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-Octagonal Photonic Crystal Fibers: Application to Ultra-flattened Dispersion

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Abstract: The dispersion in photonic crystal fibers likewise conventional optical fibers determines performance of optical systems. Fibers having near-zero dispersion and wideband flat characteristics are considered crucial for applications in both the linear and nonlinear regimes. This paper presents an octagonal photonic crystal fiber design for ultra-flattened chromatic dispersion characteristic and extremely low confinement losses. The finite difference time domain method with anisotropic perfectly matched layer boundaries is used to investigate the chromatic dispersion and confinement losses. It has been demonstrated that it is possible to obtain ultra-flattened dispersion of 0 ± 0.48 ps/(nm.km) in a wavelength range of 1.39 to 1.70 μm with extremely low confinement losses of the order less than 10^{-5} dB/km from a five ring octagonal cladding photonic crystal fiber. Photonic crystal fibers with such novel properties as wideband near-zero ultra-flattened dispersion and low confinement losses may be potential candidate for wavelength converter, optical amplification, and other environmental applications.

Key words: Photonic crystal fiber, finite difference method, confinement loss, fiber properties

INTRODUCTION

Photonic crystal fibers (PCFs) (Bjarklev *et al*., 2003) or micro structured optical fibers or holey fibers have a microstructure array of air channels running along their length around the silica core (Knight *et al*., 1996). In this way, light can be confined and guided through the fiber by mechanisms of either the total internal reflection (TIR) or the photonic band gap (PBG). In PCFs, the additional design parameters namely, the air-hole diameter d and the hole to hole spacing Λ offer flexibility in designing guiding properties. For example, PCFs have been reported to have many attractive properties as endlessly single mode operation, super high or low nonlinearities (Hansen, 2003; Okuno *et al*., 2003) , high birefringence (Chen, 2007), ultra-flattened chromatic dispersion with low confinement losses (Matsui *et al*., 2005; Poletti *et al*., 2005; Wu and Chao, 2005) and so many, and thus becoming potential for different applications. Particularly optical fibers are environmentally friendly because they do not create electromagnetic interferences with other systems. Photonic crystal fibers may also become potential for supplying sunlight to multilayer plant-panel green-houses and thereby can reduce green-house effects on the environments.

Typically conventional PCFs contain six air holes in the first-ring arranged on the vertex of an equilateral triangle. The other rings contain integer multiple of six air-holes. This type is called the hexagonal PCF. Besides the hexagonal PCFs, other PCFs (Xu *et al*., 2000; Argyros *et al*., 2001; Bouk *et al*., 2004), such as square lattice, honeycomb, and octagonal-lattice have been proposed to design claddings of the PCF (Chiang and Wu, 2006). Recently, octagonal PCFs (O-PCFs) have been reported having significant single mode wavelength range, more circular field distribution, high inherent non-linearity and low confinement losses (Chiang and Wu, 2006; Kaneshima *et al*., 2006).

Chromatic dispersion in PCFs plays an important role in optical communication as it limits the information carrying capacity of the fiber. Moreover, the confinement loss (Marcuse, 1977) is also an important parameter while evaluating the guiding characteristics of PCFs. Of the three modes that are supported by index guiding PCFs, confinement loss is considered as the loss of leaky modes (Kaneshima *et al*., 2006). So far, various PCFs with remarkable chromatic dispersion and leakage properties (Ferrando *et al*., 2000 and 2001; Ferrarini et al., 2002; Reeves *et al*., 2002; Saitoh *et al.*, 2003 and 2005; Kaneshima *et al*., 2006) have been reported. PCFs

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with ultra-flattened dispersion are investigated numerically by Ferrando *et al*., (2000, 2001). By optimizing d and Λ, they predicted a dispersion of 0 ± 1.0 ps/(nm.km) over 543 nm range centered near 1.52 µm (d ≈ 0.73µm, Λ ≈ 3.02µm) and a dispersion of 0 ± 0.50 ps/(nm.km) over a range of 428 nm (d ≈ 0.63µm, Λ ≈ 2.64µm). Saitoh *et al.*(2005) demonstrated ultra-flattened dispersion in PCFs by sub micro adjustment with a defect in the core. Besides, Saitoh *et al.*, (2003) demonstrated ultra-flattened dispersion of 0 ± 0.40 ps/(nm.km) from 1.23 µm to 1.72 µm wavelength with confinement loss of 0.10 dB/Km in the wavelength range shorter than 1.72 µm. Moreover, experimental demonstration of ultra-flattened dispersion of 0 ± 0.6 ps/(nm.km) from 1.24 µm to 1.44 µm wavelength and 0 ± 1.2 ps/(nm.km) from 1.0 µm to 1.6 µm wavelength was reported by Reeves *et al.*(2002) with confinement loss in the order of 2.0 dB/m. All of the above designs with flat dispersion characteristics can not warrant confinement losses below the Reyleigh Scattering limit.

