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Design of microstructure fibers with flat negative dispersion over large wavelength bands

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We have designed a set of microstructure fibers with triangular lattice of air holes having eleven rings which can yield ultra flat dispersion characteristics with very large normal dispersion. The dispersion characteristics and mode field of the fundamental mode have been theoretically investigated using the finite difference time domain (FDTD) method. When diameter of the air holes of the fifth, sixth and seventh rings are small in comparison to air holes of remaining rings this fiber exhibits large flat normal dispersion over a wide wavelength range covering entire S, C and L bands. The value of the exhibited uniform normal dispersion profile of the fiber can be controlled by controlling the hole diameter d of different rings and hole pitch Λ as well. Largest normal dispersion is achieved with a specific set of d and Λ. For any other combination of d and Λ the value of normal dispersion decreases from earlier optimum value. Investigated mode field in all cases show that the fundamental is mode always confined within the fiber core.

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1. Introduction

Optical fibers and integrated optical waveguides are finding extensive use, covering areas such as telecommunications, sensor technology, spectroscopy, medicine, fiber optic based devices, soliton lasers etc.[1-4]. Their operations usually rely on guiding light by total internal reflection (TIR) or index guiding. In order to achieve TIR, a core with higher refractive index compared to the surrounding cladding is required [1]. There are several limitations of conventional optical fibers, for example, they exhibit very low normal dispersion that can be used for compensating the residual dispersion from $1510\,\text{nm}$ to $1620\,\text{nm}$ wavelength range in optical communication systems [5]. In addition, exhibited optical nonlinearity in standard fiber is very small, an inevitable consequence is the inadvently large fiber length for nonlinearity based devices. To overcome fundamental limitations of these conventional silica fibers, an alternate fiber, particularly, photonic crystal fiber (PCF), also known as microstructure fiber, was recently proposed [6-10]. In a PCF, the cladding is composed of regularly arranged low index air holes that run parallel to the fiber axis. The main difference between a microstructure fiber and a conventional optical fiber is that, microstructure optical fiber features an air-silica cross-section, whereas, standard optical fiber has an all glass cross section. Another very important feature of a PCF is that it can be made of single material in contrast to all other types of optical fibers, which are manufactured with two or more materials. It is now well established that PCFs can offer more design flexibility in tailoring important optical properties of fibers. They can provide single mode operation over large wavelength range [6-8], can exhibit unique dispersion characteristics [11-23], achieve very high birefringence [16], and can offer very large or low nonlinearity [24-26] and can transport light with very low loss in certain wavelength range where conventional optical fibers are very lossy. In a PCF, air hole size and hole to hole distance provide additional degree of freedom in fiber design which facilitated a complete control on its important optical properties such as dispersion, nonlinearity mode size etc.

Due to the advantage of tailoring dispersion profile to desired value the PCFs promise a new approach for dispersion compensation [10-16]. The idea to use PCF as a tool for dispersion compensation was first contemplated by Birks et.al. [13] who proposed a PCF which promise a normal dispersion of as much as $-2000\ ps.nm^{-1}km^{-1}$ at $1550nm$. This far exceeds the dispersion of conventional compensating fibers which possesses a typical dispersion value $-100\ ps.nm^{-1}km^{-1}$ [15]. In the last few years fibers with dual concentric core structures, which are based on the optical coupling between the inner and the outer core modes, have been extensively investigated for effective dispersion compensation [14,16]. A dual core PCF was proposed [14] which promise dispersion value as high as $-18000\ ps.nm^{-1}km^{-1}$. Unfortunately, the operating wavelength over which such a large value of D is achievable is only about $4nm$, which limits its application.

Several authors have directed their effort in optimizing chromatic dispersion profile of dual-concentric core PCFs for broad band dispersion compensation [17-19]. PCFs have been also designed for ultra flattened near zero dispersion [20-23]. Along this line, in the present paper, we numerically investigate several designs of PCFs that can provide large ultra flattened normal dispersion over S, C and L wavelength bands. It must be pointed out that, in a recent publication Varshney et.al.[22] have attempted a similar problem whose prime objective was to optimize the profile of PCFs which can eliminate the residual dispersion from the telecommunication link as well as can provide identical dispersion compensation over S, C and L bands. The importance of our investigation lies in the fact that it predicts a much larger value of nearly flat dispersion over entire S,C and L bands. Thus, in this paper, our main goal is to design PCF with flat negative normal dispersion parameter that can be employed for dispersion compensation over large wavelength range including S, C and L bands.

