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Two Modes Near-zero Dispersion Flattened Photonic-crystal Fiber

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Abstract
Through massive computer simulation, a photonic-crystal fiber with seven air-hole defects as fiber core is proposed by using the software CUDOS based on the multipole method. In the given fiber parameters, the photonic-crystal fiber's fundamental and second modes are dispersion flattened simultaneously in the communication O wave band, S wave band and C wave band. It is important in the relative application of multi-mode dispersion flattened photonic-crystal fiber.

Key words: Photonic-crystal fiber; Double-mode dispersion flatten; Multipole method.

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INTRODUCTION

OCIS codes: (060.2400) Fiber properties

The concept of Photonic Crystal Fiber (PCF) was first given by Russell et al in 1992. With multiple inclusions arranged about a core—PCF have many remarkable properties such as variety adjustable dispersion and highly nonlinearity and single-mode operation over a wide range of wavelengths. Such properties have been applied in many areas. Contrasts with the general fibers, PCF have advantages in parameter control design. With different arrangement and the different diameter of the air hole, many special properties PCF which used in various special applications can be designed. For example, dispersion flattened PCF has been designed based on the variety adjustable air hole shape, air hole radius and ditch (Hoo, Jin, Ju, & Ho, 2004; Yan et al., 2013; Wang & Wang, 2011; Liu et al., 2007; Gong, Luan, Hu, & Shum, 2011; Lee, Ha, Park, Kim, & Oh, 2012; Ji & Liu, 2013; Liang, Li, & Feng, 2015; Klimczak et al., 2014; Wen, Ebendorffheidepriem, Monro, & Afshar, 2011; Saitoh & Koshiba, 2004), The dispersion flattened PCF play an important role in nonlinear optics. Dispersion flattened PCF can be used in the following areas such as supercontinuum generation (Liang et al., 2015; Klimczak et al., 2014; Wen et al., 2011; Saitoh & Koshiba, 2004; Zhang & Li, 2016; Sukhoivanov et al., 2014; Artłomiej & Iwicki, 2017); wavelength conversion, and variety high quality optical waveguide components used in integral optics. Now, the requirement is increase for the fiber used in communication, the fiber dispersion is not only flattened, but also the fiber's zero dispersion wavelength is just within the vicinity of the communication wavelength. In modern optical telecommunication system, data transmission with a dense wavelength division multiplexing technique is effective for large capacity networks. However, four-wave mixing effects and chromatic dispersion restrict the wavelength region available. By using broadband dispersion-flattened fiber, the accumulated dispersion difference in the telecommunication can be reduced. So the broadband ultra-flattened dispersion fiber is very important for data transmission. However, it is difficult to achieve a small dispersion over a wide wavelength range with conventional fiber.

There are many papers which have discussed the design of dispersion flattened PCF (Hoo et al., 2004; Yan et al., 2013; Wang & Wang, 2011; Liu et al., 2007; Gong et al., 2011; Lee et al., 2012; Ji & Liu, 2013). A PCF with ultra-flattened near-zero chromatic dispersion based on Topas cyclic olefin copolymer is designed. The dispersion values are between ±0.5 ps/km/nm over the wavelength 1.1–1.7 μm in reference (Wang & Wang, 2011). A double-cladding PCF is proposed in reference (Liu et al., 2007). The inner cladding of this optical fiber is composed of elliptical air holes. The dispersion fluctuation is 0.6–1.0 ps/nm/km in all S, C and L band. In reference (Gong et al., 2011), a PCF is designed with a large normal dispersion (352 ps^2/km) and the dispersion varies less than 3% from 1400 to 1700 nm wavelength range. Sejin et al introduced hollow ring defect structure in PCF design, a PCF with nearly flat zero dispersion of D=0±0.51 ps/nm km was obtained in the wavelength range of 1.44–1.61 μm in reference (Lee et al., 2012). We also have discussed the dispersion flattened in reference (Ji & Liu, 2013).

In this paper, the study is focus on how to chosen the parameter of PCF, so that the PCF is dispersion flattened in the nearby of zero dispersion wavelength. Usually, the dispersion flattened always means fundamental mode dispersion flattened. In this paper, a photonic-crystal fiber is designed by using the software CUDOS based on the multipole method. In this PCF, fiber core is the center's seven air-hole defections, as show in figure 1. The study shows that the PCF's fundamental mode and second mode are dispersion flattened at the same time in several communication wavelength bands.

