Study of ultraflattened dispersion square-lattice photonic crystal fiber with low confinement loss*

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A new type ultraflattened dispersion square-lattice photonic crystal fiber with two different air-hole diameters in cladding region is proposed and the dispersion is investigated using a compact 2-D finite difference frequency domain method with the anisotropic perfectly matched layers (PML) absorbing boundary conditions. Through numerical simulation and optimizing the geometrical parameters, we find that the photonic crystal fibers proposed can realize ultraflattened dispersion of 0±0.06 ps/(km·nm) in wavelength range of 1.375 μm to 1.605 μm, which is more flat than that of triangular PCF, and the confinement loss is as low as about 0.01 dB/km at wavelength of 1.55 μm.

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Photonic crystal fibers (PCFs) present greater advantages, such as endlessly single-mode at all wavelengths [1], tailorable effective modal areas[2], anomalous dispersion at visible and near infrared band[3] and highly birefringent effect [4]. Controllability of chromatic dispersion in PCFs is very important for realistic applications. In particular, ultraflattened dispersion PCFs are indispensable for optical data transmission systems over a broadband wavelength range [5], because of the reduction of the accumulated dispersion difference in telecommunication bands without any zero-dispersion wavelength. To achieve ultraflattened dispersion in PCFs, several intriguing designs have been proposed. In conventional PCFs with all the same air-hole diameter in the cladding region, the dispersion slope can be significantly reduced by lowering the ratio between hole-size d and pitch Λ [6], but it has a high confinement loss of about 0.57 dB/m at a wavelength of 1.55 μm [7]. New designs for ultraflattened dispersion PCFs with low confinement loss by varying the hole-size radial have been reported [8-10]. However, these approaches bring significant fabrication challenges because several geometrical parameters are needed to simultaneously optimize the dispersion behavior of PCFs. Recently PCFs with two kinds of air-hole diameters which can reduce the confinement loss of ultraflattened dispersion with 4 rings were proposed in Ref. [11]. Ref.[12] has demonstrated the technological feasibility of square-lattice PCFs, which can be drawn with the standard stack-and-draw fabrication process. However, previous designs are all based on triangular PCFs, and the report on ultraflattened dispersion properties of square-lattice PCFs is very few. So it is very necessary to investigate ultraflattened dispersion in square-lattice PCFs.

In this paper, we propose a new kind of square-lattice PCF with five rings air-holes whose structure is similar to that in Ref [11]. Only two different air-hole diameters are used to avoid extensive complications of the fabrication process. A compact two-dimensional (2-D) finite difference frequency domain approach described in Ref.[13] with anisotropic perfectly matched layers (PML) absorbing boundary conditions is used. The calculated results show that our proposed PCF can simultaneously realize ultra-flattened dispersion and low confinement losses in a wide wavelength range.

The schematic cross section of proposed square-lattice PCF with five rings of holes is shown in Fig.1. It is composed of circular air-holes in the cladding arranged in square array with lattice pitch Λ and $d1$ is the air hole diameter for the inner three rings, d is the air-hole diameter for the outer two rings. The chromatic dispersion D of PCFs is easily calculated from the effective index $n_{\mathrm{eff}}= B/k_0$ versus the wave-

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length using

$$D = -\frac{\lambda}{c} \cdot \frac{\mathrm{d}^2 \operatorname{Re}(n_{\mathrm{eff}})}{\mathrm{d}\lambda^2},$$

where c is the velocity of light in a vacuum and Re stands for the real part. The n_{eff} is a complex value, whose imaginary part is related to the confinement loss through the relation

$$L = \frac{20}{\ln 10} \frac{2\pi}{\lambda} \operatorname{Im}(n_{\mathrm{eff}}) \times 10^6 (\mathrm{dB/m}) .$$

