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Full Length Research Paper

Design of new square-lattice photonic crystal fibers for optical communication applications

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In this paper, two new square-lattice photonic crystal fibers (PCFs) are designed and proposed. Both fibers have identical structures with five air-hole rings, yet the diameter of air-holes differ in their structures. Finite-difference time-domain (FDTD) method with the perfectly matched layers (PML) boundary conditions has been used to investigate these fibers. The proposed photonic crystal fibers exhibit properties of ultra-flattened nearly zero dispersion and low confinement loss in wavelength range of 1.2 to 1.7 µm. Dispersion slope in both fibers is about 7×10^{-3} ps/(nm^2.km). Since dispersion and confinement loss of the first photonic crystal fiber (PCF_1) at the wavelength 1.55 µm are 0.00249 ps/(nm.km) and about 4×10^{-6} dB/km, respectively, its application as transmission medium in optical communications will be highly favored. Although, the zero dispersion wavelength of the second PCF (PCF_2) is 1.45 µm, the confinement loss of this fiber is lower than PCF_1 and below 10^{-7} dB/km in all of the studied wavelength range.

Key words: Square lattice, photonic crystal fiber, dispersion, confinement loss.

INTRODUCTION

Development of wavelength division multiplexing (WDM) networks in recent years and the requirement of transmitting data over optical fibers in high bitrates in the second and third wavelength window have caused serious concerns using conventional single mode fibers in optical communications. High dispersion in conventional single mode fibers leads to partial loss of data in long distances of data transmission. Thus, researchers began to devise new optical transmission media with zero dispersion and uniform response in different wavelength channels.

Photonic crystal fibers (PCFs) are a new generation of fibers, which are also referred to as air-silica, holey or micro-structured fibers. Their structures resemble those of the conventional fibers, as they comprise a core and a cladding, yet the cladding is of two-dimensional photonic crystal type. In conventional photonic crystal fibers, the cladding structure is formed by embedding a number of air channels which form square-lattice or triangular-lattice structures around the core and run along the fiber. The PCFs can be classified according to their core, which is air or silica. In solid-core or index guiding fibers, the index difference between the core and cladding is a positive value; hence the light is guided along the fiber through total internal reflection (TIR) mechanism. However, in fibers with air core, the refractive index of the cladding is higher than that of the core; therefore to prevent the propagation of the light into the cladding area and to confine the fundamental mode to the core, the wavelength of the beam should be chosen within the photonic band gap range. 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' diameter (d), the spacing between two adjacent holes or pitch (Λ), number of rings (N_r), arrangement of the holes and their refractive indices. 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

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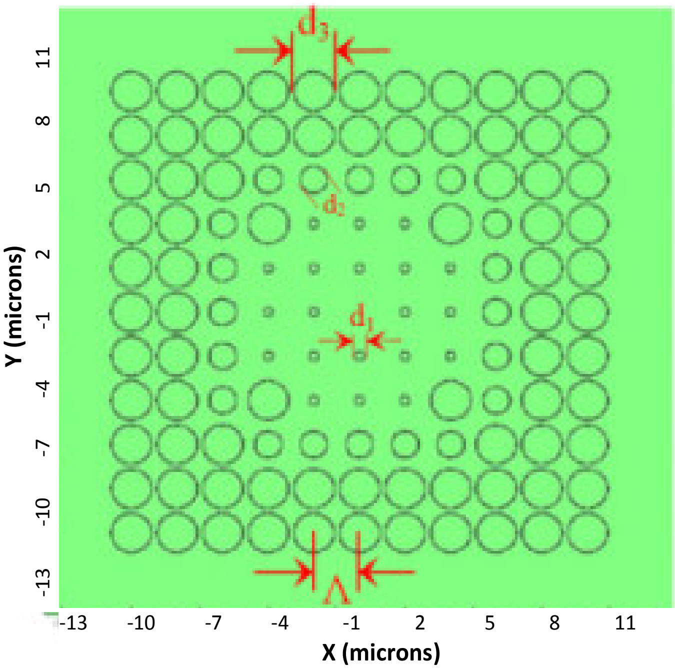

Figure 1. Cross-section of the proposed photonic crystal fiber with square-lattice structure. Diameter of the air-holes in the first two rings except the four corner ones in the second ring is d_1, the diameter of the third ring air-holes except the four air-holes in the corners is d_2, and d_3 is the diameter of the air-holes in the two outer rings and the eight corner air-holes in the second and third ring. The lattice constant is Λ.

