Design of Double Cladding Photonic Crystal Fibers with Low-loss and Broad Dispersion

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Abstract— A novel type of photonic crystal fiber structure with double cladding is proposed by full vector finite element method. The influences of this structure on its dispersion and loss are investigated with different inner cladding diameters, outer cladding diameters and air hole pitches. The results indicate that the dispersion varies from -23 ps/(nm·km) to -10 ps/(nm·km) in the band of $1.30 \sim 1.8$ μm, which has broadband dispersion compensation characteristics. The loss is 7.39×10^{-6} dB/km at the wavelength of 1.55 μm, which is by far the smallest value that has ever been reported.

1. INTRODUCTION

Photonic crystal fibers (PCFs), which is consist of a pure silica core with numerous periodically spaced airholes in the cladding region, are also called microstructure fibers or holey fibers [1]. By changing the diameters of the air holes and the air filling rate, the relative refractive index of the cladding and fiber core can be flexibly controlled so as to regulate light conduction in PCFs. According to different mechanism of light guiding, PCFs can be divided into two types, total internal reflection photonic crystal fibers (TIR-PCFs) and photonic band gap photonic crystal fibers (PBG-PCFs) [2]. PCFs have been widely applied in many fields because of these unique properties, including endlessly single-mode operation [3], controllable mode areas [4], controllable dispersion characteristic in a wide wavelength range [5], and large nonlinearity [6].

At present, researchers have already designed some new structures, such as, octagon structure, hybrid octagon structure and square structure etc.; the structure of cladding has designed from single cladding, double cladding or even multi-cladding; the fiber core has evolved from hollow-core into small-core, double-core, multi-core. These structural changes have great influence on transmission characteristics of PCFs [7–10].

This paper demonstrates a new type double-clad PCF (DC-PCF) with hexagonal air hole configuration. This kind of PCF is composed of double-cladding made by different air holes, the double-cladding structure not only makes the coupling reduced difficultly but also has a unique dispersion characteristics. In order to investigate the influences of this structure on its dispersion and loss, the effects of the inner cladding diameters, outer cladding diameters and air-hole pitches on dispersion and loss are all numerically simulated.

When the cladding structure of DC-PCF is similar as the conventional PCF, the similar dispersion characteristics can be obtained for that the dispersion characteristics of DC-PCF is mainly determined by the inner core and the surrounding air hole structure. And the loss can be reduced by optimizing the out-layer structure that affects the limited loss. In the paper, the dispersion characteristics of PCF is tailored by changing the diameters of inner and outer cladding air holes, and the effective index of which is lower than that of the fiver core so that the total internal reflection theorem is satisfied. The results indicate that values of its dispersion varies from -23 ps/(nm·km) to -10 ps(nm·km) in the band of 1.30–1.8 μm, which has broadband dispersion compensation characteristics. By changing these structure parameters carefully, the loss can reach $7.39 \cdot 10^{-6}$ dB/km at the wavelength of 1.55 μm, which is the smallest value that has ever been reported. The results of this DC-PCF provide a reference for designing some devices based on PCF with dispersion compensation, and also provides a theoretical basis for practical applications for the low loss characteristics which can increase the transmission efficiency of PCF.

2. THEORY AND METHOD

The cross section of the novel DC-PCF is shown in Fig. 1. The fiber core is consist of one deletion air hole, the cladding is consist of four layer air holes, the first and the second layer constitute the inner cladding, outer cladding is consist of the third and fourth layers, and the angle between the inner cladding and the outer cladding is 30°. Λ_1, Λ_2 and Λ_3 denote the pitch of the first layer and the second layer, the pitch of the second layer and the third layer, the pitch of the third layer and the fourth layer, respectively. d_1 and d_2 denote the diameters of the inner cladding and outer

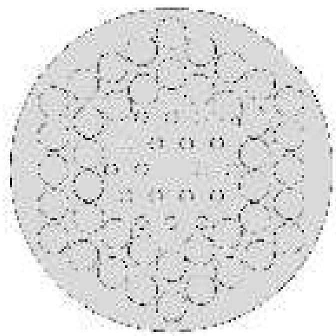


Figure 1: Cross section of DC-PCF.

cladding respectively. The background material is fused silica, whose refractive index n_1 is 1.44, and the refractive index of air hole n_0 is 1.

