A simplified dispersion-compensation microstructure fiber with seven cores*

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In order to compensate the dispersion accumulated in a single mode fiber (SMF) for higher communication capacity, a simplified dispersion-compensation microstructure fiber (DC-MSF) with seven cores is proposed in this paper. The fiber's cladding is made of pure silica without air holes, and its outer cores are composed of six germanium up-doped cylinders, which has the advantage of simple structure. The finite element method (FEM) and beam propagation method (BPM) are used to study the properties of the fiber, and the relationship between the structural parameters of the fiber and the dispersion, as well as the phase matching wavelength, is obtained. By optimizing the structural parameters of the fiber, the dispersion of the fiber can reach −5 291.47 ps·nm^{-1}·km^{-1} at 1 550 nm, and the coupling loss to the conventional single-mode fiber is only 0.137 dB. Compared with the conventional dispersion-compensation fiber, the fiber has lots of advantages, such as single mode transmission, easy to fabricate and low coupling loss with traditional SMF, etc.

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Accumulated positive dispersion in single mode fiber (SMF) causes the broadening of optical signals, which deteriorates the overall performance of the optical communication systems. In order to counter-balance it, dispersion compensation fiber (DCF) which has negative dispersion is usually employed. Microstructure fiber has the advantage of accurate dispersion management by flexibly adjusting its structure. This makes it a promising candidate for the DCF[1-5]. As early as 2004, GÉRÔME et al[6] proposed a dual-concentric-core dispersion compensation microstructure fiber (DCC-DC-MSF). A large negative dispersion can be achieved by coupling between the two concentric core modes. By this mechanism, in 2006, YANG et al[7] achieved broadband dispersion compensation in the range of 1 520—1 580 nm. In 2011, YUAN et al[8] reached a negative dispersion as high as −39 500 ps·nm^{-1}·km^{-1} at 1 550 nm by filling the outer core of DCC-DC-MSF with sugar-solution. In 2015, HSU et al[9] further optimized the structural parameters of the DCC-DC-MSF to increase the negative dispersion to −51 000 ps·nm^{-1}·km^{-1}. In 2017, WANG et al[10] proposed a novel all-solid-structure DCC- DC-MSF, where air holes were replaced by solid doped rods. With index difference as low as 0.03 between the doped rods and background material, the fiber achieved broadband dispersion compensation to conventional SMF over S+C band. In 2021, PANDEY et al[11] proposed a high birefringent DCC-DC-MSF with three rectangular holes in the inner core of the fiber. The fiber simultaneously achieved a negative dispersion of −6 586 ps·nm^{-1}·km^{-1} and a birefringence of 9.4×10^{-2} at 1 550 nm. In the same year, HOWLADERD et al[12] proposed a square-lattice DCC-DC-MSF which achieved a negative dispersion about −595 ps·nm^{-1}·km^{-1} to −1 288 ps·nm^{-1}·km^{-1} over S to L bands. In 2022, LIANG et al[13] proposed a temperature-sensitive DCC-DC-MSF. By filling a temperature-sensitive liquid with main material components as perfluorocarbons and chlorofluorocarbons into the air holes in fourth layer, a broadband negative dispersion of −1 533.2—−2 836.4 ps·nm^{-1}·km^{-1} is achieved from 1 460 nm to 1 625 nm, and its value can be controlled by the temperature. In 2023, SHAO et al[14] proposed a wavelength-tunable DCC-DC-MSF by filling the temperature-sensitive material into its air holes. The fiber achieved an ultrahigh negative dispersion of −27 315.76 ps·nm^{-1}·km^{-1} at 1 550 nm. In the same year, FENG et al[15] proposed a liquid-core photonic crystal fiber with a fully circular air hole structure through filling CS_2 into its inner core, which achieved a negative dispersion of −2 511 ps·nm^{-1}·km^{-1} and a nonlinearity of

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50 677.77 $W^{-1}\cdot km^{-1}$ at 1 550 nm.

However, the above-mentioned DCC-DC-MSFs have the following disadvantages. Firstly, these DCC-DC-MSFs are structurally sophisticated. It's a huge technical challenge to fabricate them without deformations. Secondly, to achieve large negative dispersion, a smaller inner core is required to improve the coupling strength between the inner and outer cores. This results in the mismatch of the core size between the DCC-DC-MSF and the conventional SMF. When they are spliced together, a high coupling loss is induced. Thirdly, the air-hole cladding of DCC-DC-MSFs has large air-filling fraction to increase the refractive index differences between the cores and the cladding. This usually means the DCC-DC-MSFs do not support single-mode transmission.