2. Fiber design and numerical results

We have designed index guided PCFs with a triangular lattice of air holes. The fiber has eleven rings of circular air holes which are running down the length of the fiber. A missing air hole at the center creating a high index defect which acts as the fiber core. The refractive indices of air holes and glass core are 1 and 1.45 respectively. The hole diameter is d and the distance between centers of air holes i.e., hole pitch is Λ. We have realized that flat normal dispersion profile can be achieved by introducing small air holes in some selected rings. Therefore, in the present investigation, we have considered three different types of fibers as shown in Fig 1. All air holes are of equal diameter in the first type fibers, in the second type several intermediate rings consist of smaller air holes, while in the third type fibers two innermost rings composed of small air holes. Based on FDTD simulation [27], we have investigated chromatic dispersion properties of the fundamental mode and analyzed mode field pattern of the fundamental mode. The effective refractive index of the fundamental guided mode is given by $n_{eff} = \frac{\lambda}{2\pi}\beta$, where β is the propagation constant and λ is the free space wavelength. The waveguide dispersion D_w of the PCF can be directly calculated from the modal effective index n_{eff} of the fundamental mode over a range of wavelength using the relationship $D_w = -\frac{\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2}$, where c is the velocity of light in vacuum. The total dispersion coefficient $D(\lambda)$ is calculated as a sum of material dispersion and waveguide dispersion i.e., $D(\lambda) = D_w(\lambda) + D_m(\lambda)$. The material dispersion $D_m(\lambda)$ can be obtained directly from the Sellmeier equation [1,16,28-30].

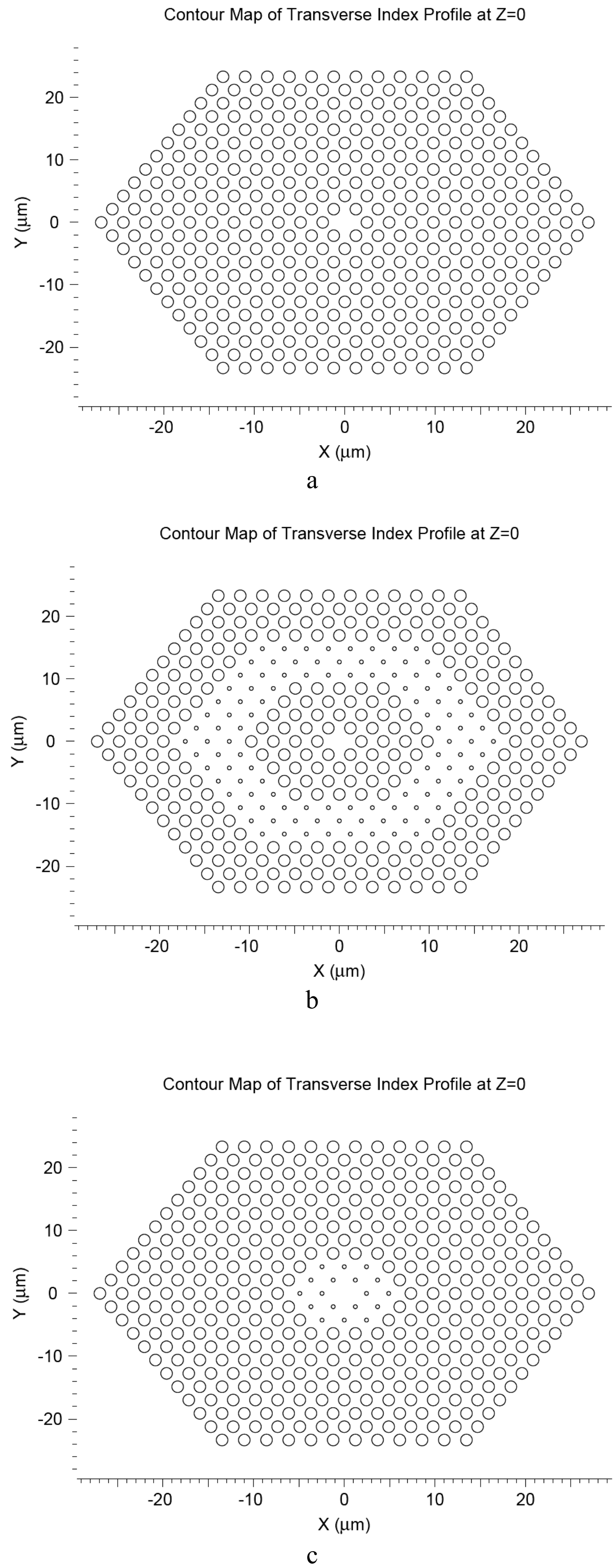
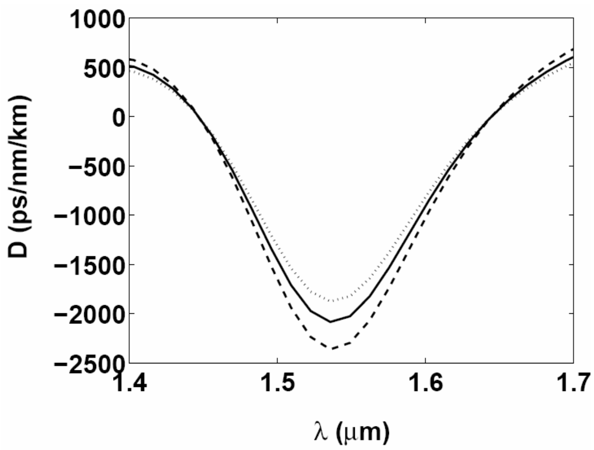