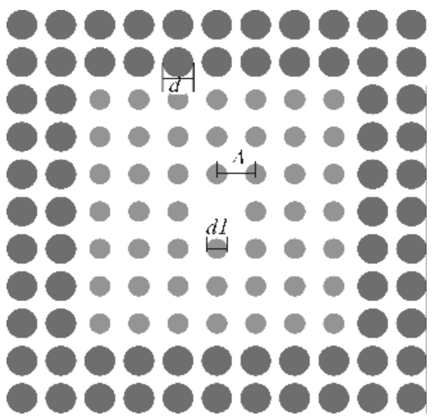


Fig.1 The schematic cross section of proposed square-lattice PCF with five rings of holes

First using the numerical scheme presented above, the dispersion as a function of wavelength for several different $d1$ is calculated, and the material dispersion given by Sellmeier's formula is directly taken into account in the calculations. Fig.2 shows the effects of $d1/\Lambda$ on the dispersion behavior with $d1/\Lambda$ = 0.28, 0.30, 0.32 and 0.34, respectively, for the fixed parameters of Λ=2 μm, d =0.8 Λ. The large air-hole diameter of outer rings is selected for better field confinement for the guided mode. From Fig.2, it is clear that the dispersion slop down-shifts from positive to negative values around 1.55 μm as $d1$ increases. There is a suitable $d1$ to make the dispersion flat, after accurate calculation, the optimizing value of parameter $d1/\Lambda$ is selected as 0.315 to realize flattened dispersion in a wide wavelength range.

For most telecom applications, a zero dispersion wavelength around 1.55 μm is desirable. Next we consider how to realize nearly zero flattened dispersion. Fig.3 shows the impact of Λ from 1.9 μm to 2.2 μm on the dispersion behavior with fixed $d1/\Lambda$=0.315, d/Λ=0.8. It is clearly seen that the parameter Λ dominantly influences the dispersion level (the dispersion increases as Λ increases), but it has little effect on the dispersion flatness. The dispersion level is about 10. 0,4.5, -1.5 and -8.5 ps/(km·nm) for Λ=2.2, 2.1, 2.0 and 1.9 μm, respectively. So the near-zero flattened dispersion can be designed by choosing proper Λ .

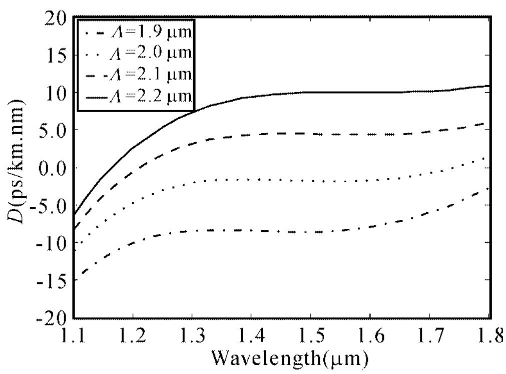


Fig.3 The dispersion as a function of wavelength for different Λ with fixed $d1/\Lambda$=0.315, d/Λ=0.8

Fig.4 shows how the dispersion property of proposed PCF changes as a function of wavelength for different parameter d with fixed value Λ=2.02 μm, $d1$=0.315 Λ. From Fig.4, it is obviously seen that the parameter d has little effect on dis-

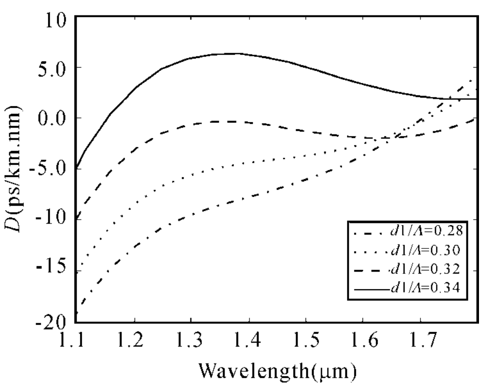


Fig.2 The dispersion as a function of wavelength for different $d1$ with fixed parameters of Λ=2 μm, d =0.8 Λ