In this paper, a simplified dispersion-compensation microstructure fiber (DC-MSF) with seven cores is proposed. The fiber consists almost entirely of solids, with its matrix being pure silica and cores being germanium up-doped silica cylinders, and there is only an air hole in its inner core. Therefore, the normalized frequency V for the inner core could be less than 2.404 8 at 1 550 nm, which means the fiber supports single mode transmission. Through reasonable parameters adjustment, the dispersion of the fiber can reach −5 291.47 $ps\cdot nm^{-1}\cdot km^{-1}$ at 1 550 nm. At the same time, its inner core size matches that of the traditional SMF. This reduces the coupling loss between the two fibers to only 0.137 dB. Compared with the conventional DC-MSF, the fiber proposed in this paper has lots of advantages, such as single mode transmission, easy to fabricate and low coupling loss with traditional SMF, etc.

In this paper, the finite element method (FEM) is used to calculate the effective refractive index and mode field area of the fiber. Based on Maxwell's equations, the basic equation of FEM can be expressed as[16]

$$\nabla\times\left(\frac{1}{\mu_r}\nabla\times\boldsymbol{E}\right)-(k_0)^2\left[\varepsilon_r\right]\boldsymbol{E}=0, \tag{1}$$

where k_0 is the wave number in vacuum, $\boldsymbol{E}$ is the electric field vector, and ε_r and μ_r represent the permeability tensors and relative permittivity, respectively.

When FEM is applied to the fiber, the cross section of the fiber is divided into a number of finite size elements. We can obtain the following equation

$$\left[\boldsymbol{K}\right]\left\{\boldsymbol{E}\right\}=(k_0)^2(n_{eff})^2\left[\boldsymbol{M}\right]\left\{\boldsymbol{E}\right\}, \tag{2}$$

where $\boldsymbol{K}$ and $\boldsymbol{M}$ are the finite element matrices, and n_{eff} is the effective refractive index of the mode. By solving Eq.(2), the effective refractive index of the required mode can be obtained.

The dispersion $D(\lambda)$ of the fiber can be determined by[17]

$$D(\lambda)=-\frac{\lambda}{c}\frac{d^2\mathrm{Re}(n_{eff})}{d^2\lambda}, \tag{3}$$

where c is the velocity of light in vacuum, λ is the wavelength, and $\mathrm{Re}(n_{eff})$ is the real part of the modal effective index.

Mode area of the fiber A_{eff} can be obtained by[18]

$$A_{eff}=\frac{(\iint|\boldsymbol{E}|^2 dxdy)^2}{\iint|\boldsymbol{E}|^4 dxdy}. \tag{4}$$

According to $A_{eff}=\pi\omega^2$, the mode field radius ω can be obtained.

Coupling loss refers to the splicing loss that occurs when the light passes through the splicing point between two different fibers. It can be caused by the inclination, gap, mode mismatch or misalignment between fibers, collapse of the air hole, incompleteness of the fiber end face, etc. In our numerical studies, we mainly focused on the coupling loss caused by the mode mismatch between fibers[19]. And the beam propagation method (BPM) is used to calculate the coupling loss L_{couple} between the proposed fiber in this paper and the conventional SMF by

$$L_{couple}=-10\log\frac{P_{out}}{P_{in}}, \tag{5}$$

where P_{in} is the input power at the connection of two optical fibers, and P_{out} is the optical power after the mode field conversion.

The normalized frequency V is also an important parameter of the fiber, for it indicates whether the fiber is single mode. Its value can be calculated by

$$V=\frac{2\pi r_1}{\lambda}\sqrt{{n_1}^2-{n_0}^2}, \tag{6}$$

where n_1 is the refractive index of the inner core, n_0 is the cladding refractive index, and r_1 is the radius of the inner core. For step index fiber, single mode transmission is achieved when V<2.404 8.

In this paper, the proposed fiber uses pure silica as background material. Its refractive index n_0 can be obtained by Sellmeier equation[20]

$$n_0=\sqrt{1+\sum_{i=1}^{j}\frac{A_i\lambda^2}{\lambda^2-B_i^2}}, \tag{7}$$

where j is equal to 3, A_1=0.696 166 3, A_2=0.407 942 6, A_3=0.897 479 4; B_1=0.068 404 3 μm, B_2=0.116 241 43 μm and B_3=9.896 161 μm.

The inner core of the fiber is a germanium up-doped ring, whose refractive index n_1 can be obtained by

$$n_1=(1+a)n_0, \tag{8}$$

where a stands for the concentration of germanium. Similarly, the refractive index n_2 of the six outer cores can also be obtained by Eq.(8).