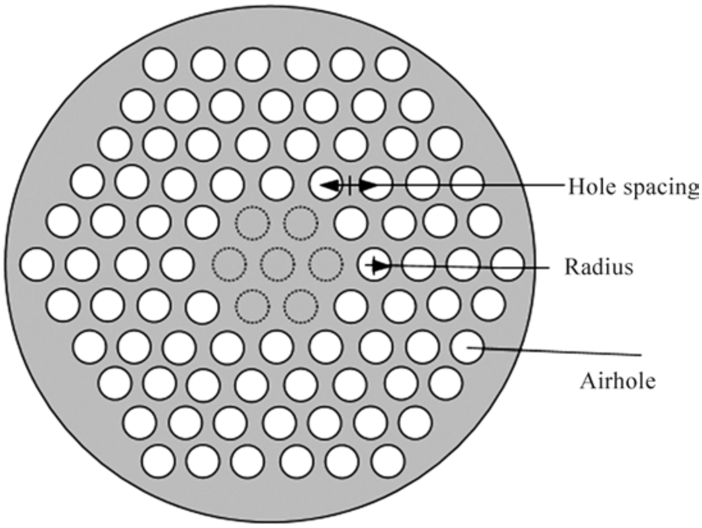


Figure 1
PCF With Seven Air-Hole Defections as Fiber Core

1. MULTIPOLE METHOD

To accurate modeling the PCF, lots of methods has been developed, such as the plane-wave expansion method, Hermite–Gaussian functions expansion method, beam propagation method and etc. Multipole method is given by T. P. White et al. (White, McPhedran, Botten, Smith, & Martijn de Sterke, 2001; White et al., 2002). Resemble as other expansion methods, multipole method expand optical field as a set of normalized functions.

The electric fields ε is expressed as a complex as follow:

$$\vec{\varepsilon}(r,\theta,z,t)=\vec{E}(r,\theta)\exp[i(\beta z-\omega t)]$$

Where, β is the propagation constant along the fiber core, z direction. In the vicinity of the cylindrical inclusion, electric field express in Fourier-Bessel series:

$$E_z=\sum_m[A_m^{El}J_m(k_\perp^e r_l)+B_m^{El}H_m^1(k_\perp^e r_l)]\exp(im\theta_l)$$

Where J_m and H_m^1 are the usual Bessel function of order m and the Hankel function of the first kind of order m, respectively. $k_\perp^e=(k^2n_e^2-\beta^2)^{1/2}$. Coefficients A_m^E and B_m^E can be obtained by using the electric and magnetic field boundary condition in the boundary of the air hole.

The β could be get by using the CUDOS, which is based on the multipole method. Then the dispersion parameter $D(\lambda)=-\frac{1}{2\pi c}\left(2\lambda\frac{d\beta}{d\lambda}+\lambda^2\frac{d^2\beta}{d\lambda^2}\right)$.

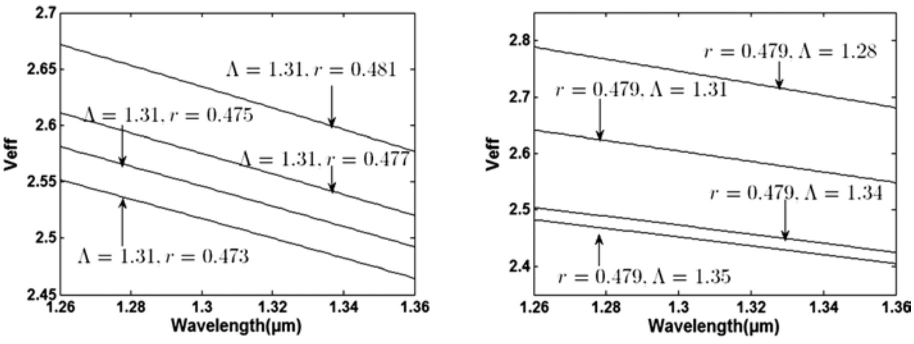
2. NUMERICAL CALCULATION AND ANALYSIS

PCF characteristic is determined by its structure parameters. That the dispersion depends on PCF structure parameter has been studied in several communication wavelength bands in this paper. The study result shows that, there is no simultaneously dispersion flattened in fundamental mode and second mode in the visible wavelength band and its vicinity. But there is a simultaneously dispersion flattened in fundamental mode and second mode at some special PCF structure parameters in O wavelength band (1260nm-1360nm), S wavelength band (1460nm-1530nm) and C wavelength band (1530nm-1565nm).

2.1 Simultaneously Dispersion Flattened in Fundamental Mode and Second Mode at O Wavelength Band (1260nm-1360nm)

Based on intensively data simulation, we have found that there is dispersion flattened in fundamental mode and second mode simultaneously in O wavelength band (1260nm-1360nm) at the following PCF structure parameters.

Figure 2 shows the PCF effective refraction V_{eff} variation with wavelength in different structure parameters. In figure 2a, the distance of air hole center, ditch Λ=1.31μm, the air hole radii, r are 0.473μm, 0.475μm, 0.477μm and 0.481μm respectively; in figure 2b, the air hole radius, r=0.479μm, the distance of air hole center, ditch Λ, are 1.28μm, 1.31μm, 1.34μm and 1.35μm respectively.