PCF, which makes it a proper choice for communication applications, is that nearly zero flattened dispersion and low confinement loss in this fiber is attainable at the same time.

Previous studies mainly focused on hexagonal photonic crystal fibers (H-PCFs) to realize both low dispersion and confinement loss (Matsui et al., 2005; Chen et al., 2008; Hai et al., 2007; Kaijage et al., 2008; Saitoh et al., 2003). H-PCF has a triangular lattice structure and its cladding is hexagonal. Various techniques have been proposed and proven successful in reducing the dispersion and confinement loss in hexagonal PCFs, e.g. adding dopants to the core (Hansen, 2003), using air-holes with unlike diameters to the cladding (Wang et al., 2004), implementing a narrow air channel in the center of the PCF (Saitoh et al., 2005) and changing the form of the air-holes in inner rings into elliptical (Hai et al., 2008).

Propagation characteristics of the photonic crystal fibers with square-lattice structures have been recently studied and reported (Wang and Yang, 2007; Liu and Lai, 2004; Ferrando and Miret, 2001, Kim et al., 2009). Dispersion properties and effective modal area of PCFs with triangular and square-lattice structures were compared (Bouk et al., 2004; Begum et al., 2007). In 2009, a square-lattice PCF structure with ultra-flattened dispersion was designed, in which dispersion demonstrated slight variations of 0 ± 0.06 ps/(km·nm) within wavelength range of 1.375 to 1.605 µm and the confinement loss was below 0.1 dB/km in the same range (Xiao-Lin et al., 2009). Despite favorable dispersion characteristics offered by this structure, confinement loss is relatively high.

In this paper, two new designs for square-lattice PCFs with 5 air-hole rings are proposed. Effects of lattice constant (Λ), diameter of the air-holes and number of rings on dispersion and confinement loss are investigated. Through optimizing the design parameters, the proposed PCFs offer nearly zero dispersion and very low confinement loss in a wide wavelength range. Finally, confinement loss and dispersion curves of the proposed square-lattice photonic crystal fiber (PCF_2) and a hexagonal fiber with similar structure are compared.

For the purpose of analyzing and simulating the propagation characteristics of the proposed photonic crystal fiber, finite-difference time-domain (FDTD) method with the anisotropic perfectly matched layers (PML) boundary conditions has been employed.

DESIGN OF SQUARE-LATTICE PCF

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 structure of such fiber. The proposed fiber comprises five air-hole rings. The diameter of the air-holes in the first and second ring is d_1, except four corner holes in the second ring and d_2 is the diameter of the air-holes in the third ring, except those four located on the corners of the ring and the diameter of the air-holes in the fourth and fifth ring, and also that of the eight corner air-holes of the second and third rings is d_3; the lattice constant of this structure is Λ. To attain an optimized design which exhibits favorable dispersion characteristics and also the least confinement loss, dependence of dispersion and confinement loss on design parameters is investigated.

Two main parameters investigated in this research are dispersion and confinement loss. The chromatic dispersion is calculated as:

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

where, $\mathrm{Re}[n_{eff}]$ is the real part of the refractive index in cladding, λ is the light wavelength in terms of µm and c is the speed of light in vacuum.

The confinement loss can be calculated from the

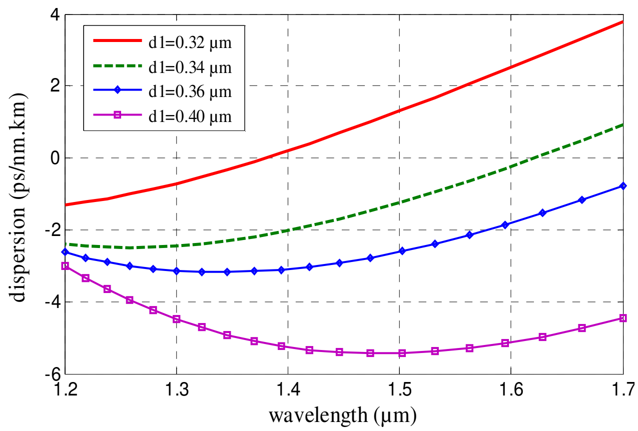

Figure 2. Effect of variations in d_1 on dispersion of the photonic crystal fiber with Λ=2 μm, d_2=1.2 μm and d_3=1.76 μm.