The nonlinearity coefficient γ of the fiber is given by[21]

$$\gamma=\frac{2\pi n_3}{\lambda A_{eff}}, \tag{9}$$

where n_3 stands for the nonlinear refractive index of the inner core.

The confinement loss L_c of the fiber is given by[21]

$$L_c = -8.686 \times \frac{2\pi}{\lambda} \times \mathrm{Im}(n_{eff}), \tag{10}$$

where $\mathrm{Im}(n_{eff})$ is the imaginary part of the effective index of the fundamental mode.

Fig.1 shows the structure of the proposed DC-MSF with seven cores. Its matrix is pure silica with refractive index n_0. The inner core is a germanium up-doped ring with refractive index n_1 and outer radius r_1. In its center, an air hole with radius r_0 is introduced. Around the center, there are six germanium up-doped cylinders symmetrically located on the vertices of a regular hexagon as the outer cores. With this distribution of the outer cores, the fiber shows a symmetry of C_{6V}, and the birefringence will be avoided in the inner core[22]. Their refractive index and radius are denoted as n_2 and r_2, respectively. The distances between the centers of inner core and each outer core are the same as the distances between the centers of adjacent outer cores, which are set as Λ. The initial parameters of the fiber are n_1=1.005n_0, n_2=1.003n_0, r_0=0.4 μm, r_1=4.1 μm, r_2=5.23 μm, and Λ=25 μm.

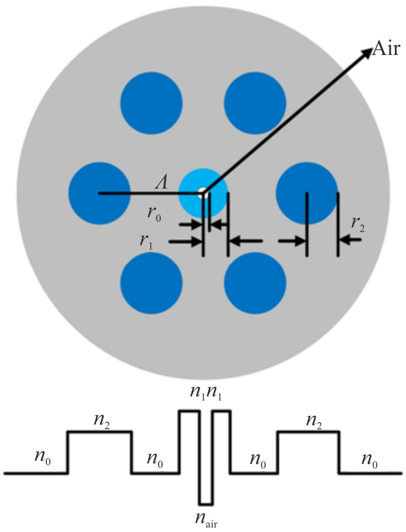

Fig.1 Cross section and equivalent refractive index distribution for the proposed DC-MSF

In order to achieve a large negative dispersion at 1 550 nm, the structure parameters of the fiber are changed one by one to obtain the relationship between the structure parameters of the fiber and the dispersion, as well as the phase matching wavelength λ_p which is the wavelength corresponding to the dispersion peak.

Fig.2 shows the variation of the dispersion with the air hole radius r_0 when other parameters are fixed. As can be seen from Fig.2, as r_0 increases, λ_p blue shifts, that is, it moves towards the shorter wavelength. At the same time, the absolute value of the dispersion increases and the negative dispersion band narrows.

Fig.3 shows the variation of the dispersion with the inner core radius r_1 when other parameters are fixed. As can be seen from Fig.3, as r_1 increases, λ_p red shifts, the absolute value of the dispersion decreases and the negative dispersion band widens.

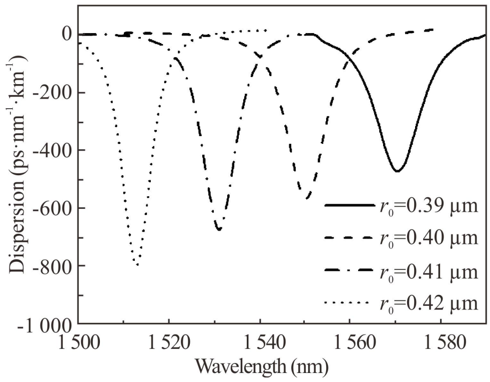

Fig.2 Dispersion curves for different r_0

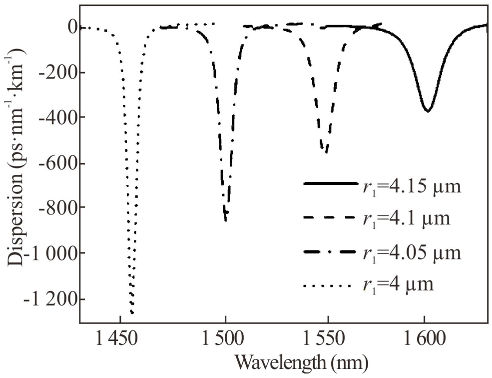

Fig.3 Dispersion curves for different r_1

Fig.4 shows the variation of the dispersion with the outer cores radius r_2 when other parameters are fixed. With the increase of r_2, λ_p moves towards the shorter wavelength. Meanwhile, the absolute value of the dispersion increases and the negative dispersion band narrows.

