A novel design for broadband dispersion compensation microstructure fiber

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A novel microstructure fiber (MF) structure is proposed for broadband dispersion compensation. Through manipulating the four air-hole parameters and the pitch, the broad band dispersion compensation MF can be efficiently designed. The newly designed MF could compensate (to within 0.8%) the dispersion of 101 times of its length of standard single mode fiber over the entire 100-nm band centered on 1550 nm. The proposed design has been simulated through the finite difference beam propagation method, and the corresponding design procedures are also presented.

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Since dispersion has become one of the primary impairments for high data rate transmission systems, dispersion compensation fiber is extensively studied and deployed[1,2]. As far as dense wavelength division multiplexing (DWDM) is concerned, chromatic dispersion compensation and dispersion slope compensation must be accounted simultaneously[3], and conventional dispersion compensation fibers cannot be changed drastically to fulfill those requirements. This limitation may be circumvented by the use of microstructure fibers (MFs). MFs possess significantly different dispersion properties because the novel cladding structure consisting of an array of wavelength-scale air holes allows for flexible tailoring of the dispersion curves[4−10]. If a MF has the appropriate dispersion slope and enough negative dispersion, it will successfully compensate a conventional single-mode fiber (CSF) over a certain range of operating wavelength. The engineer-able dispersion characteristics enable MFs as the promising devices for broadband dispersion compensation.

Several designs for the MF have been proposed to alternatively achieve the high dispersion compensation ratio (with large negative dispersion) or wide compensation bandwidth (with appropriate dispersion slope) to compensate CSFs[11−14], those MFs possess air holes arrayed in a regular triangular lattice with the same air-hole diameter or with dual core. In this letter, a novel MF structure is proposed for achieving high dispersion compensation ratio and wide compensation bandwidth simultaneously. Through optimizing the air hole diameters and scaling transformation, desired dispersion characteristics are efficiently achieved. The procedures for designing the broadband dispersion compensation MF are also presented. The newly designed MF could compensate (to within 0.8%) the dispersion of 101 times of its length of standard single mode fiber over the entire 100-nm band centered on 1550 nm.

The transverse cross section of the novel MF is shown in Fig. 1, where Λ is the pitch of the lattice, d_{1L} is the diameter of the four larger air holes in the first ring, d_{1S} is the diameter of the two smaller air holes in the first ring, d_2 is the air hole diameter of the second ring, d_3 is the air hole diameter of the other outer rings. Large normalized air-hole diameter of the first ring is selected for better field confinement of the guided mode, but two of the air-holes in the first ring are designed to be smaller because they can make four of the six silica bridges wider, ensuring the core is adequately supported.

An efficient and accurate finite difference beam propagation method (FD-BPM) is used to calculate the modal effective index $n_{\mathrm{eff}}(\lambda)$ of the proposed MF. The group velocity dispersion of the MF can be directly calculated from the modal effective index of the fundamental mode over a range of wavelength. When the material dispersion is also considered, the total dispersion of the MF is easily obtained[15]

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

where c is the velocity of the light in vacuum, λ the operating wavelength, $D_{\mathrm{m}}(\lambda)$ the material dispersion obtained from the general three-term Sellmeier formula.

To judge the dispersion compensation satisfaction over

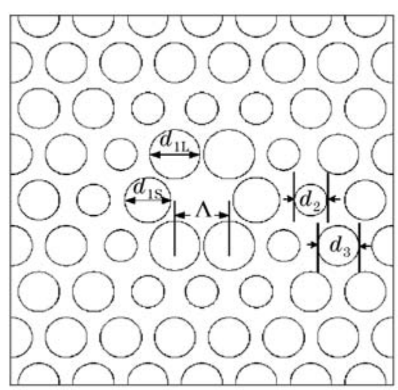

Fig. 1. Cross section of the MF with four different air-hole sizes.

a range of wavelength, the Kappa value is introduced

$$\text{Kappa} = \frac{D(\lambda_0)}{S(\lambda_0)}, \tag{2}$$

where $D(\lambda_0)$ and $S(\lambda_0)$ are respectively the dispersion and dispersion slope on operating wavelength of 1550 nm. Since both the MF and CSF proposed have slowly varied dispersion slopes, once they have equal Kappa value the MF can compensate the dispersion of the CSF over a certain range of wavelength due to their linear nature, and the exact compensation bandwidth can be calculated from the actual dispersion curves of the MF and the CSF.

As shown in Fig. 1, there are five degrees of freedom (d_{1L}, d_{1S}, d_2, d_3, and Λ) in the design procedure, those geometrical parameters must be defined simultaneously for optimizing the dispersion behavior of the MF. To design the broadband dispersion compensation MF, the four air-hole diameters and the pitch are adjusted separately and their influence on dispersion curve is investigated. The dispersion and dispersion slope at 1550 nm of the CSF for reference are 17 ps/(nm·km) and 0.06 ps/(nm^2·km), respectively, and the calculated Kappa value is 283.33 nm.