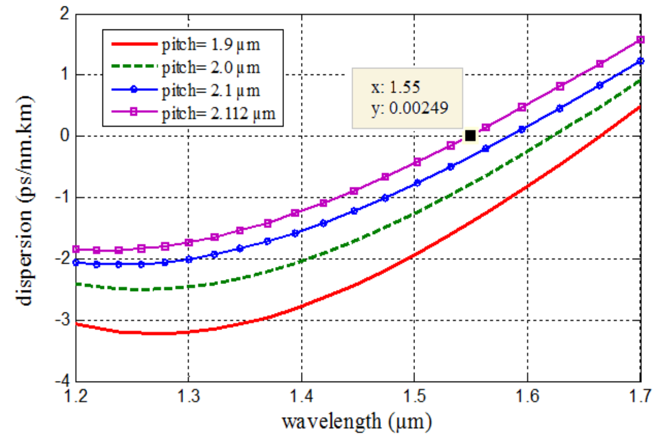

Figure 4. Dispersion of the photonic crystal fiber varying Λ from Λ =2 μm, d_2=1.2 μm and d_3=1.76 μm.

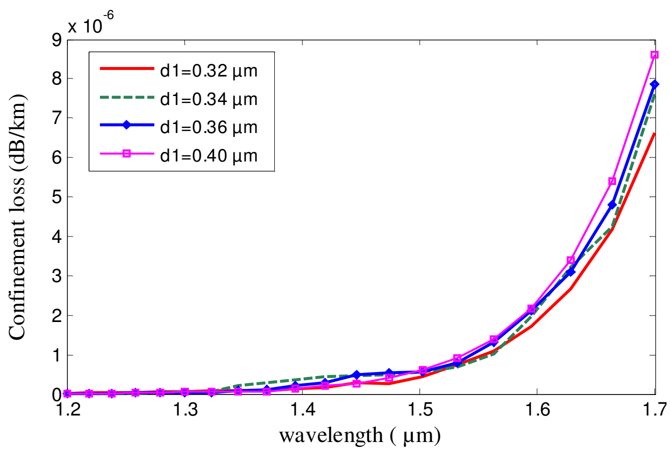

Figure 3. Effect of variations in d_1 on confinement loss of the photonic crystal fiber with Λ =2 μm, d_2=1.2 μm and d_3=1.76 μm.

imaginary part of the mode index using the following equation:

$$L_c = 8.686 k_0 \operatorname{Im}[n_{eff}] \quad (2)$$

where, $\operatorname{Im}[n_{eff}]$ is the imaginary part of effective mode index.

SIMULATION RESULTS OF THE SQUARE-LATTICE PCF

Initial values of the primary design parameters in the simulations were Λ = 2 μm, d_2 = 1.2 μm and d_3 = 1.76 μm. For d_1 = 0.32, 0.34, 0.36 and 0.4 μm confinement loss and dispersion have been studied and their corresponding curves for variations in d_1 are depicted in Figures 2 and 3, respectively. As expected, by varying d_1 the confinement loss hardly changes, yet the dispersion and its slope change drastically.

As shown in Figure 2, for higher values of d_1 the dispersion curve shifts downwards. A structure with d_1 = 0.34 μm seems to be the most appropriate, as it exhibits nearly zero dispersion and favorable dispersion slope characteristics in a wide wavelength range. One point that is worth to notice according to Figure 2 is that unlike triangular-lattice structure PCFs (Wu and Chao, 2005), in square-lattice PCFs by increasing d_1 and keeping Λ constant, the dispersion shifts towards negative values.

Diameter of the air-holes in the first two rings except the four corner ones in the second ring is d_1, the diameter of the third ring air-holes except the four air-holes in the corners is d_2, and d_3 is the diameter of the air-holes in the two outer rings and the eight corner air-holes in the second and third ring. The lattice constant is Λ.

In the next stage, the impact of changing Λ on the characteristics of the proposed PCF for d_1 = 0.34 μm, d_2 = 1.2 μm and d_3 = 1.76 μm is studied. Dispersion and confinement loss for different values of Λ are illustrated in Figures 4 and 5, respectively. Dispersion slope remains almost constant with variations of Λ; nevertheless these variations significantly affect the dispersion value and confinement loss.

Increasing Λ while keeping the diameter of the air-holes constant, results in a lower d/Λ ratio and the refractive index of the cladding rises accordingly, hence the confinement loss increases. Despite reports about the behavior of PCFs with triangular-lattice structure (Chen, 2006), in the proposed structure increasing Λ shifts the dispersion curve towards higher values.

