

Octagonal dual-concentric-core photonic crystal fiber for C-band dispersion compensation with low confinement loss

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A novel kind of octagonal dual-concentric-core photonic crystal fiber (PCF) is calculated with the finite element method (FEM) and proposed for broadband compensation. In order to realize highly negative dispersion, the hole diameter of the second ring is reduced relative to conventional PCFs. Numerical simulation results show that when the diameters of large holes and small holes are $0.77\ \mu\text{m}$ and $0.5\ \mu\text{m}$, respectively, and the pitch of the adjacent rings is $1.1\ \mu\text{m}$, the negative dispersion can achieve about $-840\ \text{ps}\cdot\text{nm}^{-1}\cdot\text{km}^{-1}$ at $1550\ \text{nm}$ and the dispersion slope can match with single mode fiber (SMF-28) perfectly. This PCF can compensate the positive dispersion and also its slope of about 50 times its length of SMF-28 fiber, which is suitable for C-band optical fiber telecommunication as a dispersion compensation fiber.

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In optic fiber communication systems, loss and dispersion of fibers restrict the propagation distance and bit rates. Nowadays, with the development and utilization of erbium doped fiber amplifiers (EDFAs), the problem of loss has been solved to some extent. Consequently, chromatic dispersion has become the main confinement of high velocity broadband communication systems. The utilization of dispersion compensating fiber (DCF) is an important approach to decrease or eliminate the accumulated chromatic dispersions. The principle of this method is to add a section of highly negative dispersion compensating fiber into the propagation circuit to offset the accumulated positive dispersion. Based on conventional step index fibers, in recent years, people have designed various DCFs such as W type fibers, multiple cladding type fibers^[1], fiber gratings and so on. However, the compensating efficiency of conventional DCFs is not very high, which generally can achieve -100 to $-400\ \text{ps}\cdot\text{nm}^{-1}\cdot\text{km}^{-1}$. Then in 1999, Birks *et al.* at the first time put forward the idea that photonic crystal fiber (PCF) can be an attractive candidate of conventional DCFs, which can compensate the dispersion of 35 times its length of SMF-28 fiber for broadband transmission at $1550\ \text{nm}$ ^[2]. Up to now, many compensating PCFs based on hexagonal lattice are proposed^[3–10]. Besides the hexagonal structures, other structures, such as square^[11], octagonal^[12,13], decagonal^[14], and circular^[15] photonic crystal fibers etc. are also presented. In contrast with hexagonal PCFs (H-PCFs), octagonal PCFs (O-PCFs) are reported with such major attractive features as wider wavelength region operating in a single mode region, more circular field distribution, and lower confinement loss.

Many papers reported H-PCFs with variable air-hole radius as dispersion compensation fibers, but most of them neglected the compensation of dispersion slopes. Nowadays, commercial dispersion compensation optical

fibers usually have obtained dispersion coefficient about from -100 to $-300\ \text{ps}\cdot\text{nm}^{-1}\cdot\text{km}^{-1}$. In this letter, a dual-concentric-core O-PCF with low confinement loss is proposed for C-band dispersion compensation. Through a number of calculations, we obtained the optimized parameters and very low confinement loss at $1550\ \text{nm}$. This kind of fiber can compensate the dispersion and also its slope of about 50 times its length of SMF-28 fiber ideally with very low confinement loss, which is useful and important for C-band dispersion compensation in optic fiber communication systems.

The basic principle of dispersion compensation fiber is as follows. At short wavelengths, the mode is confined to the inner core and, at long wavelengths, to the outer core. At the wavelength at which the effective index exhibits a kink, the mode suddenly changes from one mode distribution to the other. This is due to an anti-crossing of the two individual inner-core-guided and outer-core-guided modes. These two mode distributions have very different effective indexes. Thus at the wavelength at which the mode distribution suddenly changes from the inner core to the outer core, the effective index exhibits the kink, which results in highly negative dispersions. The coefficient of the dispersion (D) is defined as^[16]

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

where D is the dispersion coefficient, λ is the operating wavelength, c is the velocity of light in a vacuum, and $\text{Re}[n_{\text{eff}}]$ is the real part of the effective index. The material dispersion given by Sellmeier's formula is directly included in the calculation. If we only expect to compensate for single channel, the compensating for D is already enough^[17]. The dispersion coefficient and the length of the fibers should meet the following conditions:

$$D_1 L_1 + D_2 L_2 = 0, \quad (2)$$

where D_1 and L_1 are the dispersion coefficient and length of SMFs, respectively; D_2 and L_2 are the dispersion coefficient and length of the DCFs, respectively; D_1 is often a positive value, so D_2 should be a negative value. In order to decrease the propagation loss, D_2 should be highly negative.