In this paper, we use full-vector finite element method (FEM) to compute the effective refractive index n_{eff} of fundamental mode and the confinement loss α. And according to the relationship of the effective refractive index n_{eff} and the dispersion, the dispersion and the loss can both be analyzed at wavelength of $1.30 \sim 1.80\,\mu\mathrm{m}$. The total dispersion of PCF can be described as [11]:

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2 n_{eff}(\lambda)}{d\lambda^2} + D_m(\lambda) \tag{1}$$

where λ represents wavelength, c is the speed of light in vacuum, $n_{eff}(\lambda)$ represents the effective refractive index of fundamental mode, and $D_m(\lambda)$ represents the material dispersion.

P_0 is the incident power, transmission power can be described as

$$p_T = p_0 \exp(-\alpha L) \tag{2}$$

where α is attenuation coefficient and known as fiber loss, L is the length of the fiber.

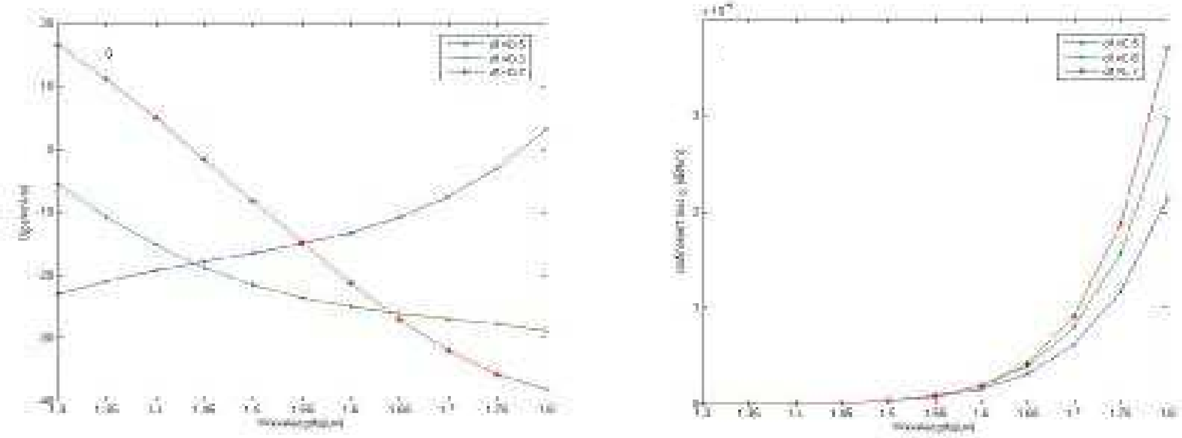
The loss of PCF represents the power attenuation of the light signal when it transmits in the fiber. The attenuation is different with different wavelength in the same fiber, and the continuous loss measurement of different wavelength is called loss spectrum measurement. In practice, the loss can be represented by the expression of attenuation coefficient

$$a = -\frac{10}{L}\lg\left(\frac{P_T}{P_0}\right) \tag{3}$$

3. NUMERICAL ANALYSIS

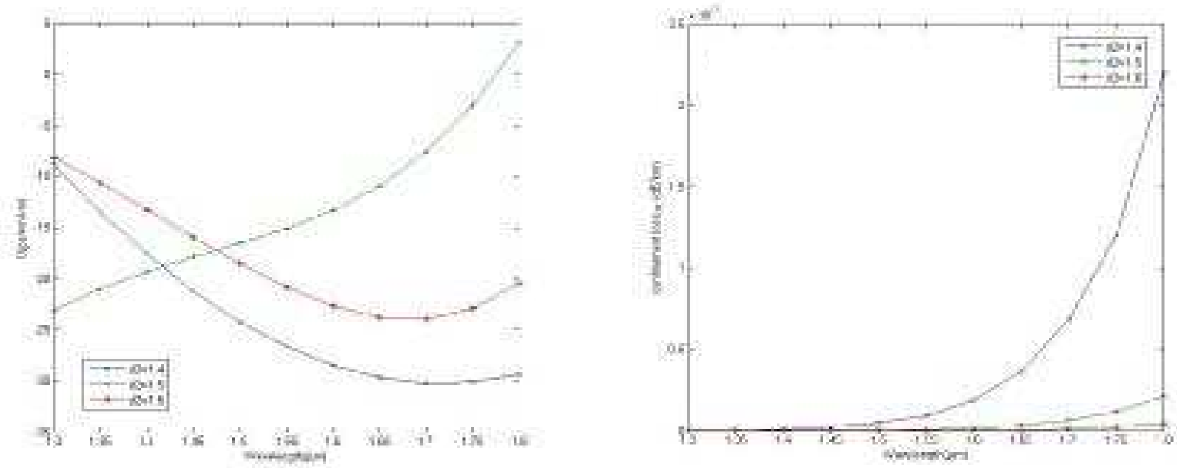
In the novel DC-PCF structure, the firs layer of air hole plays a major role on the transmission characteristics of the PCF because the mode optical field is mainly distributed near the fiber core, the influences of inner cladding diameter d_1, outer cladding diameter d_2 and the pitches of air holes (Λ_1, Λ_2, Λ_3) on the dispersion and the loss are analyzed by hexagonal air hole tailoring. The dispersion characteristics of the PCF are mainly depends on the fiber core and surrounding air holes, but outer cladding have a significant impact on confinement loss, thus the loss can be reduced by optimizing the outer cladding structure. Besides, according to total internal reflection, the periodic structure of the cladding has little influences on light-guiding characteristics of PCF with high index core.

