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Chiral photonic crystal fibers with single mode and single polarization

She Li, Junqing Li*

Department of Physics, Harbin Institute of Technology, 92 Western Dazhi, Harbin 150001, China

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Chiral photonic crystal fiber (PCF) with a solid core is numerically investigated by a modified chiral plane-wave expansion method. The effects of structural parameters and chirality strength are analyzed on single-polarization single-mode range and polarization states of guided modes. The simulation demonstrates that the chiral photonic crystal fiber compared to its achiral counterpart possesses another single-circular-polarization operation range, which is located in the short-wavelength region. The original single-polarization operation range in the long-wavelength region extends to the short wavelength caused by introducing chirality. Then this range becomes a broadened one with elliptical polarization from linear polarization. With increase of chirality, the two single-polarization single-mode ranges may fuse together. By optimizing the structure, an ultra-wide single-circular-polarization operation range from 0.5 μm to 1.67 μm for chiral PCF can be realized with moderate chirality strength.

1. Introduction

Recently, the conventional optical communication technology using single-core single-mode fiber almost approaches to its physical limit of transmission capacity of order of magnitude of $\sim$100 Tb/s caused by Shannon effect, optical nonlinearity, fiber fuse effect, as well as the limitation of optical amplifier bandwidths [1]. The development of novel optical communication technology such as spatial division multiplexing (SDM), mode division multiplexing (MDM), even polarization division multiplexing (PDM) have become one of the hotspots in the academic community. Intensive research has been implemented on multi-core fibers (MCFs), few-mode fibers (FMFs) [2] and fibers employing optical angular momentum (OAM) [3]. All of these technologies are dedicated in providing some independent channels to increase the transmission capacity and sharing the existing platform for amplification and dispersion compensation. It is clear that the main trend is to develop new type of fibers applying novel structures or new materials. As one of the candidates, chiral materials can be used to fabricate the novel fibers mentioned above [4–8]. In fact, there are many issues being worthy exploring on variety of chiral fibers. In this paper, we confine ourselves to the fiber consisting of dielectric chiral materials in order to reveal its single-polarization single-mode (SPSM) characteristics. Our research on single-core chiral fiber will be of benefit to further development of chiral MCFs, chiral FMFs and so on.

Generally, chiral fibers can be classified into dielectric and structural ones. For the former, the size of chiral structure is much less than the interesting wavelength [9–16]. In this paper, we don't deal with the latter, whose size of chiral structure is comparable to the interesting wavelength, although some applications of them have been demonstrated in polarization control, long-period grating couplers, circular-polarization-related components, even in the generation of OAM [4–8,17–20].

It is well known that the polarization-maintaining fibers are a kind of useful fibers in transmission and interaction of light, which are usually realized by high birefringence of fiber based on asymmetry in structure (anisotropy) to suppress the coupling between paired orthogonal linearly polarized (LP) modes [21–23] or by complete elimination of one of the paired modes to form a SPSM fiber (say to let one of modes be located at cutoff state) [24–28]. Here we use both anisotropy in structure and asymmetry on the dielectric level (chirality) to probe the operation mechanism of chiral SPSM PCF.

In this paper, the characteristics of guided modes of chiral PCFs are effectively analyzed by a modified PWE method. The influence of chirality and structure change on dispersion relation and mode polarization are investigated. Finally, by optimizing the structural parameters, an ultra-wide range for single-circular-polarization operation of chiral PCF is reached with moderate chirality strength.

2. Theory

2.1. Model

In order to show the chirality effects on single-polarization characteristics, a typically PCF model with triangular lattice is

* Corresponding author.
E-mail address: jqli@hit.edu.cn (J. Li).

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chosen, as exhibited in Fig. 1, where the dark background and holes denote the chiral medium and air, respectively. In the figure, Λ, d and D denote the lattice constant, the diameters of small and large holes, respectively.

Here Drude–Born–Fedorov's constitutive relations with $\boldsymbol{D} = \varepsilon_0\varepsilon_r(\boldsymbol{E} + \xi\nabla \times \boldsymbol{E})$ and $\boldsymbol{B} = \mu_0\mu_r(\boldsymbol{H} + \xi\nabla \times \boldsymbol{H})$ are adopted to describe the dielectrically chiral background, where the chirality parameter or strength ξ is related to the specific rotatory power δ of the chiral medium through $\delta = -\xi k_0^2 n^2$, in which $k_0 = 2\pi/\lambda$ and $n = \sqrt{\varepsilon_r\mu_r}$ represent the wavenumber in vacuum and the average refractive index of chiral medium, respectively. For convenience, the chiral parameter ξ is characterized by the specific rotatory power δ, and hence the air can be viewed as chiral medium with δ=0 (achiral medium).