In pursuit of both a novel structure for PCFs and an alternative to hexagonal PCFs, in this paper, an O-PCF with ultra-flattened chromatic dispersion and extremely low confinement losses is presented. This design can warrant simultaneously low confinement loss and ultra-flattened confinement losses.

MATERIALS AND METHODS

The finite difference method (FDM) with anisotropic perfectly matched layer (PML) boundaries is used to calculate the chromatic dispersion and the confinement losses of the O-PCF with only five rings. The chromatic dispersion *D*(λ) and confinement losses *Lc* of the PCF can be calculated by Kaneshima *et al*.,(2006)

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

$$Lc = 8.686 \times \mathrm{Im}[k_0 n_{eff}] \tag{2}$$

where, Re[n_{eff}] is the real part of $n_{eff,}$ λ is the wavelength and *c* is the velocity of light in vacuum. Effective index n_{eff} of PCF is obtained by solving an eigenvalue problem drawn from the Maxwell's equations using the FDM. Where, Im[$k_0 n_{eff}$] is the imaginary part of, $k_0 = 2\pi/\lambda$, the free space wave number.

Fig. 1 shows the geometry used in this paper in order to investigate ultra-flattened dispersion properties with low confinement losses. The diameter of the air holes on the first ring is d_1 except the gray colored circle that its diameter is d_2. The diameter of air holes on the other rings is d, core diameter 'a' equals 2Λ-$d_1$and Λ is the pitch. The spacing between air holes on the same ring is Λ_1, which is related to Λ by the relation $\Lambda_1 \approx 0.765\Lambda$. It is to be noted that it is possible to obtain ultra-flattened chromatic dispersion using the same air hole diameter. But, since it is difficult to control chromatic dispersion with low confinement loss using equal hole diameters and since periodicity in the cladding region is not essential to confine the guiding light in the high index core region [(7)], we have used different air hole diameters of the O-PCF, which itself have not periodic air holes in true sense as H-PCF.

In contrast to the conventional hexagonal PCF (H-PCF), the octagonal PCFs have isosceles triangular unit lattice with vertex angle 36^0. Due to the isosceles triangular unit lattice, O-PCF contains more air holes in the cladding region with the same numbers of rings as compared to H-PCF. This results higher air-filling fraction and lower refractive index around the core thereby supposed to have strong confinement ability. As we know that in PCFs, the optical attenuation sources includes imperfection caused during fabrication process, intrinsic losses due to Rayleigh scattering and confinement losses due to finite numbers of air holes in the cladding region. The guided modes in PCFs are intrinsically leaky because the core and the cladding refractive index are the same except there are air holes in the cladding. By careful arrangement of the air holes, choice of pitch, Λ numbers of rings and diameter, d, the dispersion and confinement loss can be controlled suitably. Moreover, as there are eight air holes on the first ring and placed in an octagonal rotational symmetry, O-PCF results similar fundamental field distribution as the standard step index fibers. Again, there is more energy distributed between air holes of the first ring for the H-PCF than for the O-PCF under the same air filling ratio (Chiang and Wu, 2006), H-PCF assumes more confinement losses than the O-PCF.

RESULTS AND DISCUSSION

Fig. 2 shows the chromatic dispersion of the O-PCF with different pitch, air hole diameters as indicated on the same figure. Chromatic dispersion of 0 ± 0.80 ps/(nm.km) is obtained (solid line) in the wavelength range of 1.39 µm to 1.70 µm with a defect air hole of diameter dc = 0.60µm in the core center.