It can be seen from Fig. 2(a) that the dispersion varies from -20 to $40\,\mathrm{ps/(nm{\cdot}km)}$, which means that the diameter of inner cladding d_1 is an important factors that affect the dispersion. From Fig. 2(b), we can see that the confinement loss increase with increasing d_1 at the wavelength range $1.30 \sim 1.80\,\mu\mathrm{m}$, the changes of confinement loss are small with increasing d_1 and λ at the wavelength of $1.30 \sim 1.55\,\mu\mathrm{m}$. However, the changes of confinement loss increase significantly at the wavelength of $1.55 \sim 1.80\,\mu\mathrm{m}$. When $d_1 = 0.5\,\mu\mathrm{m}$ and $\lambda = 1.55\,\mu\mathrm{m}$, the dispersion is $-15\,\mathrm{ps/(nm{\cdot}km)}$ and the confinement $\alpha = 7.39 \times 10^{-6}\,\mathrm{dB/km}$. In conclusion, the influences of the diameter of inner cladding d_1 on confinement loss are different in different wavelength range. Compared to traditional PCF, the confinement of DC-PCF is much smaller.



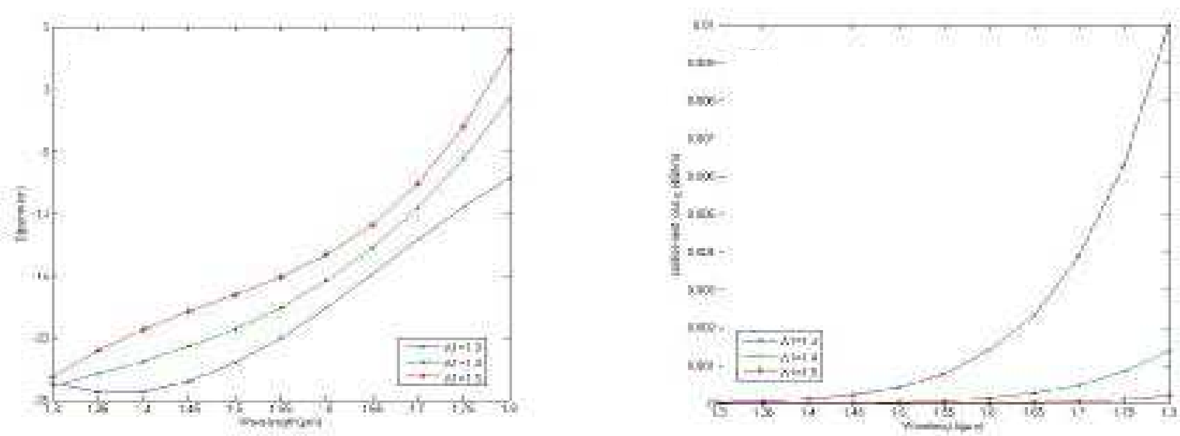
(a) (b)

Figure 2: (a) The dispersion and (b) the loss with different d_1.



(a) (b)

Figure 3: (a) The dispersion and (b) the loss with different d_2.



(a) (b)

Figure 4: (a) The dispersion and (b) the loss spectrum with different Λ_1.

