A new design of photonic crystal fiber with ultra-flattened dispersion to simultaneously minimize the dispersion and confinement loss

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Abstract. Photonic crystal fibers (PCFs) are highly suitable transmission media for wavelength-division-multiplexing (WDM) systems, in which low and ultra-flattened dispersion of PCFs is extremely desirable. It is also required to concurrently achieve both a low confinement loss as well as a large effective area in a wide range of wavelengths. Relatively low dispersion with negligible variation has become feasible in the wavelength range of 1.1 to 1.8 µm through the proposed design in this paper. According to a new structure of PCF presented in this study, the dispersion slope is $6.8 \times 10^{-4}$ ps/km.nm$^2$ and the confinement loss reaches below $10^{-6}$ dB/km in this range, while at the same time an effective area of more than 50 µm$^2$ has been attained. For the analysis of this PCF, finite-difference time-domain (FDTD) method with the perfectly matched layers (PML) boundary conditions has been used.

1. Introduction
Nowadays, in WDM networks, the single mode fibers are widely used as optical data transmission media. Optical fibers which can transmit the data in the form of short optical pulses over long distances have revolutionized telecommunication industry in the last two decades. In WDM communication systems, it is essential to maintain a uniform response in the different wavelength channels, which requires that the transmission line approach the ideal state of ultra-flattened dispersion and ultra-low loss [1]. In the recent years, photonic crystal fibers (PCFs) have attracted much interest among researchers.

Photonic crystal fiber (PCF) is formed from a strand of silica glass with an array of microscopic air channels running along its length [2]. A defect in the center of this array is deliberately created to form the core of the fiber. In this paper, an index guiding PCF is introduced. In the index guiding PCF, the refractive index of the core is higher than that of the core’s surrounding area; consequently the transmission in this type of PCFs is mainly resulting from total internal reflection (TIR).

Reducing dispersion and confinement loss are of the main concerns in designing PCFs. In conventional PCFs with uniform holes with equal diameters, proper control of dispersion and particularly its slope in a wide range of wavelengths is difficult to maintain. Today, on the other hand, exploiting multiple design parameters such as diameter and shape of the holes, the number of air hole rings and the spacing between these holes facilitates development of PCFs with improved properties.

Several designs for the PCFs have been proposed to achieve the nearly zero ultra-flattened chromatic dispersion properties and low confinement loss. Hansen proposed a hybrid-core photonic
crystal fiber with three-fold symmetry, in which dispersion and its slope is well restrained, however, the confinement loss was shown to be about $10^{-3}$ [3]. In recent years, better results have been observed [3-11] as a result of different approaches adopted, e.g. modifying the form of the hole into ellipse [8], Gradually increasing the diameter of the hole from inner ring to the outer [4], selectively filling the PCF with liquids [6], application of double cladding [10], etc.

Most PCFs have hexagonal lattice structures. In reference [12], Razzak et al. introduced an octagonal structure for PCF with a better controllability of dispersion and confinement loss, yet a large effective area has not been realized in this pattern. Matsui et al. suggested a dual-core structure and numerically shown that the proposed PCF can achieve an ultralow dispersion variation of less than 0.8ps/nm·km in 1.3-1.65µm, with both a large effective area and a low confinement loss less than 0.01 dB/km [13].

In the present paper, a novel design for dispersion flattened PCF (DF-PCF) is put forth, by which both a very low confinement loss and a large effective area are acquired. Combining perfectly matched layer (PML) for the boundary treatment, an efficient compact two-dimensional finite-difference time-domain (2-D FDTD) method [14] is developed to model this photonic crystal fiber.

2. Theoretical discussion

In this paper, the three main properties of PCF, namely confinement loss, dispersion, and effective area are studied. Thus a brief introduction of these concepts will be presented in this section. Effective mode index of a guided mode for a given wavelength is obtained by solving an eigenvalue problem drawn from the Maxwell equations using the FDTD. Effective mode index, $n_{\text{eff}}$, can be obtained as:

$$ n_{\text{eff}} = \frac{\beta}{k_0} \quad (1) $$

Here, $\beta$ is the propagation constant and $k_0 = 2\pi/\lambda$ is the free space wave number. The effective mode index has both real and imaginary parts.