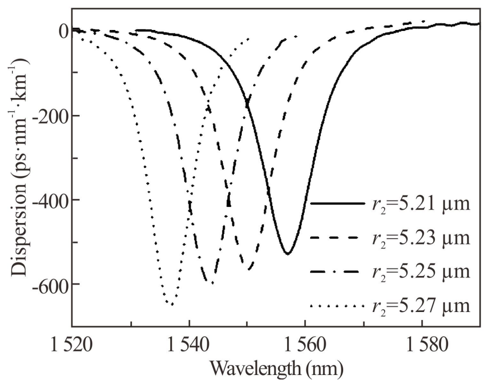

Fig.4 Dispersion curves for different r_2

Fig.5 shows the variation of dispersion with the distance Λ between the inner and outer cores when other parameters are fixed. With the increase of Λ, λ_p moves towards the longer wavelength. Meanwhile, the absolute value of the dispersion increases and the negative dispersion band narrows.

Based on the above researches, a simplified DC-MSF is obtained by optimizing the fiber parameters with n_1=

$1.005n_0$, n_2=$1.003n_0$, r_0=0.4 μm, r_1=4.1 μm, r_2=5.239 μm, Λ=31.5 μm, and the diameter of the fiber cladding is 125 μm. Fig.6 shows the effective refractive indices of its fundamental and the second order mode (left vertical axis), as well as its dispersion (right vertical axis) at different wavelengths. The mode field distributions of the two modes before and after λ_p are also presented in the insets of Fig.6. Seen from Fig.6, the λ_p of the DC-MSF has been adjusted to 1 550 nm. Before λ_p, the inner and outer core modes are the two modes with the highest refractive index, and the effective refractive index of the inner core mode is greater than that of the outer core mode. This indicates that the mode in the inner core is the fundamental mode, while the mode in the outer cores is the second order mode. However, after λ_p, the mode in the outer cores becomes the fundamental mode and the mode in the inner core becomes the second order mode, because the effective refractive index of the outer core mode is greater than that of the inner core mode[14]. At 1 550 nm, the effective refractive index of the inner core fundamental mode equals to that of the outer core mode, which means a strong coupling between the inner core and outer cores modes. This strong interaction results in sudden changes of the effective refractive indices for both the fundamental and second order mode around λ_p. As a result, a large negative dispersion as high as $-5\ 291.47\ \text{ps}\cdot\text{nm}^{-1}\cdot\text{km}^{-1}$ is achieved at 1 550 nm.

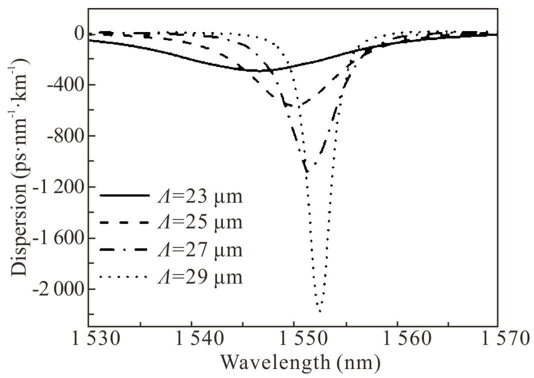

Fig.5 Dispersion curves for different Λ

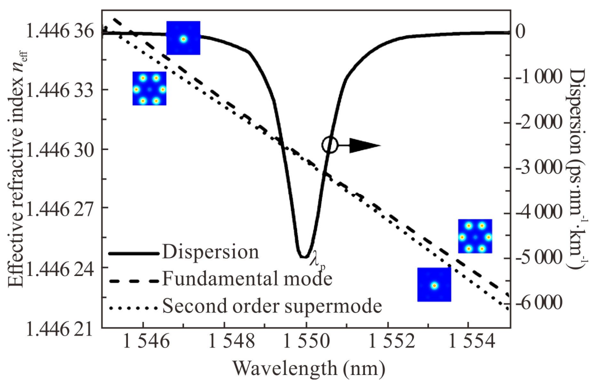

Fig.6 The effective refractive indices of the fundamental mode and the second order mode, as well as the dispersion curves

Even if the inner core is regarded as a solid cylinder without the central air hole, the normalized frequency for the inner core and the cladding V is 2.403 at 1 550 nm under the optimized parameters proposed above. The existence of the central air hole in the inner core will further reduce the V parameter, which means that the DC-MSF proposed in this paper effectively supports single mode transmission.

