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MICROSTRUCTURED FIBER AT 1550 nm WITH HIGH-BIREFRINGENCE DISPERSION COMPENSATION

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We present an elliptical-hole microstructured fiber (EHMF) consisting of two concentric cores, which can be used for dispersion compensation in a polarization maintained system. The cutoff condition for single mode operation is analyzed and we show that the fundamental mode of the proposed fiber can induce large birefringence (0.9×10^{-3}) and achieve a large negative dispersion up to -6000 ps/km·nm at 1550 nm wavelength.

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1. Introduction

Recently, microstructured Fibers (MFs) have attracted attention of research groups all over the world. MFs are fascinating because of their various novel properties, including endlessly single-mode operation [1], large and scalable dispersion and nonlinearity, surprising phenomenon of a short wavelength bend loss edge, etc. There are two kinds of guiding mechanisms for MFs: one is due to index-guiding in which the average index of core is higher than that of the periodic holey cladding; the other one is due to the photonic bandgap effects [2]. MFs in the index-guiding category are intensively studied in recent years because of its ease of fabrication compared to the bandgap-guiding category. For the purpose of this paper, we concentrate on the index-guiding MFs. We propose a microstructured fiber with elliptical air holes (EHMF) to achieve high birefringence (Hi-Bi) and large negative dispersion value so that this design is promising for dispersion compensation in a polarization maintaining optical pulse transmission system. The dispersion and birefringence properties mentioned above and the cutoff condition of fundamental modes will be explored and discussed in details.

Semi-vectorial Beam Propagation Method (SV-BPM) is used for our simulation, where the achievable effective index (n_{eff}) tolerance for SV-BPM can be as small as 10^{-9}, so that this numerical technique is capable to accurately determine properties such as birefringence and dispersion. BPM is most widely used propagation technique for modeling integrated and fiber optic photonic devices and SV-BPM can give acceptable accuracy and efficiency when applied for our EHMFs and superstructure of complex geometries. Furthermore this method includes the effects of both guided and radiating fields as well as mode coupling and conversion. In this finite-difference method, the geometry of the problem is defined entirely by the refractive index distribution. The field in the transverse plane is represented only at discrete points on a grid, and at discrete planes along the propagation direction, numerical equation is derived to relate the fields in the previous and next planes as follows [3]:

$$\frac{u_i^{n+1}-u_i^n}{\Delta z}=\frac{i}{2\bar{k}}\left(\frac{\delta^2}{\Delta x^2}+(k(x_i,z_{n+1/2})^2-\bar{k}^2)\right)\frac{u_i^{n+1}+u_i^n}{2} \tag{1}$$

$$\delta^2 u_i=(u_{i+1}+u_{i-1}-2u_i);\quad z_{n+1/2}=z_n+\Delta z/2$$

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where u_i^n denotes the field at the transverse grid *i* and longitudinal plane *n*, and assuming the grids and planes are equally separated by Δx and Δz. $k(x,z) = 2\pi n(x,z)/\lambda$ is the x-direction spatially dependent wave number, $\bar{k}$ is the average phase variation of the field which is a constant.

In this paper we investigate the birefringence properties of EHMF for different ellipticity and different rings of holes. The cutoff condition for single mode operation in EHMF is evaluated from the calculated effective V-value, and endlessly single mode structured is derived from the simulation results. Furthermore, the tailorable dispersion characteristics are analyzed and a novel EHMF superstructure is proposed to obtain super large negative dispersion value at 1550 nm.

2. Results and analysis

2.1 Birefringence properties

Conventional circularly symmetric optical fibers do not maintain the polarization state of the guided mode along the fiber length. Highly birefringent (Hi-Bi) fibers (in which large birefringence is induced by shape or stress) are fabricated to maintain the two polarization states during the transmission. The birefringence is defined as: $B=n_x-n_y$, where n_x and n_y are the modal n_{eff} values of the two orthogonal states (HE_{11}^x and HE_{11}^y) of the fundamental mode. In MFs, the sixfold symmetry of the fibers guarantees the degeneracy of the fundamental modes. But birefringence can be produced intentionally by local elongation of the core region [4]. In EHMFs, the birefringence is from the global origin – elliptical cladding holes, rather than the local effects.