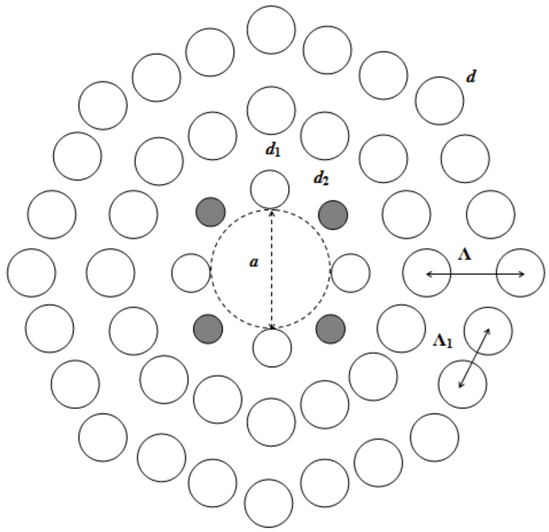

Fig. 1: Geometry of the proposed O-PCF

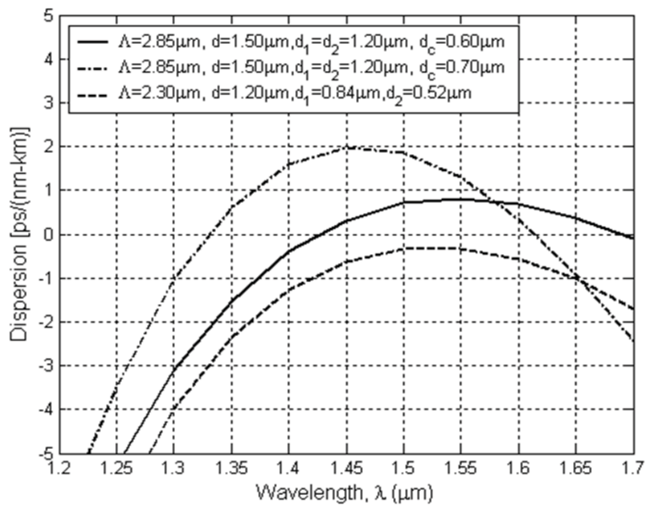

Fig. 2: Chromatic dispersion of the five periods O-PCF with the indicated pitch, air hole diameters.

Fig. 3 shows the chromatic dispersion properties with three different pitch and air-hole diameters. It is seen that, with Λ = 2.51 μm and equal air hole diameters d = 0.83 μm, dispersion of 0 ± 1.20 ps/(nm.km) is obtained (dotted line) in the wavelength range of 1.30 μm to 1.58 μm but the confinement loss is between 0.01 dB/km to 0.50 dB/km as shown in Fig. 4. It also shows that the confinement loss can be reduced by using different air-hole diameters.

With Λ = 2.30 μm, d = 1.23 μm, d_1 = 0.84 μm, d_2 = 0.53 μm dispersion of 0 ± 0.48 ps/(nm.km) is obtained (solid line)in the wavelength range of 1.39 μm to 1.70 μm and confinement loss of less than 10^{-5} dB/km in the wavelength below 1.70 μm. Since, the O-PCFs have more air holes in comparison to the conventional H-PCF with the same periods, the former possess lower confinement loss as the confinement loss decreases with increase in the numbers of air holes. This key advantage of the O-PCFs is utilized fully in this paper.

Finally, Fig.5 shows mode field profiles of the proposed PCF in both 2-D and 3-D. it shows that the fundamental mode field has confined within the second rings of the cladding. Figure 5b shows the intensity profile.

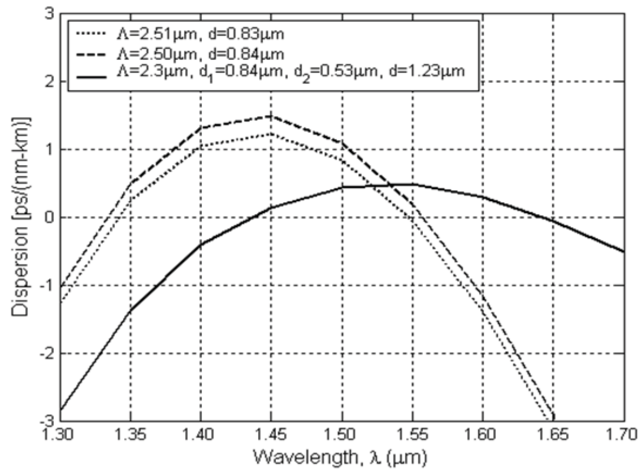

Fig. 3: Chromatic dispersion of the five periods O-PCF with the indicated pitch, air hole diameters.