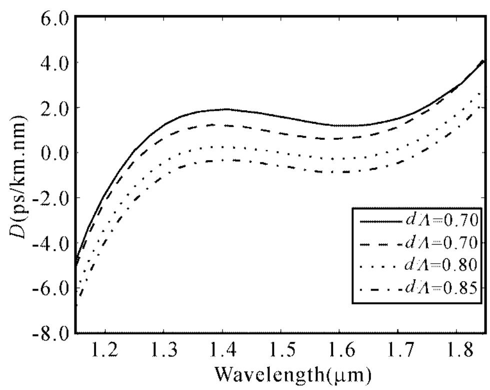


Fig.4 The dispersion as a function of wavelength for different d with fixed Λ=2.02 μm, $d1$=0.315 Λ

persion flatness, and the variation of dispersion level is smaller compared with Fig.3, which is because the fundamental mode is mostly confined in the core, and the dispersion is affected more significantly by inner rings than by outer rings, so we can make micro-adjustments of dispersion by tuning d to obtain our desirable ultraflattened dispersion value. A large value of d/Λ can realize good field confinement, but it also results in multimode operation. Finally the optimal value d/Λ is selected at 0.77 for our proposed PCF.

In order to see the difference with different geometry structures, we plot a comparison of ultraflattened dispersion between square-lattice PCF and triangular one with the same structure in Fig.5. The optimal parameters of square-lattice PCF are Λ=2.02 μm, d=0.77 Λ, d1=0.315 Λ, while Λ=2.068 μm, d=0.767Λ, d1=0.299 Λ for triangular PCF. We can see that the difference of dispersions between these two types of PCFs is not obvious, especially at long wavelength. Moreover, the dispersion value obtained with square-lattice PCF is between -0.06 and 0.06 ps/(km·nm) with corresponding wavelength from 1.375 μm to 1.605 μm, while -0.12 and 0.12 ps/(km·nm) for triangular one in this range. This indicates that proposed square-lattice PCF can achieve better nearly zero ultraflattened dispersion than triangular one around 1.55 μm.

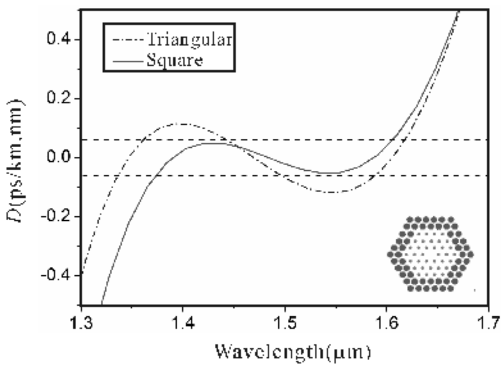


Fig.5 A comparison of ultraflattened dispersions between square-lattice PCF and triangular one (the inset in the right lower is a cross section for triangular PCF)

Fig.6 shows a comparison between the corresponding effective areas of the two types of PCFs with the same structure parameters to Fig.5. The square-lattice PCF has an effective area of 21.34 μm at 1.55 μm which is 17% larger than that of the triangular one. The difference can be explained by the lower air-filling fraction of square-lattice PCF. Fig.7 shows the wavelength dependence of confinement loss of fundamental mode of the above two types of PCFs. Although the confinement loss of square-lattice PCF is a little higher than that of triangular one, it still remains as low as about 0.01 dB/km at wavelength of 1.55 μm. In theory, our proposed PCF is not rigorous single mode, but the higher confinement loss of second-order mode suggests that it is likely to be effectively single mode in practice.