As shown in Figure 4, for lattice constant of 2.112 μm and at the wavelength 1.55 μm, dispersion and confinement loss of the proposed PCF are limited to

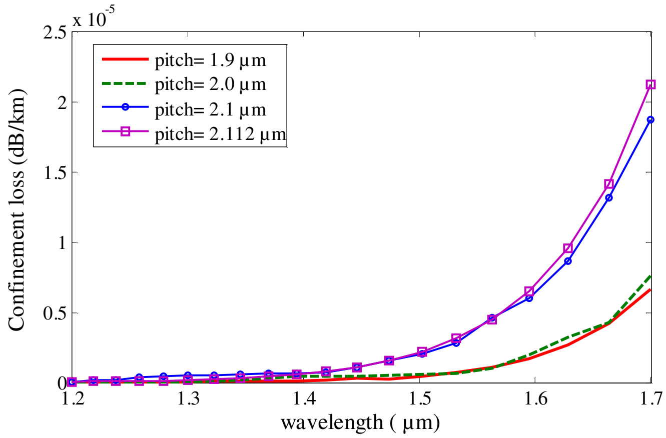

Figure 5. Confinement loss of the photonic crystal fiber varying Λ from 1.9 to 2.112 µm for d1=0.34 µm, d_2=1.2 µm and d_3=1.76 µm.

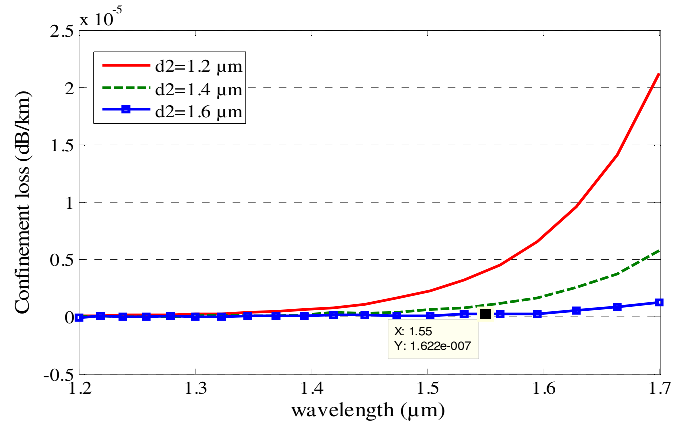

Figure 7. Effect of variations in d_2 on confinement loss of the PCF for Λ =2.112µm, d_1=0.34µm and d_3=1.76µm.

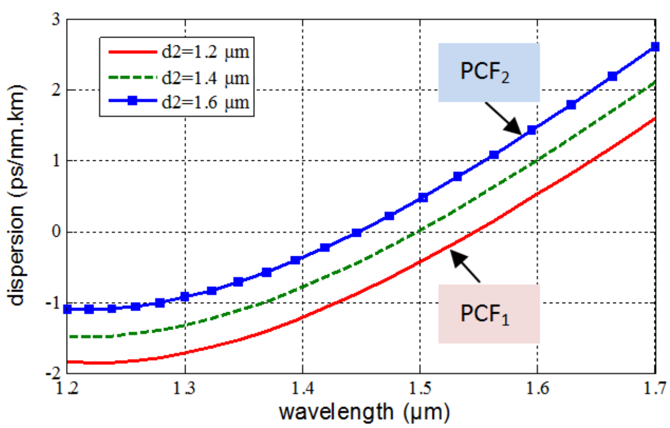

Figure 6. Effect of variations in d_2 on dispersion of the PCF for Λ =2.112 µm, d_1=0.34 µm and d_3=1.76 µm.

0.00249 ps/(nm.km) and 4 × 10^{-6} dB/km, respectively. A fiber with such properties (PCF_1) provides a suitable optical transmission medium in communication lines.

To reduce the confinement loss further, d_2 is modified. In Figure 6, a comparison of dispersion curves for Λ = 2.112 µm, d_1 = 0.34 µm, d_3 = 1.76 µm and d_2 = 1.2, 1.4 and 1.6 µm is presented. It is clearly shown in Figure 6 that variations in d_2 have less impact on dispersion. Dispersion increases for higher values of d_2, yet the dispersion slope remains unchanged. Figure 7 depicts the confinement loss of the PCF with the same constant parameters Λ, d_1, d_3 and varying parameter d_2 as mentioned earlier.