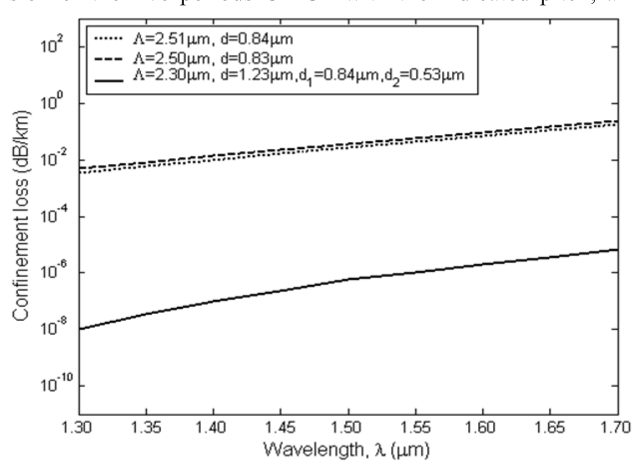

Fig. 4: Confinement loss of the five periods O-PCFwith the indicated pitch, air hole diameters.

Therefore, in the light of the above numerical simulation results, it can be concluded that O-PCFs can be effectively used in the applications where flattened dispersion with low confinement losses are needed. For example, in the DWDM communication systems, optical parametric amplification, super continuum generation in the infrared and so on.

Conclusion:

Chromatic dispersion tailorability with low confinement losses for the octagonal PCF has been reported. It has been shown through numerical simulation results that an ultra-flattened dispersion of 0 ± 0.48 ps/(nm.km) can be obtained in the wavelength range of 1.39 to 1.70μm with confinement loss of less than 10^{-5}dB/km in the wavelength below 1.70μm from a five period O-PCF. The dispersion can be reduced further by further investigations. Investigations based on the O-PCF in order to obtain highly non-linear dispersion flattened fiber are underway.

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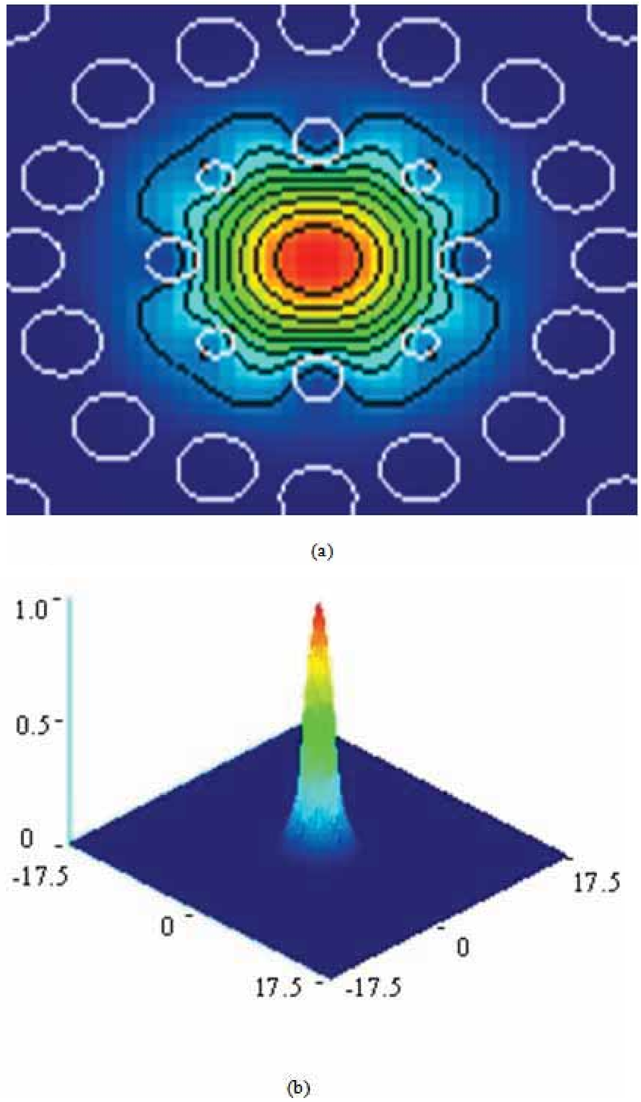

Fig. 5: Mode field distribution at 1.55 μm wavelength: (a) 2-D distribution, and (b) 3-D distribution.

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