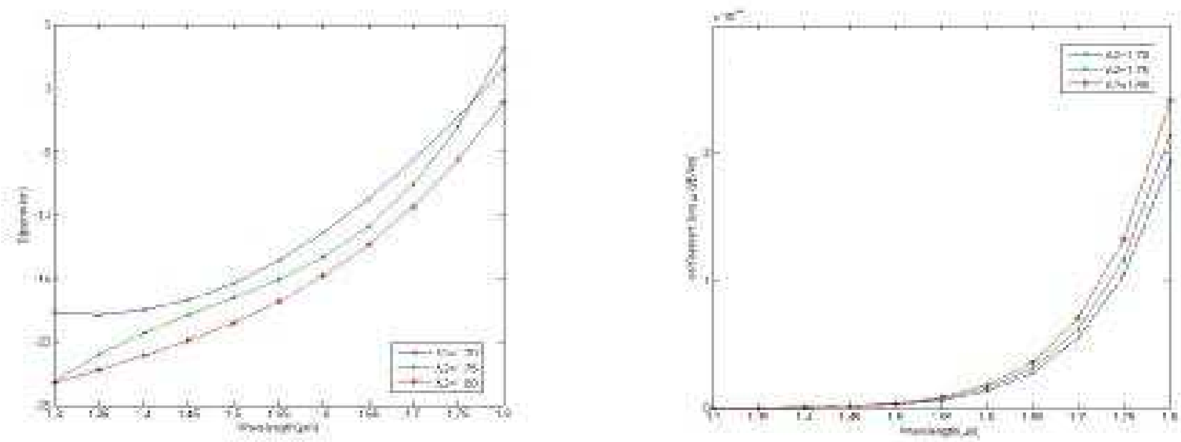
In Fig. 3(a), the parameters d_1, Λ_1, Λ_2, and Λ_3 are given to 0.5 µm, 1.5 µm, 1.75 µm, 2 µm, respectively. And the dispersion first decreases and then increases as wavelength increases when d_2

is 1.4 µm and 1.6 µm at the wavelength of 1.30–1.80 µm, but the dispersion increases as wavelength increases when d_2 is 1.5 µm. In this context, the diameter d_2 of outer cladding air hole has a significant influence to dispersion. As can be seen from Fig. 3(b), confinement loss reduces gradually as d_2 increases, and confinement loss increases gradually as d_2 increases.

In Fig. 4(a), the parameters d_1, d_2, Λ_2, and Λ_3 are given to 0.5 µm, 1.5 µm, 1.75 µm, 2 µm, respectively, the dispersion increases by increasing Λ_1 and λ at the wavelength of $1.30 \sim 1.80$ µm, and zero dispersion point shifts toward the shorter wavelength. As shown in Fig. 4(b), confinement loss decreases with the increase of Λ_1 and reaches to zero at last. And the loss increases gradually as the wavelength increases. In conclusion, Λ_1 has a significant influence to dispersion and confinement loss.

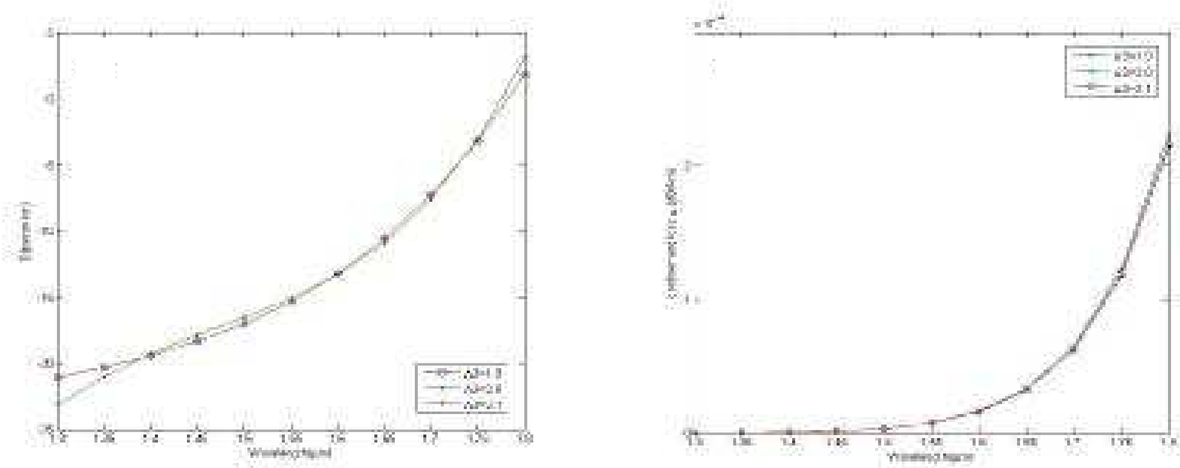
In Fig. 5(a) and Fig. 5(b), the parameters d_1, d_2, Λ_1, and Λ_3 are given to 0.5 µm, 1.5 µm, 1.5 µm, 2 µm, respectively. As can be seen from Fig. 5(a), both the dispersion becomes larger with decreasing Λ_2 and increasing λ at the wavelength of $1.30 \sim 1.80$ µm. The confinement loss increases with increasing Λ_2 at the wavelength of $1.30 \sim 1.80$ µm. But the confinement loss increases faster as the wavelength increases, and the confinement loss keeps almost flat at the wavelength of $1.30 \sim 1.55$ µm. Results show that Λ_2 has a significant influence to dispersion and confinement loss at the wavelength of $1.30 \sim 1.80$ µm. But the influence of Λ_2 on confinement loss is smaller than d_1.