Modification of the design parameter d_2 has a substantial effect on confinement loss of the PCF, as the confinement loss drops considerably with an increase in d_2. For d_2 = 1.6 µm and in the whole wavelength range of 1.2 to 1.7 µm, the confinement loss is below 10^{-7} dB/km and the dispersion is brought within -1 to 2.6 ps/(nm.km). Variations in d_2 cause greater changes in confinement loss than in dispersion.

As shown in Figure 6, the only difference between PCF_1 and PCF_2 is the value of d_2. In PCF_1 and PCF_2, d_2 is chosen to be 1.2 and 1.6 µm, respectively. Several papers on optimizing the characteristics of photonic crystal fibers with triangular-lattice structure have been published (Hansen, 2003; Wang et al., 2004; Hai et al., 2008; Saitoh et al., 2005; Olyaee and Taghipour, 2010); nevertheless fewer researches have been conducted on the properties of square-lattice PCFs (Wang and Yang, 2007; Liu and Lai, 2004; Ferrando and Miret, 2001; Kim et al., 2009).

COMPARISON STUDY BETWEEN SQUARE-LATTICE AND TRIANGULAR-LATTICE PCFS

Figure 8 shows the cross-section of a triangular-lattice structure PCF with structure and parameters similar to those of the square-lattice fiber PCF_2.

In Figure 9, dispersion characteristics of similar photonic crystal fibers with triangular and square-lattice structures are compared. The design parameters in both structure are Λ = 2.112 µm, d_1 = 0.34 µm, d_2 = 1.6 µm, d_3 = 1.76 µm and N = 5. The square-lattice structure PCF exhibits better dispersion characteristics when compared with the triangular-lattice fiber, namely it offers nearly-zero dispersion in a wide wavelength range.

In Figure 10, confinement losses of the triangular and the proposed square-lattice photonic crystal fibers (PCF_2) are compared. In a broad wavelength range, these two structures exhibit almost equal losses; however at the wavelength 1.55 µm, which is the wavelength of choice in most telecom applications, the confinement losses in

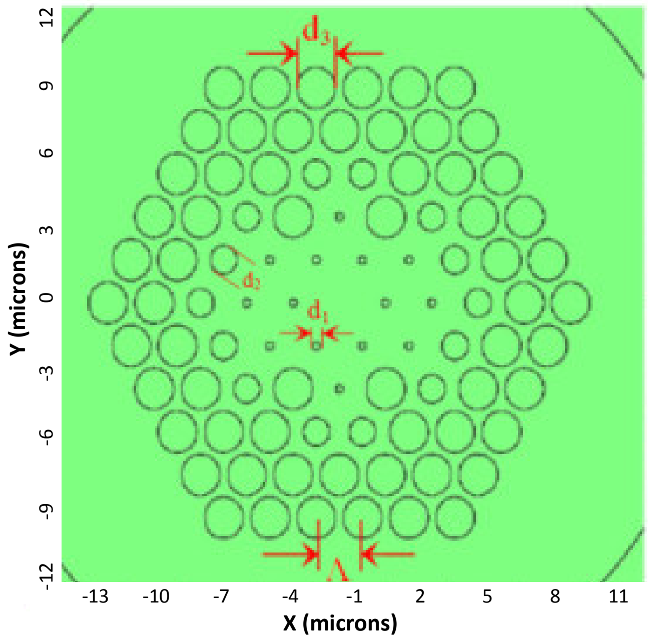

Figure 8. Cross-section of triangular-lattice photonic crystal fiber with structure and parameters similar to those of the proposed square-lattice fiber as depicted in Figure 1.

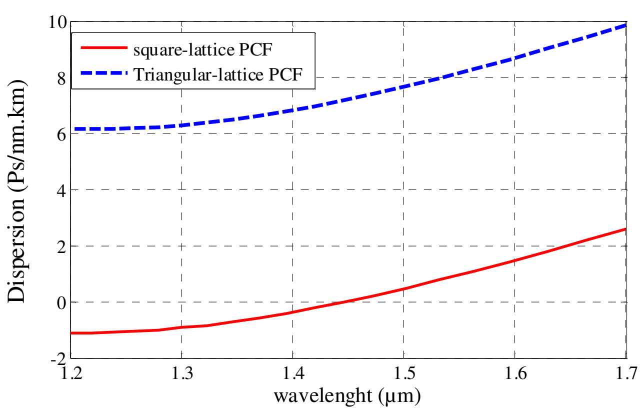

Figure 9. Comparison of dispersion in the triangular and square-lattice structure PCFs for Λ =2.112μm, d_1=0.34μm, d_2=1.6μm, d_3=1.76μm and N=5.

square and triangular-lattice fibers are 2.10^{-7} and 5.10^{-8} dB/km, respectively. From Figures 9 and 10, it is concluded that the square-lattice structure PCF offers better and more favorable properties. Mode field distribution of these two structures at the wavelength 1.55 μm is shown in Figure 11.