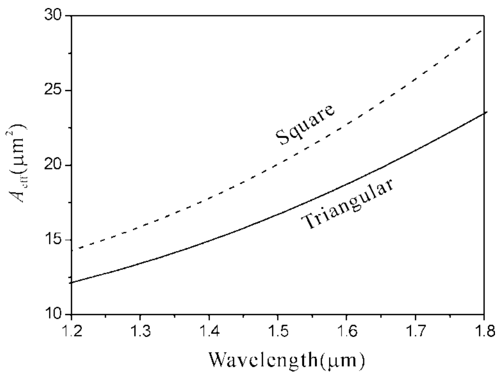


Fig.6 A comparison of the corresponding effective mode areas between square-lattice PCF and triangular one

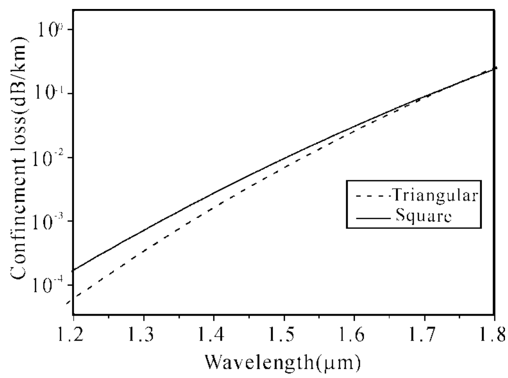
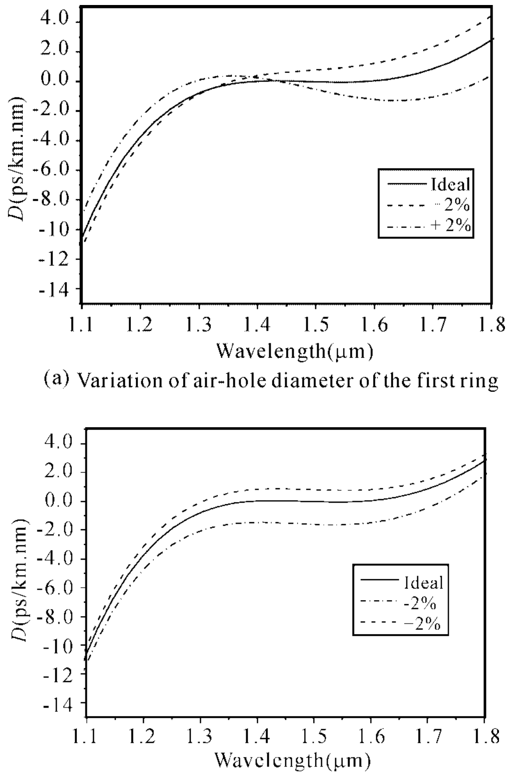


Fig.7 A comparison of confinement losses of fundamental mode between square-lattice PCF and triangular one

In practical fabrication, the fluctuation of air holes, especially air holes in the first two rings, is inevitable and may lead to a significant deviation from the anticipated dispersion properties. In order to evaluate the sensitivity of dispersion to these errors, the fabrication tolerances of ±2% of the first two rings have been investigated. When air-hole diameter of the first ring varies within 2% from its optimal value by keeping the other parameters fixed, the flatness is disturbed and the dispersion fluctuation is about 10% (see Fig. 8(a)), so it is particularly crucial to make air-hole diameter of the first ring approximate to the optimal value in practical fabrication. Similarly, the tolerance in the second ring within ±2% is investigated as Fig.8(b). The impact of the second ring on the dispersion is still obvious, but the error can be compensated through an overall scaling of the structure[14].



(a) Variation of air-hole diameter of the first ring

(b) Variation of air-hole diameter of the second ring

Fig.8 Influence of the fiber tolerances on the dispersion property of proposed PCF

In this paper, we propose a new type square-lattice PCF with two different air-hole diameters in cladding region and investigate it by using the finite difference frequency domain method with anisotropic PML absorbing boundary conditions. It is shown through numerical simulations that our proposed PCF with five rings can simultaneously realize ultraflattened dispersion and low confinement loss. Further, tolerance analysis has been carried out for our proposed fiber design. We believe that our proposed PCF will be useful in ultra-broadband transmission application.

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