The total dispersion is sum of the material dispersion and the waveguide dispersion. The chromatic dispersion, $D(\lambda)$ of a PCF is easily calculated from the second derivative of the real part of the effective mode index:

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

where, Re[$n_{\text{eff}}$] is the real part of $n_{\text{eff}}$, $\lambda$ is the wavelength in units of µm, and C is the velocity of light in vacuum. The material dispersion given by Sellmeier formula is directly included in the calculation. Therefore, D in Eq. (2) corresponds to the total dispersion of the PCF [15].

The confinement losses, $L_c$, are due to the finite number of air-holes which can be made in the fiber cross section. As a consequence, all the PCF guided modes are leaky. In the solid-core PCF for small values of $d/\Lambda$, the resulting loss can be large unless a sufficiently large number of periods is used [16]. The confinement loss can be calculated from the imaginary part of the mode index as:

$$ L_c = 8.686k_0 \text{Im}[n_{\text{eff}}] \quad (3) $$

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

The effective mode area is another important parameter for fiber design. The effective area of fiber $A_{\text{eff}}$ is calculated as:

$$ A_{\text{eff}} = \frac{\iint |E|^2 \, dx \, dy}{\iint |E|^2 \, dx \, dy} \quad (4) $$

in µm², where E is the electric field distribution derived by solving an eigenvalue problem drawn from Maxwell’s equations. By changing the geometric characteristics of the fiber cross-section, it is possible to design PCFs with completely different properties, which is with large effective area.

It is possible to significantly increase the effective area by narrowing the air-holes for a fixed $\Lambda$, or by enlarging the pitch for a fixed $d/\Lambda$ value. Large mode area PCF can suppress undesirable nonlinear
impairments [13]. On The other hand, low confinement losses and/or small effective mode areas are needed for some particular applications like nonlinear ones.

3. Design principles and results

The preliminary design of the proposed PCF is illustrated in Figure 1(a). This PCF comprises 6 air hole rings, embedded in pure silica with a refractive index of 1.45. The diameter of the holes in the inner two rings is chosen to be 0.6µm and that of the four outer rings equals 1.8µm. The lattice structure of the cladding in this PCF is hexagonal and the spacing between the centers of adjacent holes, Λ, is 2.3µm.

In index guiding PCF, the holes closer to the core have a stronger impact on dispersion, though their effect on confinement loss is quite negligible. A lower ratio of d/Λ in the cladding reduces the dispersion and its slope, therefore in this design the holes of the inner rings are chosen to be smaller. On the other hand, increasing the d/Λ results in reduction of the confinement loss, hence the choice of larger diameter for the holes in outer rings. By omitting the holes in the six corners of cladding in the hexagon structure, PCF will have even less dispersion.

Choice of unequal diameters for air holes provides better control of dispersion curve and also the confinement loss can be brought within the acceptable range with a less number of rings. Figure 1(b) shows the mode field distribution. As depicted in this figure, the field is confined well to the area proximately surrounding the center of the fiber. An effective area of 26.838µm² is achieved in the wavelength of 1.55µm.

The confinement loss of the PCF as a function of wavelength in the range of 1.35-1.8µm is illustrated in Figure 2(a). According to the figure, the confinement loss for wavelengths of less than 1.7µm drops to below 10⁻⁷. Figure 2(b) illustrates the dispersion curve in the wavelength range 1.4-1.75µm. For a wavelength of 1.55µm, the dispersion is about -2.5ps/nm.km, which is fairly suitable and close to zero. Nevertheless we seek an even less slope of dispersion, which is not possible in this design. Thus for simultaneous improvement of dispersion slope, confinement loss and effective area, the preliminary design was modified which ultimately led to DF-PCF with the cross-section shown in Figure 3(a).