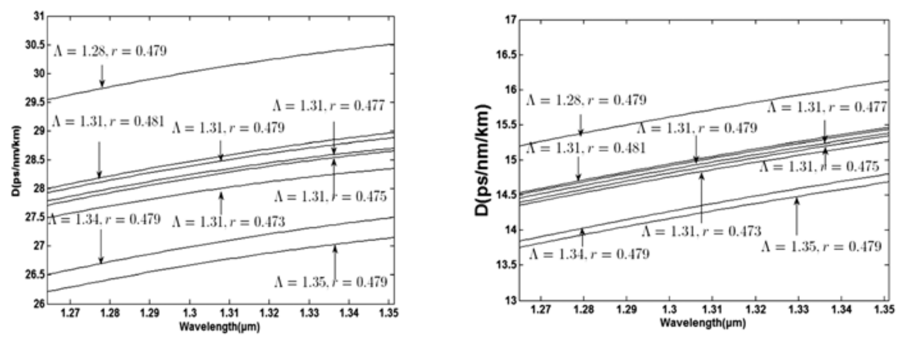


(a)Λ=1.31μm, various r　　(b)r=0.479μm,various Λ

Figure 2
Effective Refraction Veff Variation Corresponding with Wavelength

Figure 2 shows that the effective refraction index V_{eff}>2.405 in the given PCF parameters. That means that there is fundamental mode and second mode exist simultaneously in the PCF in those parameter regions.

Figure 3 shows the dispersion parameter D variation with the wavelength at some structure parameters. Figure 3a shows the fundamental mode dispersion parameter variation with the wavelength when air hole distance, ditch Λ=1.31μm, air hole radii are 0.473μm, 0.475μm, 0.477μm,and 0.481μm respectively; air hole radius r=0.479μm, air hole distance, ditch Λ are 1.28μm, 1.31μm, 1.34μm, and 1.35μm respectively. Figure 3b shows the second mode dispersion parameter variation with the wavelength at the same structure parameters. Figure 3a and figure 3b show that the dispersion coefficient D is increase with the wavelength increase. In figure 3, fluctuation of the dispersion parameter D is smaller than 1$ps/nm/km$ in every curve for fundamental mode and second mode. This means that we have found the PCF, which fundamental mode and second mode dispersion are flat simultaneously in communication O wavelength band.

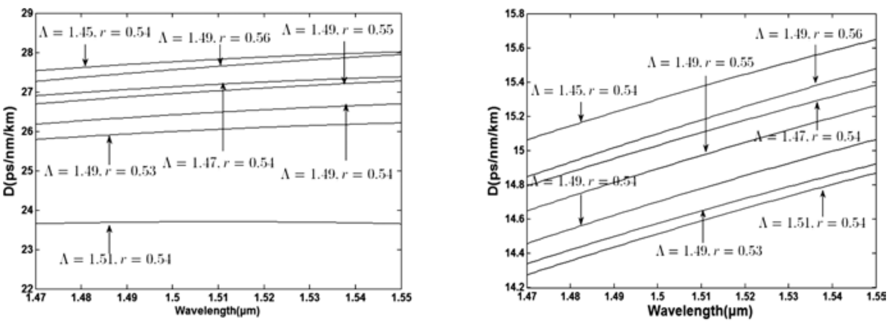


(a)Fundamental mode　　(b) Second mode

Figure 3
Dispersion Parameter D Variation Corresponding With the Wavelength at O Band

2.2 Dispersion Flattened in Fundamental Mode and Second Mode at S and C Communication Wavelength Band Simultaneously

Figure 4 shows the dispersion parameter D variation with the wavelength at some structure parameters at S and C communication wavelength band. Figure 4a shows the fundamental mode dispersion parameter variation with the wavelength when air hole distance, ditch Λ=1.49μm, air hole radii are 0.53μm, 0.54μm, 0.55μm,and 0.56μm respectively; air hole radius r=0.54μm, air hole distance, ditch Λ are 1.45μm, 1.47μm, 1.49μm,and 1.51μm respectively. Figure 4b shows the second mode dispersion parameter variation with the wavelength at the same structure parameter. Figure 4a shows that the fundamental mode dispersion parameter is increases with the wavelength increase, but the increment is very small. The dispersion parameter minimum variation is 0.5*ps*/*nm*/*km* when Λ=1.51*μm* *r*=0.54*μm*. The dispersion parameter maximum variation is 0.7*ps*/*nm*/*km* when Λ=1.49*μm* *r*=0.56*μm*. Figure 4b shows that the second order mode dispersion parameter is increases with the wavelength increase too. The increment is about 0.65~0.90*ps*/*nm*/*km*. This means that the PCF's fundamental mode and second order mode dispersion are flattened simultaneously at communication wavelength band S (1460nm-1530nm) and C (1530nm-1565nm).



(a)Fundamental mode (b)Second mode

Figure 4
Dispersion Parameter D Variation Corresponding With the Wavelength at C and S Band

Result show that when air hole radii are between 0.473μm -0.481μm, air hole center distance are between 1.28μm -1.35μm, the dispersion parameter D variation is smaller than 1*ps*/*nm*/*km* for fundamental mode and second mode in communication O wavelength band. When air hole radius is 0.54μm, air hole center distance is 1.51μm, the fundamental mode dispersion parameter is between 23.7±0.1 ps/km/nm, the second mode dispersion parameter is between 14.3-14.7 ps/km/nm over the wavelength 1.47μm–1.55μm. Further more, contrast with reference (Wang & Wang, 2011; Liu et al., 2007; Gong et al., 2011; Lee et al., 2012; Ji & Liu, 2013), the fabrication of this fiber is easier because the design using the same air hole shape.

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