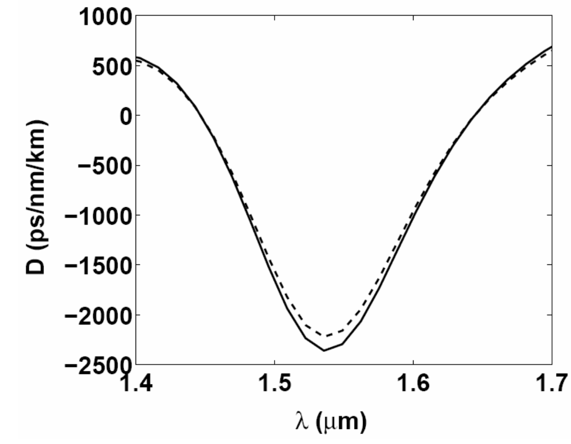
Fig. 1. Proposed eleven ring PCF with triangular lattice of air holes. (a) Air holes in all rings are identical. (b) Fifth, sixth and seventh rings are composed of smaller air holes while other rings are composed of large air holes. (c) Two innermost rings are composed of small air holes, while other rings are composed of large air holes.

2.A. Type I fiber with concave dispersion profile

To begin with, we analyze the dispersion properties of the PCF by considering identical air holes in all rings in the fiber cross section. The hole diameter of each ring is $d = 1.5\ \mu m$. Fig. 2(a) depicts the chromatic dispersion profile of the fundamental mode for three different value of hole pitch i.e., $\Lambda = 2.45\ \mu m$, $\Lambda = 2.85\ \mu m$ and $\Lambda = 3.25\ \mu m$. The dispersion profile is concave in appearance and possesses large negative dispersion coefficient. Due to large refractive index difference between core and cladding, PCF exhibits such large normal dispersion of as much as -2400 ps/nm.km at 1550nm with large dispersion slope in the wavelength band $1440\,nm - 1640\,nm$. For fixed hole diameter, an increase in the hole pitch decreases refractive index difference, resulting in decrease in the value of chromatic dispersion of the fundamental mode. This behavior is evident from figure. The value of dispersion coefficient can be manipulated by controlling hole pitch Λ and the air hole diameter d as well. For example, reduction of hole diameter yields smaller dispersion coefficient. This feature has been depicted in Fig.2(b).



a



b

Fig. 2. Variation of total dispersion with λ for equal hole diameters in all rings. a) Dashed line Λ = 2.45 μm, solid line Λ = 2.85μm and dotted line Λ=3.25μm. For all profiles d = 1.5; b) Solid line d = 1.5, dotted line d=1.35. For both profiles Λ=2.45μm.