Figure 2 shows the effect of normalized diameter of the larger air-holes in the first ring (d_{1L}/Λ) on the dispersion behavior with $\Lambda = 0.98$ μm, $d_{1S}/\Lambda = 0.86$, $d_2/\Lambda = 0.64$, and $d_3/\Lambda = 0.76$. As the normalized diameter d_{1L}/Λ is enlarged from 0.90 to 0.94, the dispersion at 1550 nm decreases from -956.0 to -1236.2 ps/(nm·km) and the Kappa value decreases from 227.5 to 199.6 nm. In the short-wave region, the modal field is well limited in the fiber core, the outer air-holes are almost ineffective, and therefore changing air-hole diameter of the first ring has very little impact on the dispersive value. In the long-wavelength region, the modal field will spread wider as the wavelength increases, and consequently more rings of air-holes will jointly affect dispersive value. The field distribution of different operating wavelengths is demonstrated in Fig. 3.

Figure 4 shows the effect of d_{1S}/Λ on the dispersion behavior with $\Lambda = 0.98$ μm, $d_{1L}/\Lambda = 0.94$, $d_2/\Lambda = 0.64$, and $d_3/\Lambda = 0.76$. As the normalized diameter d_{1S}/Λ is enlarged from 0.84 to 0.88, the dispersion at 1550 nm decreases from -1130.6 to -1324.0 ps/(nm·km) and Kappa value decreases from 212.3 to 193.4 nm. From Figs. 2 and 3, it is apparent that if we constantly increase the air-hole dimension of the first ring, larger negative dispersion will be obtained, but the Kappa value will be away from the referred CSF and the silicon bridges could be too fine to support the core, so the first ring air-hole diameter must be upper limited.

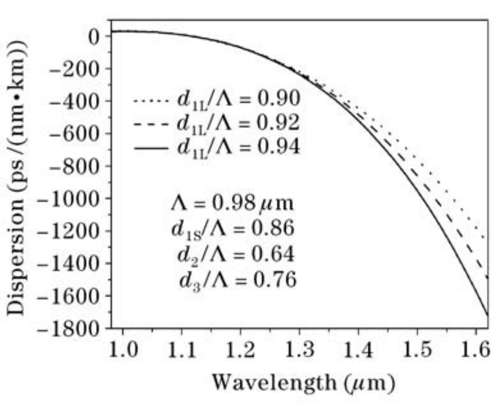

Fig. 2. Effect of d_{1L} on the dispersion behavior.

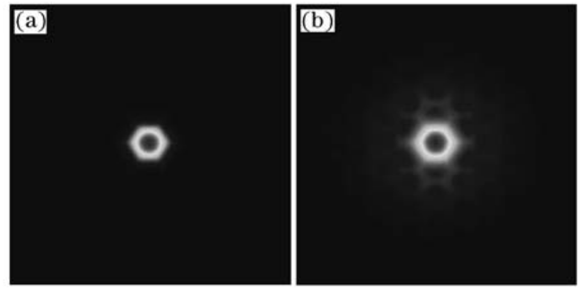

Fig. 3. Field distribution for different operating wavelengths of 980 nm (a) and 1550 nm (b).

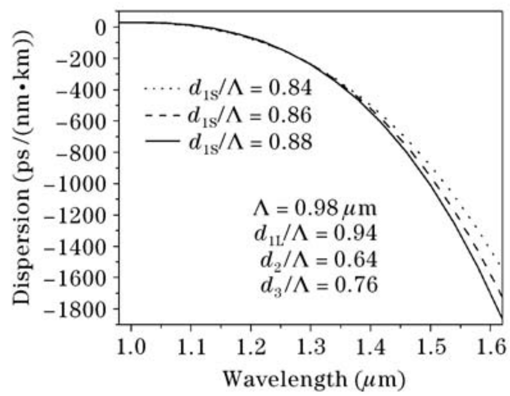

Fig. 4. Effect of d_{1S} on the dispersion behavior.

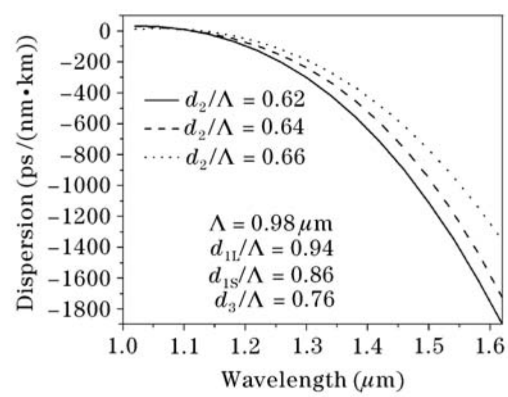

Fig. 5. Effect of d_2 on the dispersion behavior.

Figure 5 shows the effect of d_2/Λ on the dispersion behavior with $\Lambda = 0.98$ μm, $d_{1L}/\Lambda = 0.94$, $d_{1S}/\Lambda = 0.86$, and $d_3/\Lambda = 0.76$. As the normalized diameter d_2/Λ is reduced from 0.66 to 0.62, the dispersion at 1550 nm decreases from -1019.4 to -1389.9 ps/(nm·km), and the Kappa value decreases from 223.1 to 185.1 nm. The trend is that smaller d_2/Λ can yield larger negative dispersion and Kappa value, but the d_2/Λ must be large enough for good field confinement.