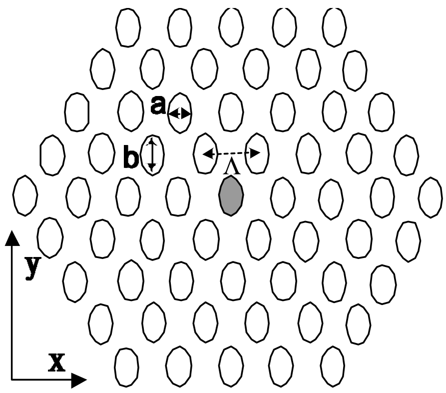

Fig. 1. The scheme of a periodic microstructure: *a* – elliptical-hole diameter in x direction, *b* – elliptical-hole diameter in y direction, Λ – hole-to-hole distance.

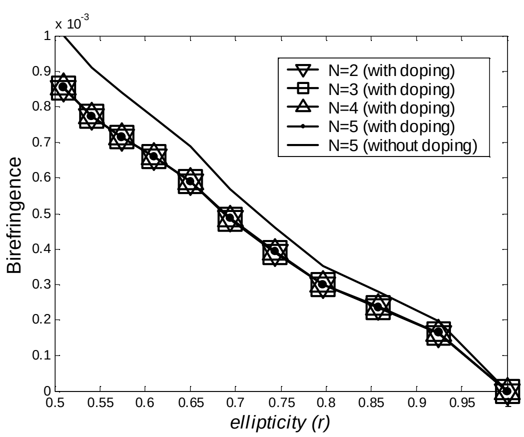

Fig. 2. The birefringence of elliptical holey microstructured fiber versus different ellipticity is shown in Fig. 1. Number of air-hole rings is increased from 2 to 5; the dashed line is the birefringence for a 5 rings structure without doping in the centre.

The cross-section of a four-ring EHMF structure is shown in Fig. 1, the grey region is doped, with a refractive index 1.462. Four parameters that define the structure are: the number of air-hole rings **N**, the diameters of the air holes (*a* and *b*) in horizontal and vertical directions and the center-to-center distance between adjacent air holes (Λ). The air-filling fraction for the elliptical structure is kept constant ($A_{elliptical} = \pi ab = \pi 0.25\Lambda^2$, Λ=2.3 μm) and ellipticity is varied in our birefringence calculation at 1550 nm. Birefringence value as large as 0.9×10^{-3} is obtained as shown in Fig. 2, which is promising for polarization maintaining applications. The birefringence curve exhibits the same behavior for the number of air hole rings less than five and we can expect that the same behavior when the number of air hole rings increases. This conclusion is logic since the outer rings of air holes less affect the mode as the number of air hole rings increases.

2.2 Cutoff conditions

Waveguide properties of conventional standard fiber are often parameterized by the so-called V parameter, which gives the cutoff condition for single mode operation. The effective V for MFs was discussed in the previous work on endlessly single-mode properties [5]. N. A. Montensen *et al.* also derived more straightforward results, which are applicable for all structures with constant lattice pitch [6]:

$$V_{eff}^{MF} = \frac{2\pi\Lambda}{\lambda}\sqrt{n_{eff}^2 - n_{cl\_eff}^2} \qquad (2)$$

where n_{eff} is the effective index of the fundamental mode and n_{cl_eff} is the effective index of the microstructured cladding, which can be calculated from the fundamental space-filling mode in the periodic air-hole lattice. The cutoff occurs at $V_{eff} = \pi$, and this result has been proven to be applicable regardless of the air-hole structures in the periodic cross-section. Fig. 3 shows that the V_{eff} curve for EHMFs with different air-filling fractions converges to a finite value as the wavelength decreases, the so called endlessly single mode operation is achievable in EHMFs with the condition: the air-filling fraction (for a hexagonal unit cell, air-filling fraction = $A_{elliptical}/A_{unitcell} = 2\pi ab/\sqrt{3}\Lambda^2$) is less than 0.45.