An interesting issue is whether for a given value of pitch Λ the peak value of negative dispersion can be further enhanced by increasing the value of d beyond 1.5. We have verified that fibers with $d > 1.5$ yield dispersion curve which is W shaped and peak magnitude of dispersion is also much smaller in comparison to a fiber with $d = 1.5$. Therefore, we conclude $d = 1.5$ is the optimum value for largest normal dispersion with given Λ. Coming back to the issue of dispersion compensation it is evident from the figure that, in the C band (1530 nm to 1565 nm) dispersion is larger than (-2300 ps/nm.km) and in the L band (1570 nm to 1610 nm), the dispersion varies between (-1000 ps/nm.km) to (-1800 $ps/nm.km$). Similarly in the S band (1480 nm to 1525 nm) it varies between (-1000 $ps/nm.km$) to (-2250 $ps/nm.km$). The dispersion of the proposed fiber is much larger than the conventional dispersion compensating fibers. Commercially available dispersion compensating fibers usually show a dispersion value as low as -100 $ps/nm.km$ to -150 $ps/nm.km$ in the C band (i.e. 1530 nm to 1565 nm). Therefore, the proposed fiber can be used as a dispersion compensating fiber in the S, C and L bands.

2B. Type II fibers with large ultra flat normal dispersion

In this category, we investigate fibers which have two types of air holes. Several intermediate rings consist of air holes of reduced diameter, while remaining rings composed of large air holes. The diameter of air holes in the ith ring is identified with d_i and in a given ring all air holes are identical. As an illustration, we take hole pitch $\Lambda = 2.45$ since this particular value yields largest normal dispersion. Starting from the fifth ring we gradually increase the number of rings with small air holes and examine the dispersion characteristics. In each case small air hole diameter has been fixed at $d_i = 0.5\ \mu m$, while the diameter of each large air hole is $1.5\ \mu m$. In Fig. 3(a) we have depicted dispersion characteristics for second category fibers in which number of intermediate rings with smaller air holes vary from two to five. A careful examination reveals that largest dispersion is obtained when 5th, 6th and 7th rings composed of smaller air holes. For this particular case, represented by curve (ii) in Fig. 3(a), the dispersion coefficient is $-550\ ps/nm.km$ and it remains constant over a wide bandwidth. An increase in the number of rings with smaller air holes significantly decreases dispersion coefficient. Dispersion coefficient also decreases significantly if the number of rings with smaller air holes is less than three. This is amply clear from curve (i) of Fig. 3(a). A unique feature which is evident from the figure is that the dispersion profile practically remains flat in the wavelength range from $1.4\mu m$ to $1.7\mu m$ i.e., over a bandwidth of $300nm$. Note that the largest dispersion coefficient of the PCF is almost thrice of that reported in Varshney et. al. [22]. To the best of our knowledge, it is the largest value of ultra flat dispersion reported so far.

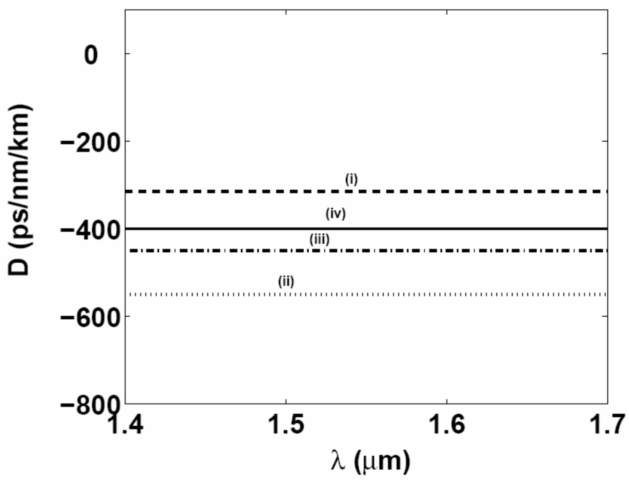


Fig. 3.(a) Variation of total dispersion coefficient with λ for variable number of intermediate rings with small air holes. Number of rings with small air holes is not more than five. For all cases hole pitch Λ=2.45 μm. (i) $d_1=\ldots d_4=d_7=d_8=d_9=d_{10}=d_{11}=1.5\mu m$, and $d_5=d_6=0.5$ μm (ii) $d_1=\ldots d_4=d_8=d_9\ldots d_{11}=1.5\mu m$, $d_5=d_6=d_7=0.5\mu m$,. (iii) $d_1=\ldots d_4=d_9=\ldots=d_{11}=1.5\mu m$, $d_5=d_6=d_7=d_8=0.5\mu m$,. (iv) $d_1=\ldots d_4=d_{10}=d_{11}=1.5\mu m$, $d_5=d_6=d_7=d_8=d_9=0.5\mu m$,.