![Figure 1. (a) The cross section of a typical PCF. The air-holes in the cladding are arranged in a triangular configuration with lattice constant Λ, 1st and 2nd ring’s air-hole diameter d₁, and diameter of air-holes on 3rd to 6th rings’ is d₃,d₄=0.6µm, d₅=1.8µm, and Λ=2.3µm. (b) Mode field pattern of the fundamental mode at 1550nm.](image-url)
In the initial design (Figure 1), parameters of $d_1$, $d_2$, $\Lambda$ and the six air hole rings provide the control of the properties of the PCF, while in the final design improved results are made possible by manipulating a variety of other parameters, though the multiplicity of the parameters makes the fabrication process slightly more elaborate. The values of these parameters in the final design are as follows:

- $d_1 = 0.4\mu m$ (diameter of the holes in the first ring)
- $d_2 = 0.76\mu m$ (diameter of the holes in the second ring)
- $d_3 = 1.8\mu m$ (diameter of the holes in the last five rings)
- $\Lambda_1 = 1.5\mu m$ (spacing between the adjacent holes in the first ring)
- $\Lambda = 2.3\mu m$ (spacing between the adjacent holes in other rings)

![Figure 2](image)

**Figure 2.** (a) The confinement loss and (b) dispersion characteristics as a function of wavelength for the photonic crystal fiber of Figure 1.

![Figure 3](image)

**Figure 3.** (a) Cross section of the proposed PCF (DF-PCF) structure with lattice constant $\Lambda_1$ for 1st ring and $\Lambda$ for 2nd to 7th rings and 1st ring’s air-hole diameter $d_1$, 2nd rings’ air-hole diameters $d_2$, and diameter of air-holes on 3th to 7th rings’ is $d_3$. $d_1=0.4\mu m$, $d_2=0.76\mu m$, $d_3=1.8\mu m$, $\Lambda=2.3\mu m$, and $\Lambda_1=3.45\mu m$. This PCF structure can exhibit ultra-flattened dispersion characteristics with low confinement losses and large effective area. (b) The mode field pattern of the fundamental mode at 1550nm.
In order to reduce the dispersion even further, diameter of the holes in the first ring is decreased. Considering the fact that choosing smaller values for $d$ and higher values for $\Lambda$ in the inner rings leads to reduction of dispersion and its slope, the value of $\Lambda$ is chosen as $\Lambda_1=1.5\Lambda$. Increasing the value of $\Lambda$ and introducing the new parameter of $\Lambda_1$, as the lattice constant of the first ring, offer two main benefits. First, it contributes to reduction of the variations in dispersion in a broad range of wavelengths. Second, it increases the effective area in DF-PCF. However, choosing smaller values for $d_1$ and higher values for $\Lambda_1$ exacerbates the confinement loss; as a result an extra ring of holes with a diameter of $d_3$ is added to the final structure to offset this issue.

Figure 3(b) shows the mode field distribution of DF-PCF. As clearly shown in this figure, not only is the field still confined to the area around the core, but also the effective area is much larger compared to the initial design. In the proposed structure, the effective area is almost twice as large as in the preliminary design and reaches 53.279$\mu$m$^2$. Large mode area PCF can suppress undesirable nonlinear impairments [13].

Effective refractive index as a function of wavelength is presented in Figure 4(a). As previously mentioned in the second section, dispersion and confinement loss may then be calculated using the corresponding value of $n_{eff}$ in a given wavelength. In Figure 4(b), the confinement loss curve as a function of wavelength is shown for a DF-PCF with 7 air-hole rings in the range of 1.2-1.7$\mu$m. Despite the large effective area in the whole wavelength range, loss has a value less than $10^{-7}$. Figure 4(c) illustrates the dispersion of this PCF, and it is shown that in a wide range of wavelengths, both lower dispersion and very small variations of about 0.55ps/nm.km are obtained.

4. Conclusion
This paper shows that lower values of dispersion and confinement loss can be acquired by reducing the diameters of the holes in the inner rings and increasing the size of the holes in the outer rings. Moreover, increasing the spacing between adjacent holes in the first ring $\Lambda_1$ is shown to aid reaching ultra-low dispersion slope and large effective area, which are of our main concerns in designing the PCFs. In a broad wavelength range, dispersion rate of $6.8 \times 10^{-4}$ps/km.nm$^2$ is obtained, and concurrently confinement loss less than $10^{-7}$ and effective area larger than 50$\mu$m$^2$ are made feasible. Due to its low dispersion variations, small confinement loss and large effective area, this new design can be properly utilized in wideband transmission applications and can be suppress undesirable nonlinear impairments.

![Figure 4](image-url). (a) The effective index, (b) confinement loss, and (c) dispersion characteristics as a function of wavelength for the designed photonic crystal fiber shown in Figure 3.
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