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Design on a highly birefringent and highly nonlinear tellurite ellipse core photonic crystal fiber with two zero dispersion wavelengths

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ABSTRACT

In this paper, a new photonic crystal fiber (PCF) with two zero dispersion wavelengths (ZDWs) based on the tellurite ellipse core is designed. The air holes in the cladding region have a V-shape distribution, which can increase the birefringence. By adjusting the size of tellurite ellipse core, different birefringence and nonlinearity coefficient can be obtained, and the dispersion can also be tailored. When the long axis of the tellurite ellipse core is 0.5 μm and the short axis is 0.25 μm, the birefringence of 7.66×10^{-2} and nonlinearity of 3400 W^{-1} km^{-1} around 1550 nm are obtained. This PCF structure provides a way to get the high birefringence and nonlinearity at the same time, which can find extensive applications in the optical communication and sensor system.

1. Introduction

Photonic crystal fibers (PCFs) have attracted great attentions due to their unique optical characteristics, such as high birefringence, the tailored dispersion, and high nonlinearity [1–3]. PCFs have extensive applications in the fields of optical fiber sensing, optical communication, and nonlinear fiber optics [4,5].

PCF has a high flexibility in the structure design. By destroying the symmetry of the cladding structure or the core shape, the high birefringence and tailored dispersion can be easily achieved. Yue et al. obtained a birefringence of 10^{-2} magnitude by using the ellipse holes in PCF cladding, but there is nothing improvement of the nonlinearity coefficient [6]. Hu et al. designed a PCF by introducing a ellipse hole defect in the core and obtained a birefringence of 10^{-3} magnitude, but the nonlinearity coefficient is small [7]. Xia et al. studied a PCF of V-type distributing cladding holes and obtained a birefringence of 10^{-2} magnitude and a nonlinearity of 300 $W^{-1} \cdot km^{-1}$ around 1550 nm [8]. Liang et al. got a birefringence of 10^{-3} magnitude by introducing a row of ellipse holes in the core [9]. Cao et al. designed a PCF by introducing two ellipse holes in the core and obtained a birefringence of 10^{-2} magnitude and a nonlinearity coefficient of only 34 W^{-1} km^{-1} [10]. Because of being fabricated by silica glass, which has small refractive index and low nonlinear-index coefficient, the conventional birefringent PCFs are difficult to achieve high birefringence degree and high nonlinearity coefficient simultaneously.

Recently, because of the progress on the new fabrication techniques, lots of interests have been concentrated on the non-silica glasses with wide infrared transmission windows, such as tellurite, fluoride, and chalcogenide glasses. Tellurite glass has a higher refractive index and a higher nonlinear-index coefficient than that of silica glass by at least one order of magnitude. Because of the huge relative index difference caused by the tellurite glass core, the PCFs with the tellurite sub-wavelength core can form a very small effective mode area, and show a higher Kerr nonlinear coefficient. Moreover, the tellurite glass has good chemical and thermal stability [11]. By proportionally doping the rare earth element, the working temperature range can be enlarged, and the damage threshold of tellurite glasses can be greatly improved, which will have an important applications in the high-power Raman amplifiers or lasers. Thus, the optical characteristics and applications of tellurite glass have become the new research hotspot [12–17].

In this paper, we design a new PCF based on tellurite ellipse core and V-shape distribution air holes. Due to the huge refractive index difference between the tellurite ellipse core and the cladding air holes, the optical field being almost confined in the core, and the PCF obtains a high nonlinearity coefficient. Meanwhile, because the core is ellipse structure, the HE^{x}_{11} and HE^{x}_{11} mode fields extend to *x*-axis and *y*-axis, and form a high birefringence. The air holes with V-shape distribution can also enhance the index difference between *x*-axis and *y*-axis to increase the birefringence. Due to the tellurite

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ellipse core, the PCFs can obtain the high birefringence degree and high nonlinearity coefficient at the same time. We also analyze the dispersion characteristic of the PCF, which has two zero dispersion wavelengths (ZDWs).

2. Theory model

Finite element method (FEM) is used to analyze the PCF. The principle of FEM based on the Maxwell formula and the electromagnetic wave equation is as follow

$$\nabla \times \left[\frac{1}{\varepsilon_r}\nabla \times H\right] = \left[\frac{\omega}{c}\right]^2 \mu_r H \tag{1}$$

where H is the magnetic field intensity, ω is angular frequency, c is the light velocity, ε_r and μ_r are the dielectric constant and magnetic conductivity, respectively. In order to obtain more exact solution, the boundary condition of anisotropy perfectly matched layer (PML) is applied in the modeling and solution of equation. By high order algebraic solution, the propagation constant β and effective refractive index n_{eff} of fundamental mode can be obtained directly, and other optical fiber parameters can be obtained from n_{eff}.

The waveguide dispersion of fundamental mode can be defined as

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

Far away from the resonances of medium, the refractive index of tellurite glass can be approximated by the Sellmeier equation

$$n^2(\lambda) = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3} \tag{3}$$

where B_1, B_2, B_3, C_1, C_2, and C_3 are the material constants. For the tellurite glass T2, the parameters are 0.71, 1.28, 1.28, 9.85×10^4 nm^2, -3×10^4 nm^2, and -3×10^4 nm^2 , respectively.