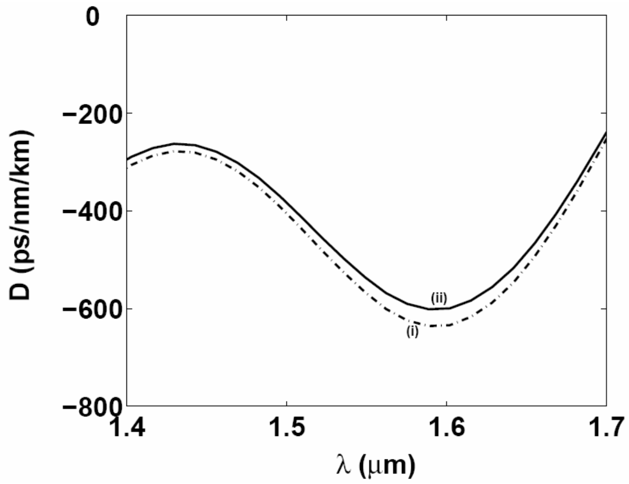


Fig. 3. (b) Variation of total dispersion with λ for variable number of intermediate rings with small air holes. Number of rings with small air holes is more than five. For all cases hole pitch Λ=2.45 μm. (i) $d_1=\ldots d_4=d_{11}=1.5$ μm, $d_5=d_6=d_7=d_8=d_9=d_{10}=0.5$ μm, (ii) $d_1=\ldots d_4=1.5\mu m$, $d_5=d_6=d_7=d_8=d_9=d_{10}=d_{11}=0.5$ μm,.

We extend our investigation to study the effect of introduction of rings of small air holes further. An increase in the number of rings with small air holes from five in the outward direction will decrease the refraction index contrast further which is not conducive for uniform dispersion. Fig. 3(b) represents chromatic dispersion of the fundamental mode when more than five rings composed of small air holes. From figure it is evident that introduction of one more ring with smaller air holes in the outer region distorts the flat nature of the dispersion profile in the 1450-1700nm wavelength band, they are converted to a concave profile. Therefore, three intermediate rings with smaller air holes are most effective in yielding ultra flat dispersion profile.

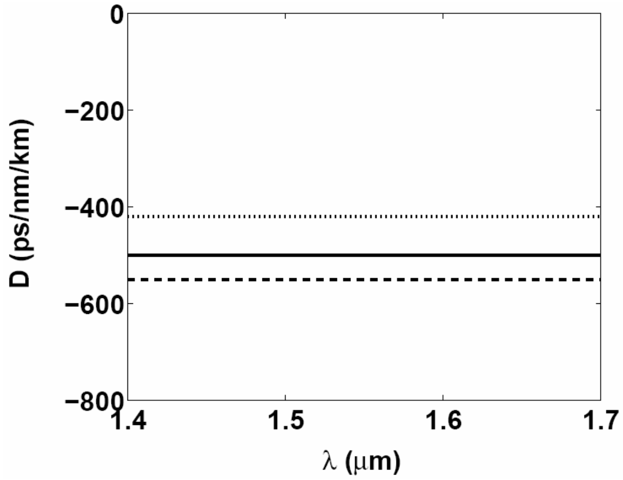


Fig. 4. Variation of total dispersion with λ for different Λ. Fifth, sixth and seventh rings consisting of small air holes while other rings are made of large air holes. $d_1=\ldots d_4=d_8=d_9=\ldots=d_{11}=1.5$ μm, $d_5=d_6=d_7=0.5$ μm. Dashed line Λ = 2.45 μm, solid line Λ=2.85μm and dotted line Λ=3.25 μm.

At this stage it is worth pursuing the investigation to reveal the influence of the hole pitch on the dispersion characteristics. In order to do that we take a PCF in which fifth, sixth and seventh rings are made of smaller air holes since this combination yields largest normal dispersion. Diameter of small air holes is taken $0.5\,\mu m$ while that of large air holes is $1.5\,\mu m$. Fig. 4 displays chromatic dispersion profile of the fundamental mode for three different values of the pitch, $\Lambda = 2.45\,\mu m$, $\Lambda = 2.85\,\mu m$ and $\Lambda = 3.25\,\mu m$. Though the dispersion profiles remain ultra flat over large wavelength band covering 1400-1700nm, the value of dispersion coefficient significantly decreases with the increase in the value of the pitch. It must be highlighted that the largest value of the dispersion coefficient is achieved for $\Lambda = 2.45\,\mu m$. As an illustration, we have displayed mode profile of the fundamental mode in figure 5 which is confined in the core region.