Figure 6 shows the effect of d_3/Λ on the dispersion behavior with $\Lambda = 0.98$ μm, $d_{1L}/\Lambda = 0.94$, $d_{1S}/\Lambda = 0.86$, and $d_2/\Lambda = 0.64$. As the normalized diameter d_3/Λ is enlarged from 0.74 to 0.78, the dispersion at 1550 nm

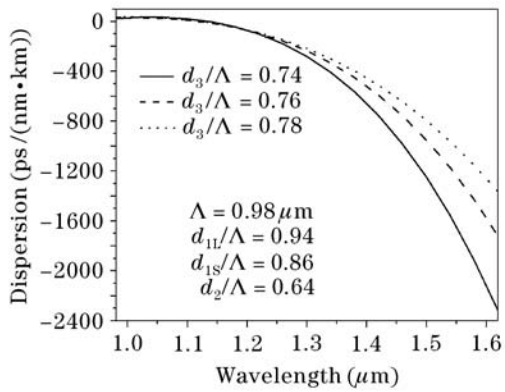

Fig. 6. Effect of d_3 on the dispersion behavior.

increases from −1642.8 to −1009.1 ps/(nm·km), and the Kappa value increases from 190.7 to 218.2 nm. During the adjustment of d_3/Λ, there is a compromise between larger negative dispersion and smaller Kappa value.

All of the above procedures are with a fixed pitch. Then we scale the cross section, the pitch varies from 0.96 to 1.00 μm with $d_{1L}/\Lambda = 0.94$, $d_{1S}/\Lambda = 0.86$, $d_2/\Lambda = 0.64$, and $d_3/\Lambda = 0.76$, the result is shown in Fig. 7. As the geometrical structure is enlarged, the Kappa value and dispersion absolute value decrease at the same time, these results provide a useful method to accurately adjust geometrical parameters for the given Kappa value. For example, if the normalized air-hole diameters of the MF have been selected as $d_{1L}/\Lambda = 0.94$, $d_{1S}/\Lambda = 0.86$,

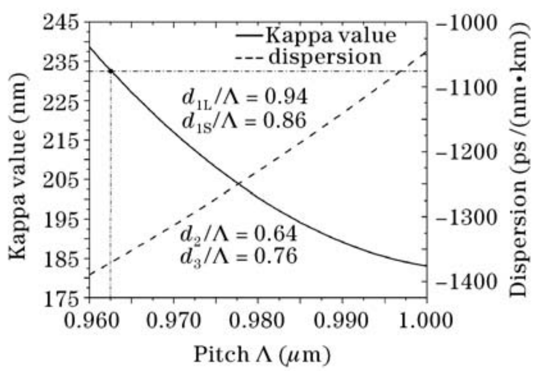

Fig. 7. Kappa value and dispersion as functions of pitch with fixed normalized air-hole diameters.

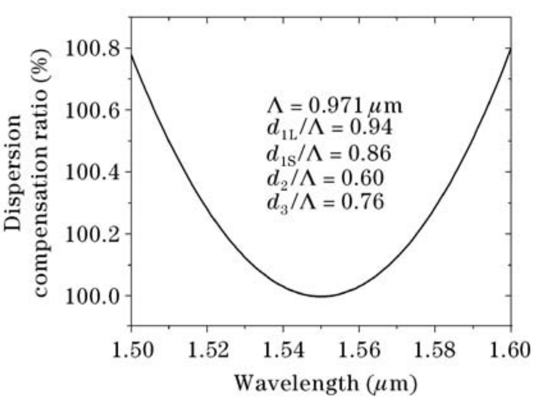

Fig. 8. Dispersion compensation ratio versus wavelength.

$d_2/\Lambda = 0.64$, and $d_3/\Lambda = 0.76$, and the MF is designed to compensate the CSF with Kappa value of 232.5 nm, then from Fig. 7 the pitch should be chosen as $\Lambda = 0.9625$ μm.

Based on the above analysis, we adjusted the geometrical parameters of the MF as $\Lambda = 0.9710$ μm, $d_{1L}/\Lambda = 0.94$, $d_{1S}/\Lambda = 0.86$, $d_2/\Lambda = 0.60$, and $d_3/\Lambda = 0.76$, the calculations show that the dispersion at 1550 nm and the Kappa value of the MF are −1725.1 ps/(nm·km) and 283.34 nm, respectively. The MF can compensate the dispersion of 101 times its length of standard fiber, and it can do this to within 0.8% over the entire 100-nm band centered on 1550 nm. The compensation ratio versus wavelength for the proposed MF is shown in Fig. 8.

In conclusion, a novel MF structure with large negative chromatic dispersion and appropriate Kappa value is proposed. Through optimizing geometrical parameters, the broadband dispersion compensation MF can be efficiently designed. Compared with previously presented dispersion compensation MFs, the design procedure for this novel structure could be more flexible and the broadband compensation results could be better. As an example, a designed MF which could compensate (to within 0.8%) the dispersion of 101 times of its length of standard single mode fiber over a 100-nm range is numerically demonstrated.

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