One design parameter which has a considerable impact on the characteristics of the PCF is the number of the air-hole rings, N. To facilitate the fabrication process,

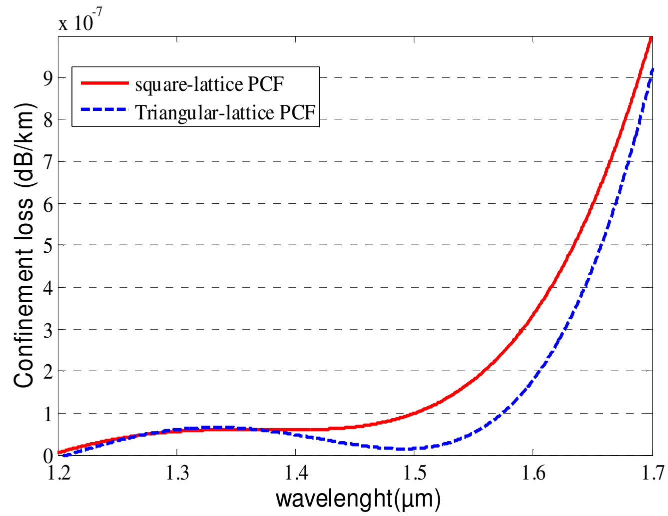

Figure 10. Comparison of confinement loss in the triangular and square-lattice structure PCFs for Λ =2.112μm, d_1=0.34μm, d_2=1.6μm, d_3=1.76μm and N=5.

the number of rings must be reduced as far as possible in the design phase. Hence, the last air-hole ring in the proposed structure will be omitted and so N = 4.

The dispersion characteristics and confinement loss of the square-lattice PCF with four and five air-hole rings N = 4 and N = 5 and for Λ = 2.112 μm, d_1 = 0.34 μm, d_2 = 1.6 μm, d_3 = 1.76 μm are displayed in Figures 12 and 13, respectively.

According to Figure 12, an increased number of air-hole rings results in a higher air-filling fraction, which consequently shifts the dispersion curve towards positive and near zero values. Therefore, in such structure assuming five air-hole rings improves the dispersion characteristics. It is also seen that the number of air-hole rings has no effect on the dispersion slope.

Figure 13, clearly demonstrates that increasing the number of air-hole rings decreases the confinement loss exponentially. Among design parameters of the photonic crystal fiber, d_1 appears to have the most significant effect on dispersion, yet the confinement loss seems to be most efficiently limited by N.

Conclusions

In this paper, two photonic crystal fibers with five rings and air-holes with 3 different diameters are proposed. Both fibers exhibit ultra-flattened nearly zero dispersion and low confinement loss in a broad wavelength range of 1.2 to 1.7μm. The only difference in their structures is the value of d_2. This modification of the diameter of the air-holes in the third ring lowers the confinement loss of