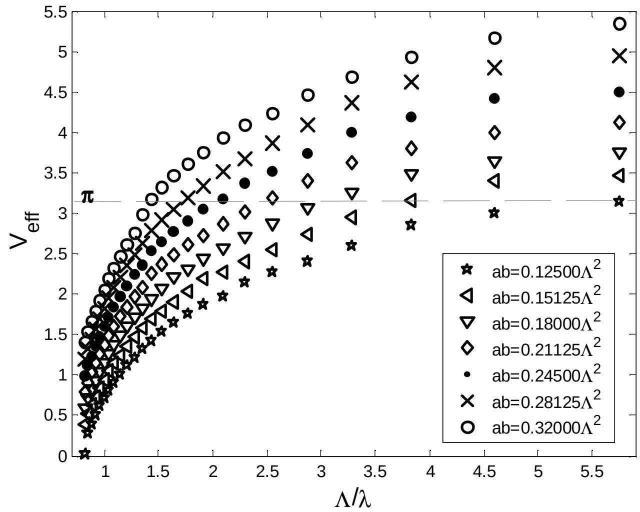

Fig. 3. Effective-V for structures shown in Fig. 1, with different air-filling fraction: $A_{ellip}=\pi ab$, the ellipticity is fixed ($r=0.5$).

2.3 Dispersion properties

The group velocity dispersion or simply the dispersion of MFs can be directly calculated from the model effective index n_{eff} of the fundamental mode over a range of wavelengths [7].

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

where c is the velocity of light in a vacuum and λ is the operating wavelength. Since the effective index n_{eff} of MFs is a strong function of wavelength such that the change of dispersion with respect to wavelength might be scalable to extremely small or large values. By varying the ellipticity of the elliptical air holes, flattened waveguide dispersion can be achieved in a wide range of wavelength: λ=1.3~1.6 μm with a very small dispersion slope (<0.01 ps/km/nm^2) over the entire flat dispersion region as shown in Fig. 4, which is potentially of great interest for ultrabroad-band WDM applications [8].

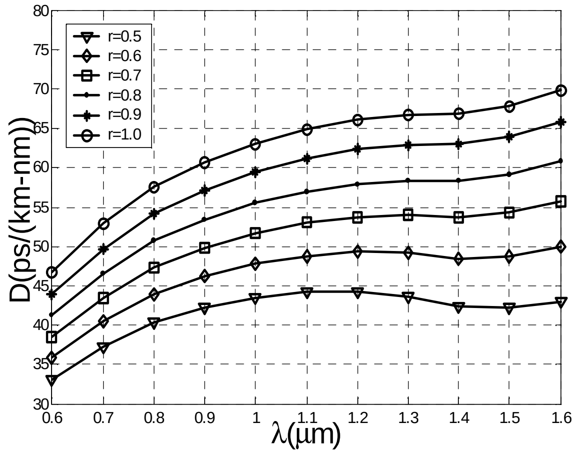

Fig. 4. Waveguide dispersion for four-ring EHMFs with different ellipticity r. (Λ=2.3 μm).

Fiber with a large normal dispersion value at 1550 *nm* can be very useful for compensating anomalous dispersion contributed by transmission fibers currently deployed in communication systems. Thyagarajan *et al*. [9] have shown that a concentric core dispersion compensation fiber (DCF) design that is capable to provide dispersion values about -5000 ps/km·nm. Furthermore, a concentric core dispersion compensation microstructured fiber (DC-MF) was proposed by the authors of this paper previously to achieve a dispersion value as negative as -6000 ps/km·nm at 1.55 μm [10].

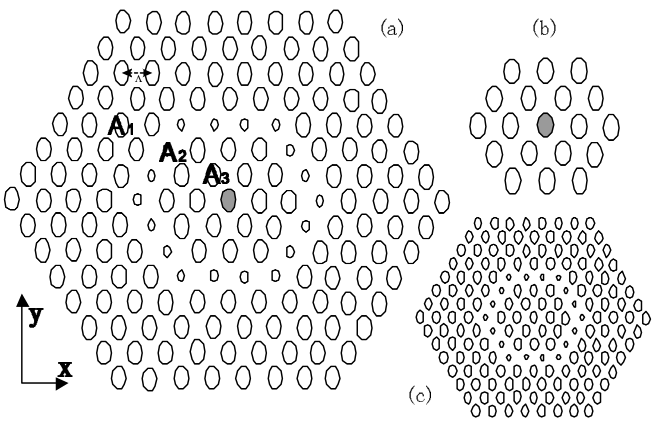

Fig. 5. Schematic of the way in which the transverse dielectric microstructure is constructed: (a) superstructure: A_1 – elliptical-hole area in the outer cladding ($A_1 = \pi 0.1764\Lambda^2$), A_2 – elliptical-hole area in the outer core ($A_2 = \pi 0.005\Lambda^2$), A_3 – elliptical-hole area in the inner cladding and inner core ($A_3 = \pi 0.125\Lambda^2$), Λ – hole-to-hole distance, ellipticity of all holes are the same: r=0.5, (b) inner-core waveguide structure, (c) outer-core waveguide structure.