The material dispersion of tellurite glass T2 is

$$D_M = -\frac{\lambda}{c}\frac{d^2 n(\lambda)}{d\lambda^2} \tag{4}$$

The total dispersion of PCFs is

$$D = D_W + D_M \tag{5}$$

The strength of fundamental mode birefringence is defined by a dimensionless parameter

$$B_m = \left|\mathrm{Re}(n_{eff}^x) - \mathrm{Re}(n_{eff}^y)\right| \tag{6}$$

where n_{eff}^x and n_{eff}^y are the refractive indices of fundamental mode for the two orthogonally polarized states.

The effective mode area A_{eff} is defined as

$$A_{eff} = \frac{p\left[\iint |E(x,y)|^2\,dx\,dy\right]^2}{\iint |E(x,y)|^4\,dx\,dy} \tag{7}$$

here, $E(x, y)$ is the electric field transverse distribution of the fundamental mode.

The nonlinear parameter γ is defined as

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \tag{8}$$

here, λ is wavelength. n_2 is nonlinear-index coefficient of tellurite glass T2 ($n_2 \approx 5.9 \times 10^{-19}$ m^{-1} W^{-1} in Ref. [13]).

3. PCF structure and simulation result

The PCF structure designed is shown in Fig. 1 (a), where the red circle is the central ellipse core of tellurite glass T2 ($77TeO_2$–$10Na_2O$–$10ZnO$–$3PbO$ [12]), which has the refractive index n = 2.078. The substrate material is the silica glass. The air holes with V-shape distribution in the cladding have different size along the x-axis and y-axis, which can increase the relative index difference between the x-axis and y-axis.

The structure parameters are as follows: the pitch Λ = 1.2 μm, the big hole radius R = 0.55 μm, the small hole radius r = 0.25 μm, the long axis radius of the tellurite ellipse core is a, and the short axis radius is b. Here, we designed three sizes of ellipse core: (1) Fiber 1, a = 0.5 μm, b = 0.25 μm; (2) Fiber 2, a = 0.6 μm, b = 0.3 μm; (3) Fiber 3, a = 0.8 μm, b = 0.4 μm.

As seen from Fig. 1(b) and (c), due to the huge relative index difference between the tellurite ellipse core and the cladding air holes, it can be seen that the light is mainly confined in the core region. For HE_{11}^y mode, more light energy extends to y-axis than that of HE_{11}^x mode. This stretching degree difference induces the relative index difference between the x-axis and y-axis, which leads to bigger birefringence degree.

Fig. 2 shows the birefringence curve of the designed PCFs. For all PCFs, as the wavelength increases, the birefringence increases firstly, reaches a maximum at the long wavelength region, then begins to decrease. For Fiber 1, Fiber 2, and Fiber 3, the maximal birefringences of 8.24×10^{-2}, 9.56×10^{-2}, 1.19×10^{-1} at the wavelengths of 1900 nm, 2500 nm, 3270 nm are achieved, respectively. At the short wavelength side, PCF with the smaller ellipse core obtains the bigger birefringence at the same wavelength because the smaller ellipse core can confine the light field more tightly to induce a bigger index difference between x-axis and y-axis. At the wavelength of 1550 nm, the birefringences of Fiber 1, Fiber 2, and Fiber 3 are 7.66×10^{-2}, 6.53×10^{-2}, 4.18×10^{-2}.

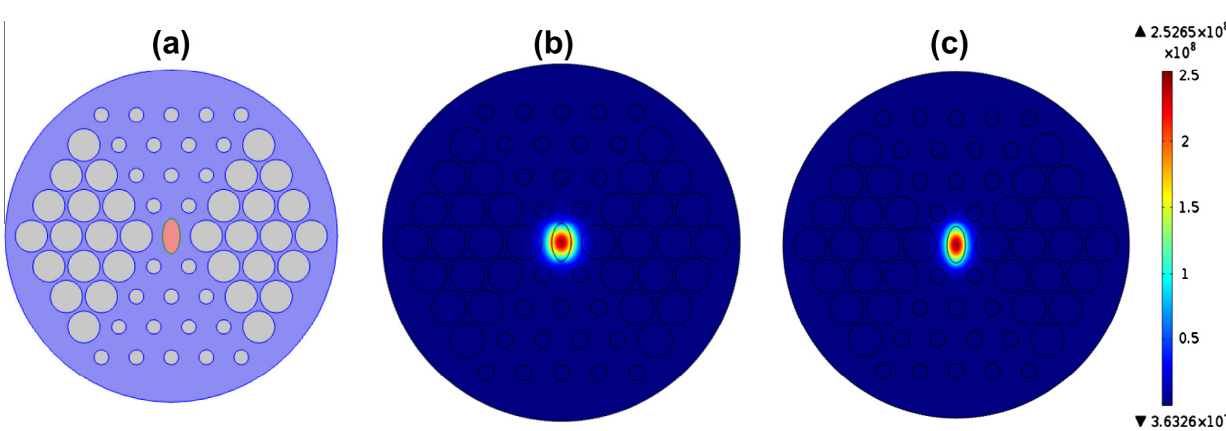

Fig. 1. PCF structure and fundamental mode field.