However, with the development of communication speed, broadband compensation is often needed. To realize broadband compensation, dispersion slope is also needed to be compensated. The slope of the dispersion and the length of the fibers should at the same time conform to the following formula in addition to Eq. (2):

$$D_{\text{slope}1}L_1 + D_{\text{slope}2}L_2 = 0, \quad (3)$$

where $D_{\text{slope}1}$ and L_1 are the slope of the dispersion coefficient curve and length of the SMFs, respectively, $D_{\text{slope}2}$ and L_2 are the slope of the dispersion coefficient curve and length of the DCFs, respectively. In general, $D_{\text{slope}1}$ is positive. Therefore, $D_{\text{slope}2}$ must be negative. In order to evaluate the broadband compensating ability of DCFs, a parameter has been defined namely relative dispersion slope (*RDS*):

$$RDS = \frac{D_{\text{slope}}}{D}. \quad (4)$$

To realize full slope compensation, the *RDS* of DCF must be approximate or equal to that of SMF, namely

$$RDS_{\text{DCF}} = RDS_{\text{SMF}}. \quad (5)$$

For SMF-28 fiber, the parameters are $D = 17 \text{ ps} \cdot \text{nm}^{-1} \cdot \text{km}^{-1}$, $D_{\text{slope}} = 0.058 \text{ ps} \cdot \text{nm}^{-2} \cdot \text{km}^{-1}$. Eq. (4), we can obtain $RDS_{\text{SMF-28}} = 0.0034 \text{ nm}^{-1}$.

Confinement loss is another important parameter to describe the light confinement ability within the core region. The confinement loss L_c can be obtained from the imaginary part of n_{eff} as

$$L_c(\text{dB/m}) = \frac{(20 \times 10^6)}{\ln(10)} k_0 \text{Im}[n_{\text{eff}}], \quad (6)$$

where $\text{Im}[n_{\text{eff}}]$ is the imaginary part of the effective index, $k_0 = 2\pi/\lambda$ is the wavenumber in free space.

Figure 1 is the cross section of the dispersion compensating photonic crystal fiber we proposed for broadband compensation. The center of the fiber has one defect, which forms the inner core, and the diameter of the second ring is decreased, which forms the outer core. The material of the green region is silica and the white region is filled with air. The diameter of the O-PCF is set to be $125 \mu\text{m}$. In addition, the diameter of the big holes is d_1 , the diameter of the small holes is d_2 and the pitch of the two adjacent rings is Λ .

To calculate the dispersion curves, we used FEM (COMSOL Multiphysics) with perfectly matched layers (PMLs). Based on a large number of calculations, we found that, with decreasing the pitch, the chromatic dispersion reduced from positive to negative, and the negative absolute value increased gradually. Simulations show that when the pitch Λ is near $1.1 \mu\text{m}$ the negative dispersion can be very high. Therefore we determined pitch Λ as $1.1 \mu\text{m}$. Also we found that with increasing the

diameter of big holes (also d_1/Λ), the dispersion slope decreased from positive to negative. We confirmed the air filling ratio (d_1/Λ) as 0.7.

Figure 2 shows the mode field distributions of power flow when the operating wavelength is 1550 nm . From Fig. 2(a), we can see the fundamental inner-core-guided mode is confined in the inner core region. It is seen from Fig. 2(b) that the second order outer-core-guided mode is limited in the outer core. The highly negative dispersion coefficients are obtained due to the interaction of these two modes, as can be explained from above mentioned principle.

In Figs. 3 and 4, we confirm $\Lambda = 1.1 \mu\text{m}$, $d = 0.77 \mu\text{m}$ and change the diameter of small holes d_2 from 0.50 to $0.48 \mu\text{m}$. As can be seen from Fig. 3, with the decrease of d_2 , the absolute value of the dispersion dip is reduced. At the same time, the wavelength positions of the dip shift to shorter wavelength. At the wavelength of 1550

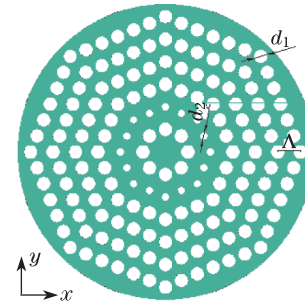


Fig. 1. Cross section of proposed O-PCF for broadband dispersion compensation. The origin of the coordinates is at the center of the circle.

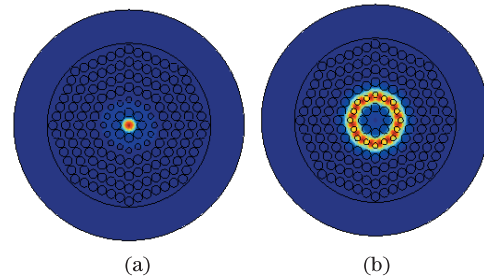


Fig. 2. The mode field distribution of power flow when the operating wavelength is 1550 nm . (a) Inner-core-guided mode; (b) outer-core-guided mode.

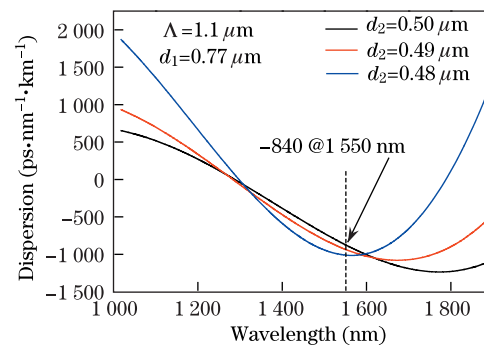


Fig. 3. Chromatic dispersion of O-PCFs as a function of wavelength when $\Lambda = 1.1 \mu\text{m}$, $d_1 = 0.77 \mu\text{m}$, and $d_2 = 0.50, 0.49, 0.48 \mu\text{m}$, respectively.

nm, the dispersions for $d_2 = 0.50, 0.49, 0.48 \mu\text{m}$ are $-840, -927, \text{ and } -1\,010 \text{ ps}\cdot\text{nm}^{-1}\cdot\text{km}^{-1}$, respectively.