2.2. Modified chiral PWE method

To study the propagation of electromagnetic waves in chiral PCFs, we separate the fields into transverse and parallel components with respect to the z-axis as in [29,30]

$$\boldsymbol{H}(x, y, z, t) = [\boldsymbol{H}_t(x, y) + H_z(x, y)\hat{z}]\exp(i\beta z - i\omega t) \tag{1}$$

where $\hat{z}$, β, $\boldsymbol{H}_t$(x,y), and H_z respectively denote the unit vector along z-direction, propagation constant, transverse field and parallel field to z-direction. Then Eq. (1) is substituted into Maxwell's equations and the wave equation for magnetic field $\boldsymbol{H}_t$ is obtained as

$$\beta^2(k_0^2\xi^2 - \frac{1}{\varepsilon_r})\mathbf{H}_t + i\beta 2k_0^2\xi\hat{z} \times \mathbf{H}_t + (\frac{1}{\varepsilon_r} - k_0^2\xi^2)\nabla_t^2\mathbf{H}_t$$
$$+[k_0^2\nabla_t\xi^2 - \nabla_t(\frac{1}{\varepsilon_r})] \times (\nabla_t \times \mathbf{H}_t) + k_0^2\mathbf{H}_t = 0 \tag{2}$$

where $\boldsymbol{H}_t$ ($\boldsymbol{H}_x$;$\boldsymbol{H}_y$) indicates a column vector. In order to solve $\boldsymbol{H}_x$ and $\boldsymbol{H}_y$, the magnetic field $\boldsymbol{H}_t$ and the other periodically distributed electromagnetic parameters should be expanded in reciprocal space as follows:

$$\boldsymbol{H}_t(\boldsymbol{r}) = \sum_{\boldsymbol{G}} \hat{\boldsymbol{H}}_t(\boldsymbol{G})e^{i\boldsymbol{G}\cdot\boldsymbol{r}} \qquad 1/\varepsilon_r(\boldsymbol{r}) = \sum_{\boldsymbol{G}} \hat{\varepsilon}(\boldsymbol{G})e^{i\boldsymbol{G}\cdot\boldsymbol{r}}$$
$$\xi(\boldsymbol{r}) = \sum_{\boldsymbol{G}} \hat{\xi}(\boldsymbol{G})e^{i\boldsymbol{G}\cdot\boldsymbol{r}} \qquad \xi^2(\boldsymbol{r}) = \sum_{\boldsymbol{G}} \hat{\xi}'(\boldsymbol{G})e^{i\boldsymbol{G}\cdot\boldsymbol{r}} \tag{3}$$

where $\mathbf{G}$ represents the reciprocal lattice vector. Then substituting Eq. (3) into Eq. (2), a generalized eigenvalue equation for propagation constant is obtained:

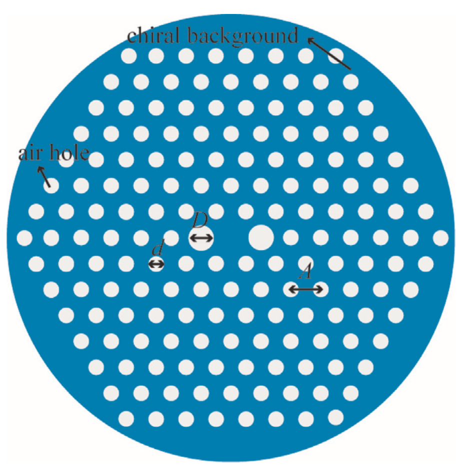

Fig. 1. Schematic diagram of a chiral PCF.