In Fig. 6(a) and Fig. 6(b), the parameters d_1, d_2, Λ_1, and Λ_2 are given to 0.5 µm, 1.5 µm, 1.5 µm, 1.75 µm, respectively. As can be seen from Fig. 6(a), the dispersion increases as the wavelength



(a) (b)

Figure 5: (a) The dispersion and (b) the loss spectrum with different Λ_2.



(a) (b)

Figure 6: (a) The dispersion and (b) the loss spectrum with different Λ_3.

increases at the wavelength of $1.30 \sim 1.80\,\mu m$. And dispersion curves overlap each other when $\Lambda_3 = 1.9\,\mu m$ and $\Lambda_3 = 2.1\,\mu m$, which means that the values of dispersion are the same in both cases. As can be seen from Fig. 6(b), the confinement loss increases with both increasing Λ_3 and increasing λ at the wavelength of $1.30 \sim 1.80\,\mu m$. It follows that Λ_3 has little influence to dispersion and confinement loss at the wavelength of $1.30 \sim 1.80\,\mu m$.

4. CONCLUSION

In this paper, we simulate and analyze the double cladding photonic crystal fiber by full-vector finite element method. Results show that PCF not only compensates broadband dispersion, but also attains low loss by reasonable tailoring the diameters and the pitches of air holes. The numerical results show that the PCF present broadband dispersion characteristics at the wavelength of 1.30–1.80 μm, and the confinement loss can reach 7.39×10^{-6} dB/km at wavelength of 1.55 μm. This structure of PCF provide references on design and application of dispersion compensation fiber, the low loss characteristic of this structure can improve the transmission efficiency of PCF, These results provided theoretical basis for application.

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REFERENCES

1. Russell, P. St. J., "Photonic-crystal fibers," *J. Lightwave Technol.*, Vol. 24, 4729–4749, 2006.
2. Knight, J. C., T. A. Birks, and P. St. J. Russell, "All-silica single-mode optical fiber with photonic crystal cladding," *Opt. Lett.*, Vol. 19, No. 21, 1547–1549, 1996.
3. Yi, C. S., S. X. Dai, P. J. Zhang, X. S. Wang, X. Shen, T. F. Xu, and Q. H. Nie, "Design of a novel single-mode large mode area infrared chalcogenide glass photonic crystal fibers," *Acta. Phys. Sin.*, Vol. 62, 084206, 2013.
4. Zheng, S. W., Z. Lin, G. B. Ren, and S. Jian, "Design and analysis of novel multi-core dual-mode large-mode-area optical fiber," *Acta. Phys. Sin.*, Vol. 62, 044224, 2013.
5. Chen, X., X. B. Zhang, X. Zhu, L. Cheng, J. G. Peng, N. L. Dai, H. Q. Li, and J. Y. Li, "Effects of structure parameters on the dispersion properties of dispersion compensation photonic crystal fiber," *Acta. Phys. Sin.*, Vol. 62, 044222, 2013.
6. Cherif, R., M. Zghal, and L. Tartara, "Characterization of stimulated Brillouin scattering in small core microstructured chalcogenide fiber," *Opti. Communi.*, Vol. 285, 341–346, 2012.
7. Hou, Y., G. Y. Zhou, L. T. Hou, et al., "Analysis of dispersion properties of octagonal structural photonic crystal fiber with double cladding," *Chinese J. Lasers*, Vol. 4, No. 37, 1068–1072, 2010.
8. Wang, D. and Y. Zheng, "Numerical simulation and analysis of double cladding photonic crystal fiber with flattened dispersion," *Acta Optica Sinica*, Vol. 8, No. 21, 0806010, 2011.
9. Wang, J., C. Jiang, W. Hua, et al., "Modified design of photonic crystal fibers with flattened dispersion," *Opt. Laser Technol.*, Vol. 3, No. 38, 169–172, 2006.
10. Wang, D. and Y. Zheng, "Design and numerical investigation of a novel microstructured optical fiber," *Acta Optica Sinica*, Vol. 8, No. 32, 0806003, 2012.
11. Yuan, J. H., L. T. Hou, G. Y. Zhou, et al., "Investigation of a step-structure photonic crytal fiber with flattened dispersion," *Acta Optica Sinica*, Vol. 6, No. 28, 1167–1171, 2008.
12. Cui, Y. L. and L. T. Hou, "Dispersion characteristic of a new hybrid cladding photonic crystal fiber," *Acta Phys. Sin.*, Vol. 4, No. 59, 2571–2576, 2010.