In order to deploy this concept into the Polarization-Maintaining transmission system, EHMF with two ring-shaped cores is proposed and the cross-section of the EHMF design is shown in Fig. 5. The inner core is a doping area with $n_{innercore}$=1.462, the outer core is composed of pure silica ring. The air hole region is characterized by hole-diameter in x and y directions (*a*, *b*), and pitch (Λ). The major axis is directed along the y-axis, and we define the ellipticity $r=b/a$. The refractive index profile of the proposed EHMF design is shown schematically in Fig. 6. It consists of two concentric cores: the inner core with a large refractive index difference and the outer core with a small difference. The two effective core indices are chosen for the two cores to support single azimuthally symmetric propagation modes at 1.55 μm independently. During the design process, we can separate the proposed superstructure into two structures and treat them independently. By calculating the effective index of the fundamental mode for the two separated structures, change the hole size or doping factors until they have a crossing near λ=1.55 μm. Effective mode indices as a function of wavelength are plotted in Fig. 6 for the inner core and outer core respectively. It is clearly shown that the two curves for inner core mode and outer core mode cross each other around λ=1.55 μm. This crossing of the inner and outer core index curves suggests a pair of super-modes. From reference [11], we find that the two supermodes are symmetric, thus analyzing one is sufficient to illustrate the dispersion compensation characteristics of such a design. Zooming into the wavelength region near cross-point and calculating the fundamental mode of the superstructure we can observe the coupling of mode from inner-core to outer-core. The behavior of the fundamental mode is the same as the one in [9]: at wavelength before the crossing point, the field is essentially confined in the inner core, after this crossing point, most of the fundamental mode field is coupled to the outer core. This abrupt change in effective index for our super-mode will give rise to a very large dispersion value, which is calculated as the second derivative of the effective index curve according to Equation 4. Dispersion for the proposed waveguide is shown in Fig. 8 while more effective mode indices are calculated near 1.55 μm to give a mode smooth dispersion curve. It shows dispersion value at λ = 1.55 μm is nearly -6000 ps/km·nm. By combining the novel dispersion characteristic and the large local birefringence induced from the elliptical holes (which is roughly a seven-ring EHMF structure, the birefringence at 1.55 μm is around 0.9×10^{-3}), we may expect this structure is promising for dispersion compensation application in a polarization maintaining optical system.

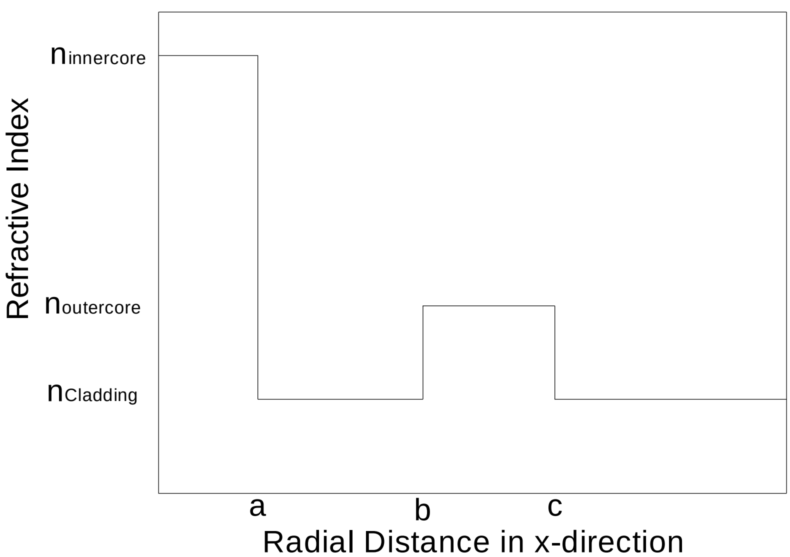

Fig. 6. Refractive Index Profile (RIP) of the proposed dispersion compensation microstructured fiber long the radial distance in x-direction.