$$\beta^2 \sum_{n,v} A_{mn}^{uv}H_n^v + \beta \sum_{n,v} B_{mn}^{uv}H_n^v + \sum_{n,v} C_{mn}^{uv}H_n^v = 0 \tag{4}$$

where H_n^v denotes one component of the nth Fourier component of transverse magnetic field $\hat{\boldsymbol{H}}_t(\boldsymbol{G})$. Here $A_{mn}^{uv} = M_{mn}\boldsymbol{e}_v\cdot \boldsymbol{e}_u$, $C_{mn}^{uv} = [M_{mn}\cdot(\mathbf{G}_m\cdot\mathbf{G}_n)\delta_{mn}\boldsymbol{e}_v - M_{mn}\cdot(\mathbf{G}_m - \mathbf{G}_n) \times \mathbf{G}_n \times \boldsymbol{e}_v + k_0^2\delta_{mn}\delta_{uv}\boldsymbol{e}_v]\cdot\boldsymbol{e}_u$, $B_{mn}^{uv} = (i2N_{mn}\boldsymbol{e}_z \times \boldsymbol{e}_v)\cdot\boldsymbol{e}_u$, where $M_{mn} = \varepsilon^{-1}(\mathbf{G}_m - \mathbf{G}_n) - k_0^2\xi'(\mathbf{G}_m - \mathbf{G}_n)$, $N_{mn} = k_0^2\xi(\mathbf{G}_m - \mathbf{G}_n)$, where $\boldsymbol{e}_v$ denotes unity vector in reciprocal space, u, v=x, y and m, n=1, 2, …, s(s indicates the number of plane wave used in the simulation).

Compared to the 3D chiral PWE method [11], the longitudinal field is neglected in this modified method because it is much less than the two transverse components. It has been demonstrated that the results calculated by this chiral PWE method agree well with that by the 3D chiral PWE method [16]. This method can be considered as universal one and applied in both the chiral and achiral cases (by setting the chiral strength $\xi(\boldsymbol{r})$=0) [29,30].

For a given wavelength λ, the propagation constant $\beta(\lambda)$ and field $\boldsymbol{H}_t(\boldsymbol{r})$ corresponding to the eigenmodes can be calculated by solving Eq. (4). By changing the wavelengths, the relations of propagation constant with wavelength and then dispersion may be obtained. The dispersion parameter can be calculated by $D(\lambda)=-(\lambda/ck_0)(d^2\beta/d\lambda^2)$ [29]. The polarization distribution of guided modes can be achieved in terms of the third localized Stokes parameter of $s_3=2\mathrm{Im}\{E_xE_y^*\}/(|E_x|^2+|E_y|^2)$ [11], where E_x and E_y denote the complex amplitude of two transverse orthogonal field components. Changing the wavelength, we can show the dispersive property of the polarization distribution.

This expansion method can be used to analyze the fundamental space-filling mode (FSM) of PCF [30]. For the chiral PCFs with same structure and size, the consumption of time by the modified method is much less than that by 3D PWE method. Therefore, using the same computer, more accurate results can be obtained with much more than plane waves.

In the simulation, polymethyl methacrylate (PMMA) doped griseofulvin is chosen as the background of chiral PCFs. It is well known that, compared with silicon or inorganic materials, polymer has a wider range of processing option for preform, including casting, drilling, stacking and squeezing, which allows us to easily and cheaply produce a variety of structures. In addition, polymer has better mechanical property and lower processing temperature, which permits larger squeeze and a wider range of organic and inorganic dopants [31]. Microstructured polymer optical fibers were intensively investigated and found wide applications in short-distance transmission including fiber to the home (FTTH) and high speed connections within or between electronic consumers [32,33]. Since more dilute dopant hardly affects the material dispersion of PMMA [34], so without loss of generality, the material dispersion is described by using the formula of the pure PMMA with $n^2 - 1 = \sum_{i=1}^{3} A_i\lambda^2/(\lambda^2 - l_i^2)$, where A_1=0.4963, l_1=71.8 nm; A_2=0.6965, l_2=117.4 nm and A_3=0.3223, l_3=9237 nm [34].

Chirality can be introduced by griseofulvin with solution doping technique, and the corresponding optical rotatory dispersion could be expressed by the empirical Boltzmann formula $\delta= B_1/\lambda^2+B_2/\lambda^4 +\cdots$, where the first two terms are dominant and the coefficients are related to doping concentration. Here we employed $B_1=1.46 \times 10^4$ nm^2/mm, $B_2=1.82 \times 10^{10}$ nm^4/mm as in the literature [35].

2.3. Description of polarized states

For the sake of description of polarization of guided modes, the localized and normalized third Stokes parameter s_3 is adopted to characterize the mode polarization distribution. Because the intensity is mainly confined to the core (the central defect), in which