As is shown in Fig. 4, with the decrease of d_2 , the dip of the dispersion slopes also shift to shorter wavelength. When $\Lambda = 1.1 \mu\text{m}$, $d_1 = 0.77 \mu\text{m}$, and $d_2 = 0.50, 0.49, 0.48 \mu\text{m}$, the dispersion slopes are $-2.84, -2.11, \text{ and } -0.4 \text{ ps}\cdot\text{nm}^{-1}\cdot\text{km}^{-1}$, respectively.

In order to realize broadband compensation for C-band (1 530–1 565 nm), according to Eq. (4), we can calculate RDS at 1 550 nm of the above-mentioned three O-PCFs. The results are 0.0034, 0.0023, and 0.0004 nm^{-1} , respectively. The RDS of the first O-PCF is exactly equal to RDS_{SMF-28} . That is to say the O-PCF with $\Lambda = 1.1 \mu\text{m}$, $d_1 = 0.77 \mu\text{m}$, and $d_2 = 0.50 \mu\text{m}$ is expected to compensate both the dispersion and the slope of about 50 times its length of SMF-28 ideally.

Yang *et al.* has presented a modified dual-core photonic crystal fiber, based on pure silica, with special grapefruit holes in the inner cladding^[4]. The fiber has large, broadband negative dispersion, and the dispersion value varies linearly from -380 to $-420 \text{ ps}\cdot\text{nm}^{-1}\cdot\text{km}^{-1}$ in the C-band. Compared with this presentation, the negative dispersion efficient of the O-PCF proposed is from -790 to $-887 \text{ ps}\cdot\text{nm}^{-1}\cdot\text{km}^{-1}$ in the C-band, which is about twice the value of the PCF proposed in Ref. [4]. In addition, the fabrication of our proposed PCF is not very difficult in contrast with Ref. [4]. Therefore our proposition is valuable for C-band dispersion compensation.

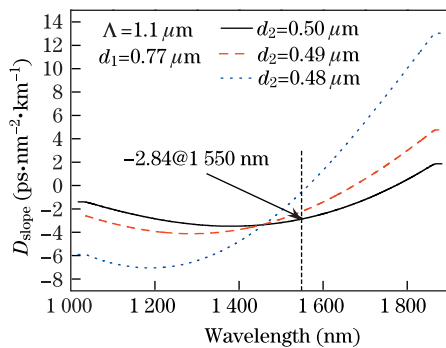


Fig. 4. Dispersion slope of O-PCFs as a function of wavelength, when $\Lambda = 1.1 \mu\text{m}$, $d_1 = 0.77 \mu\text{m}$, $d_2 = 0.50, 0.49, 0.48 \mu\text{m}$, respectively.

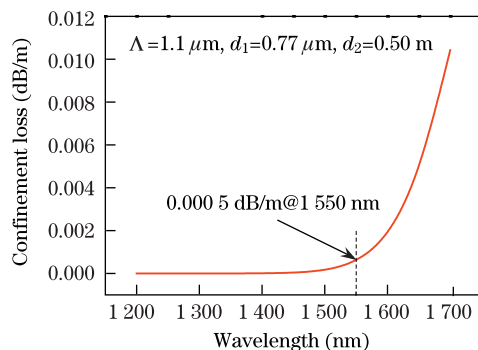


Fig. 5. Confinement loss of the fundamental mode of optimized O-PCF as a function of wavelength when $\Lambda = 1.1 \mu\text{m}$, $d_1 = 0.77 \mu\text{m}$, $d_2 = 0.50 \mu\text{m}$.

Based on Eq. (6), we can obtain the relationship of the confinement loss with wavelength which is shown in Fig. 5. From this figure, we can see that the confinement loss is very low when the wavelength is less than 1 600 nm, but it increases sharply when the wavelength is larger than 1 600 nm. Near 1 550 nm, the confinement loss is about 0.0005 dB/m, and we can add one layer to further decrease the confinement loss, which is useful for C-band telecommunication.

In conclusion, a novel octagonal photonic crystal fiber with variable air holes for C-band dispersion compensation is proposed and discussed. The optimized parameters are $\Lambda = 1.1 \mu\text{m}$, $d_1 = 0.77 \mu\text{m}$, $d_2 = 0.50 \mu\text{m}$. This O-PCF can compensate both the dispersion and its slope of about 50 times its length of SMF-28 fiber for C-band compensation perfectly. In addition, the fabrication of this PCF is not very difficult. Furthermore, the confinement loss of the proposed O-PCF is 0.0005 dB/m at 1 550 nm, which is almost negligible and suitable for C-band dispersion compensation in telecommunication systems.

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