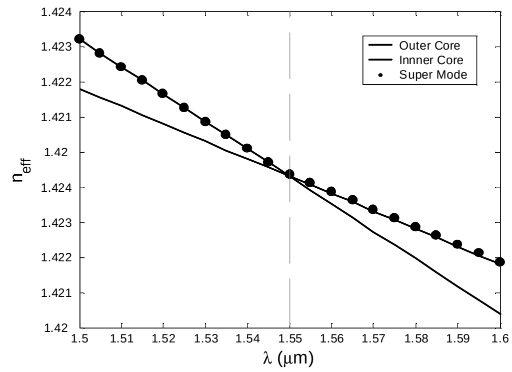

Fig. 7. Variation of the effective mode index with wavelength. Solid curve corresponds to the effective mode index of the inner core (doped), the dashed curve corresponds to the effective mode index of the outer core (pure silica ring), and the dotted curve corresponds to the effective index of the superposition mode.

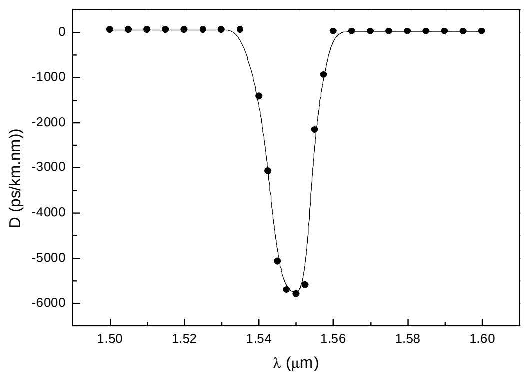

Fig. 8. Variation of chromatic dispersion with wavelength for the dispersion compensation EHMF structure shown in Fig. 4.

3. Conclusions

In summary, we have analyzed various optical properties of EHMFs. Dependence of birefringent (~0.9×10^{-3}) characteristics on ellipticity of the air holes as well as the number of air hole rings is analyzed. Cutoff condition for EHMFs is explored by varying the air-filled fraction. We also proposed a dispersion compensation EHMF design that exhibits very large negative dispersion (-6000 ps/km·nm) at 1550 nm wavelength. Such fiber has great potential for dispersion compensation purpose in polarization maintaining systems. However, the wavelength range for such dispersion compensation fiber design is around 15~20 nm. The fiber increases the wavelength range of large dispersion value that remains a challenge for further exploration.

References

[1] J. C. Knight, T. A. Birks, P. St. J. Russel, Opt. Lett. **21**, 1547 (1996).
[2] T. A. Birks, P. J. Robert, P. St. J. Russell, Electron. Lett. **31**, 1941 (1997).
[3] R. Scarmozzino, R. M. Osgood, Jr., J. Opt. Soc. Amer. A, **8**, 724 (1991).
[4] M. J. Steel, R. M. Osgood, Jr., Opt. Lett. **26**, 229 (2001).
[5] J. C. Knight, T. A. Birks, P. St. J. Russell, J. Opt. Soc. Am. A, **15**, 748 (1998).
[6] N. A. Mortensen, J. R. Folkenberg, M. D. Nielsen, K. P. Hansen, Opt. Lett. **28**, 1879 (2003).
[7] G. Agrawal, Nonlinear Fiber Optics. New York: Academic, (1995).
[8] T. M. Monro, D. J. Richardson, N. G. R. B roderick, IEEE J. Lightwave Technol. **17**, 1093 (1999).
[9] Thyagarajan, R. K. Varshney, P. Palai, A. K. Ghatak, I. C. Goyal, IEEE Photon. Technol. Lett. **8**, 1510 (1996).
[10] X. Yu, M. Yan, P. Shum, C. Lu, Y. Zhu, H. T. Hui, Proceeding of International Conference on Optical Communications and Networks, Bangalore, India, (2003).
[11] U. Peschel, T. Peschel, F. Lederer, Appl. Phys. Lett. **67**, 2111 (1995).