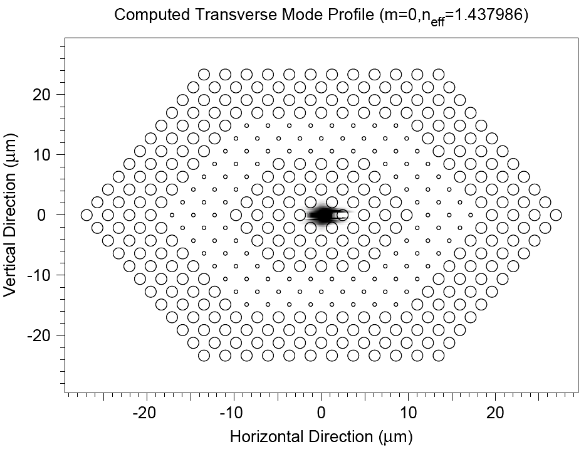


Fig. 5. A typical mode field pattern of proposed eleven ring PCF with small air holes in different rings Λ=3.25 µm, d_1 = … d_4 = d_8 = d_9 = … = 1.5 µm, d_5 = d_6 = d_7 = 0.5 µm.

2C. Type III fibers with low ultra flat dispersion

In this category, we investigate fibers which have two innermost rings with smaller air holes, while air holes of other rings consist of larger air holes. For illustration, we have taken $d_1 = d_2 = 0.5$ µm and $d_3 = d_4 = \ldots\ldots\ldots d_{11} = 1.5$ µm. Fig. 6 depicts the dispersion profile of the fundamental mode for three different hole pitch $\Lambda = 2.45\ \mu m$, $\Lambda = 2.85\ \mu m$ and $\Lambda = 3.25\ \mu m$. From figure it is clear that introduction of smaller air holes in the two innermost rings also yields ultra flat dispersion profile, albeit with a considerable reduction in the value of dispersion coefficient. As in the previous two cases, a common feature is the largest value of the dispersion coefficient at a pitch value of $\Lambda = 2.45\ \mu m$. Moreover, the profile is flat over entire S, C and L bands covering from 1400-1700nm.

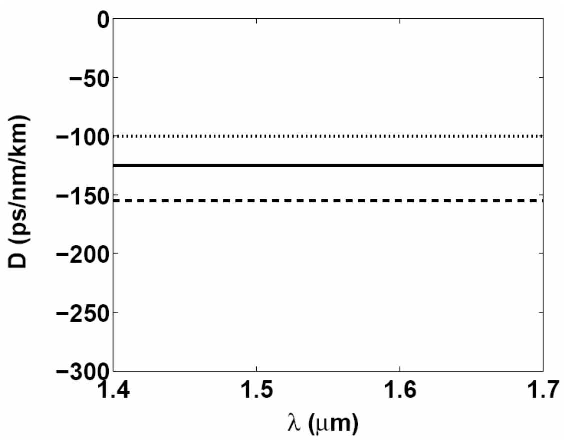


Fig. 6. Variation of total dispersion with λ for different Λ. The PCF consist of two innermost rings with small air holes while other rings are made of air holes with large diameter. d_1 = d_2 = 0.5 µm, d_3 = d_4 = …… = d_{10} = 1.5 µm. Dashed line Λ=2.45µm, solid line Λ=2.85 µm and dotted line Λ=3.25µm.

3. Conclusion

In conclusion, we have designed and investigated a set of photonic crystal fibers with triangular lattice of air holes having eleven rings which can yield ultra flat dispersion characteristics with very large normal dispersion. Through optimizing only three geometrical parameters, i.e., two air hole diameters and one whole pitch, the ultra flattened normal dispersion PCF can be designed. As an example, eleven rings PCF with flattened dispersion of -550ps/km.nm from 1.4 to 1.7 μm wavelength is numerically demonstrated.

The value of the exhibited uniform normal dispersion profile of the fiber can be controlled by controlling the hole diameter d of different rings and hole pitch Λ as well. It has been realized that air holes of fifth, sixth and seventh rings play most important role in determining the large value of flat negative dispersion. Largest normal dispersion is achieved with a specific set of d and Λ. For any other combination of d and Λ, the value of normal dispersion decreases from earlier optimum value. Investigated mode field in all cases shows that the fundamental mode is always confined within the fiber core. The proposed fiber can compensate effectively for dispersion in the entire optical communication wavelength covering the S, C and L bands.

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