The coupling loss between the DC-MSF and the conventional SMF is also a very important parameter. The variations of the inner core mode field radius ω_1 of the DC-MSF, the mode field radius ω_2 of the SMF-28 and the coupling loss between two fibers with wavelength are shown in Fig.7. It can be seen that the mode field radius difference between the two fibers is less than 0.15 μm in the range of 1 520—1 580 nm. The coupling loss between the DC-MSF and the SMF-28 is only 0.137 dB at 1 550 nm.

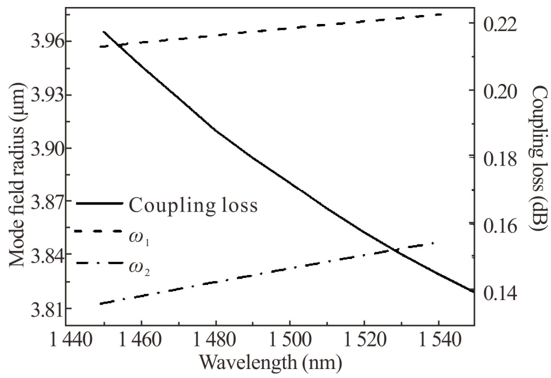

Fig.7 The mode field radii of the DC-MSF and the SMF-28 and the coupling loss between the two fibers at different wavelengths

Nonlinearity coefficient and confinement loss are also important parameters for evaluating fiber. The variations of the nonlinearity coefficient and the confinement loss of the DC-MSF with wavelength are shown in Fig.8. It can be seen from Fig.8 that the nonlinearity coefficient of the fiber decreases with the increase of wavelength. And the nonlinearity coefficient of the fiber decreases from $1.902\ \text{W}^{-1}\cdot\text{km}^{-1}$ to $1.764\ \text{W}^{-1}\cdot\text{km}^{-1}$ between 1 450—1 550 nm. The confinement loss of the fiber increases with the increase of wavelength, which is only 0.092 dB/km at 1 550 nm. The total loss of a real microstructure fiber is also caused by material absorption, structural deformation, etc, compared to which such a small confinement loss is almost negligible.

The DC-MSF can be fabricated by the method used to fabricate panda type polarization maintaining fiber. The initial fiber preform with the core can be made by the modified chemical vapor deposition process. Then, one central hole and six outer core holes are drilled according to their sizes. At last, the final preform is obtained after the six outer core holes filled with the germanium up-doped inclusions, which can be drawn to the fiber[23].

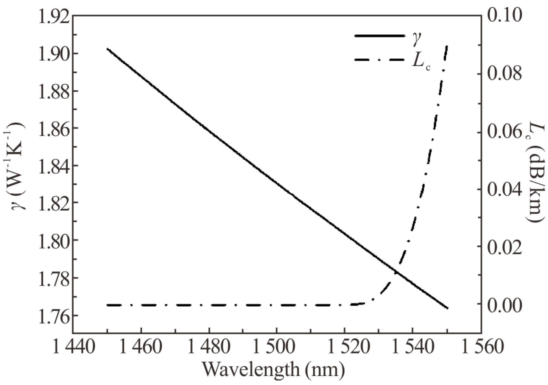

Fig.8 The nonlinearity coefficient and the confinement loss of the DC-MSF at different wavelengths

The paper proposed a simplified DC-MSF with seven cores. The mode and dispersion compensation characteristics of the DC-MSF were theoretically studied by changing its structure parameters one by one. It was found that decreasing the air hole and the outer cores radius, or increasing the inner core radius resulted in both the reduced absolute value of dispersion and red shift of the λ_p. The decrease of Λ also reduced the absolute value of dispersion. However, it caused a bule shift of the λ_p. After a time-consuming parameters optimization process, the dispersion of the DC-MSF can reach as high as −5 291.47 ps·nm^{-1}·km^{-1} at 1 550 nm, with n_1=1.005n_0, n_2=1.003n_0, r_0=0.4 μm, r_1=4.1 μm, r_2=5.239 μm, and Λ=31.5 μm. The numerical result also showed that the normalized frequency V for the inner core is less than 2.404 8, which means that single mode transmission is supported by the DC-MSF. Besides, the mode field radius mismatch between the DC-MSF and SMF-28 is less than 0.15 μm in the range of 1 520—1 580 nm, and the coupling loss between them is only 0.137 dB at 1 550 nm. The DC-MSF proposed in this paper has lots of advantages, such as single mode transmission, easy to fabricate and low coupling loss with conventional SMF, etc. It can be used in high-speed and long-distance optical communication systems.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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