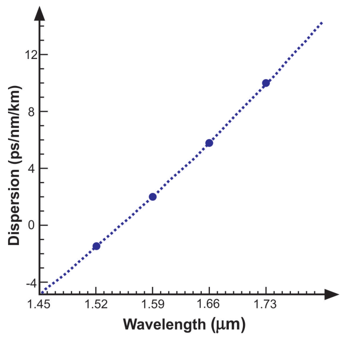

Figure 7: The chromatic dispersion curve of the second proposed IGPCF as a function of wavelength.

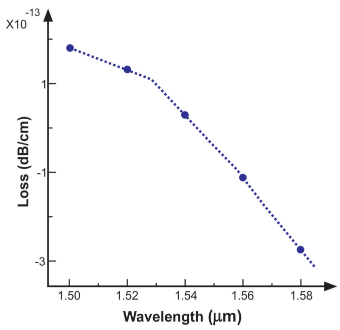

Figure 8: The confinement loss curve of the secondary proposed IGPCF with respect to the wavelength.

pitch of the lattice, Λ, is 2300 nm. The transverse cross-section of the PCF is demonstrated in Figure 6.

The dispersion curve of the second design is demonstrated in Figure 7. The chromatic dispersion at the wavelength of 1200 nm is very low. At the wavelength of 1550 nm, the chromatic dispersion of the same structure is near 1 ps/(nm.km). The zero chromatic dispersion occurs at the wavelength of 1530 nm. The average chromatic dispersion is -1.5 ps/(nm.km) over the wavelength range of 1200-1600 nm, which is fairly low and negative. Below this wavelength range, the structure has even lower negative dispersion and above that, the positive dispersion increases. The best chromatic dispersion is achieved with Λ=2300 nm.

The loss characteristic of the presented second structure within the wavelength range of 1480-1600 nm is plotted in Figure 8. As it can be seen from the figure, an ultra-low loss is achieved at the wavelength of 1550 nm. Moreover, the PCF shows the losses of $3.5\times10^{-13} \sim 2\times10^{-13}$ dB/cm over the wavelength range of 1480-1600 nm and less than 10^{-12} dB/cm over the other wavelengths.

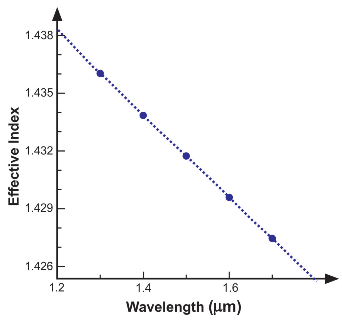

Figure 9: The effective index curve of the second proposed IGPCF with respect to the wavelength.

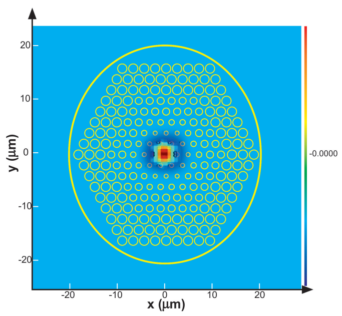

Figure 10: The field distribution of the first-order mode for the second proposed IG-PCF at λ=1.55μm.

Figure 9 illustrates the variation of the neff with respect to the wavelength in the second proposed IGPCF. In the secondary proposed design, a strong confinement of light in the core of the IG-PCF is obtained. The mode field is mainly distributed and guided in the silica core region. We calculated the first-order mode for the secondary IGPCF at λ= 1550 nm. The light is well trapped at the center of the structure and the mode effective area of 32.93 μm^2 is achieved, as shown in Figure 10. In the proposed structure, with such a very large mode area, the unwanted nonlinear impairments are prevented and hence, the nonlinear effects are decreased. We calculated the nonlinear coefficient for the second IGPCF as small as 3.690 $w^{-1}.km^{-1}$. Table 1 compares our proposed PCFs with other PCFs in the literature.

Table 1: Comparison results at 1.55 μm amongst the presented PCFs and other PCFs in the literature.

	Dispersion (ps/nm/km)	Loss (dB/cm)	Effect mode area (μm^2)	Nonlinearity ($w^{-1}.km^{-1}$)
Primary design	1	0.34	26.34	4.61
Secondary design	0.001	0.3×10^{-13}	32.93	3.69
Ref. [13]	-195	0.3×10^{-5}	-	-
Ref. [18]	2.7	0.3×10^{-10}	61.2	-
Ref. [5]	3	10^{-10}	7.7	18
Ref. [16] PCF_1	0.002	10^{-11}	-	-
Ref. [16] PCF_2	8.2	2×10^{-11}	-	-

5. Conclusions

In this paper, two new index-guiding photonic crystal fibers based on pure silica have been designed and simulated. According to the results, the improved properties including lower values for chromatic dispersion, nonlinear effects, and confinement loss can be acquired by reducing the size of the holes in the inner rings and increasing the diameters of the holes in the outer rings. The primary PCF has a simple structure with a defect at center of the PCF. In the second IGPCF, the results show that both negative and zero dispersion can be obtained. The main advantages of the second PCF are zero chromatic dispersion, very low confinement loss, and nearly zero nonlinearity effects with very large mode area.

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