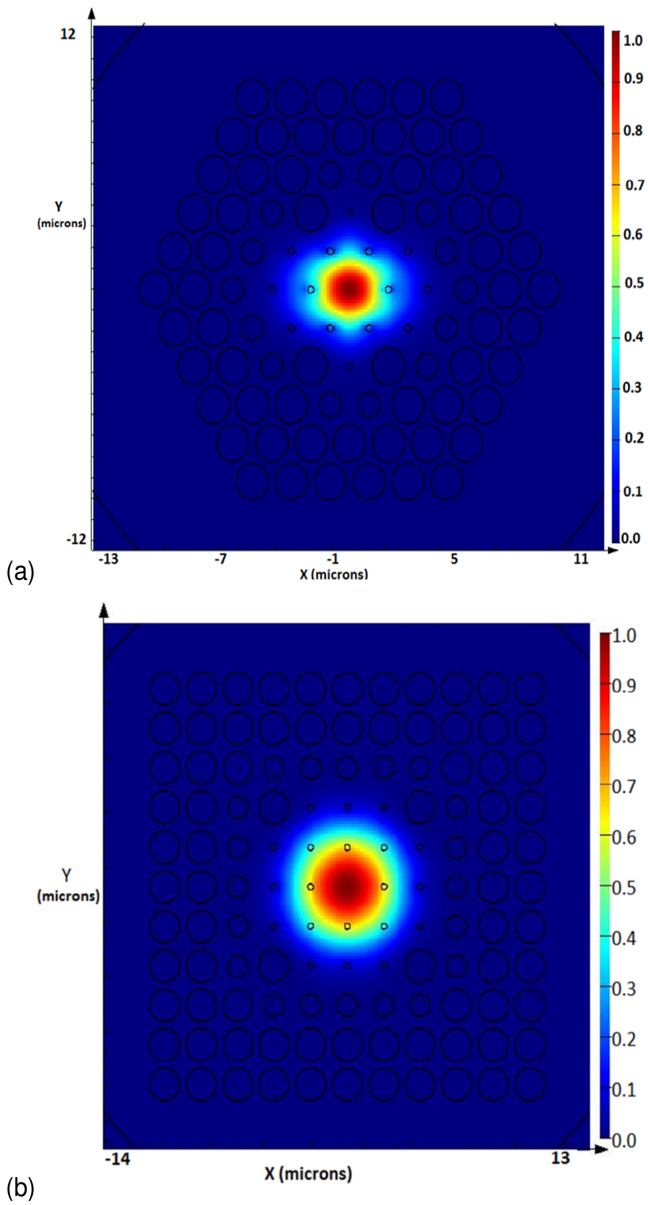

Figure 11. Mode field distribution of photonic crystal fiber with (a) triangular-lattice structure and (b) square-lattice structure PCF_2 at wavelength 1.55 µm.

PCF_2 even further when compared with PCF_1. On the other hand, PCF_1 with nearly zero dispersion and low confinement loss at the wavelength 1.55 µm provides a favorable transmission medium for optical communication applications.

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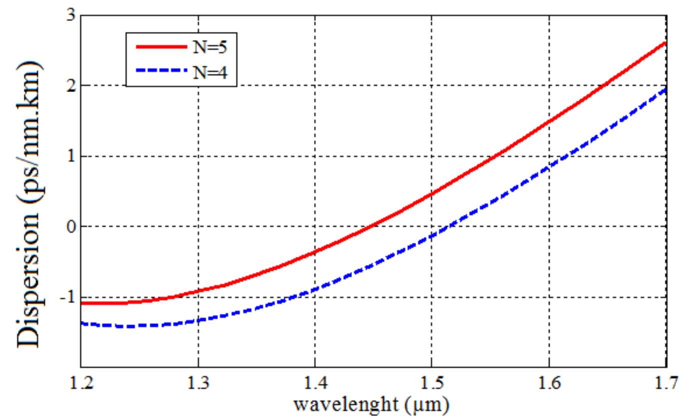

Figure 12. Dispersion of the square-lattice structure PCFs for Λ =2.112 µm, d_1=0.34 µm, d_2=1.6 µm, d_3=1.76 µm and N = 4, 5.

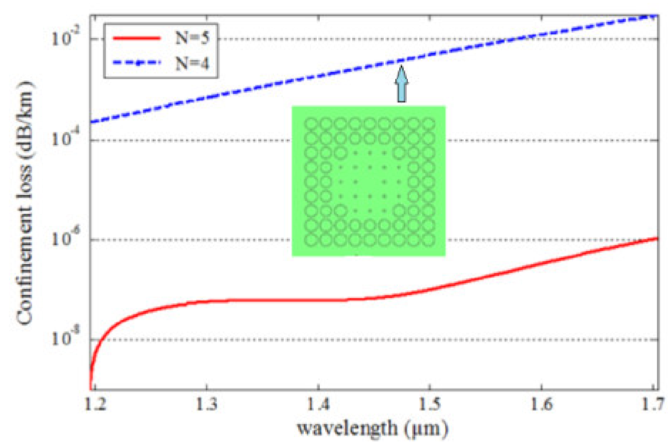

Figure 13. Confinement loss of the square-lattice structure PCFs for Λ =2.112µm, d_1=0.34µm, d_2=1.6µm, d_3=1.76µm and N=4, 5.

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