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Guided modes in squeezed chiral microstructured fibers

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ABSTRACT

Dielectrically chiral micro-structured optical fibers with solid-core squeezed structure were investigated using plane-wave expansion method. The modal dispersion, birefringence and polarization of the fundamental modes were studied in detail. Numerical results show that between chirality and squeeze there exist a cooperative effect in birefringence and a competitive effect in polarization.

1. Introduction

Microstructured optical fibers (MOFs) or photonic crystal fibers can confine light in the core surrounded by a cladding with regularly arranged rods or holes. Most of the MOFs are made of silicon [1–6] and polymer [7–14]. Compared with silicon, polymer has a wider range of processing option for performs, including casting, drilling, stacking and squeezing, which allows us to produce a variety of structures very easily and cheaply. In addition, polymer has better mechanical property and lower processing temperature, which permits larger squeeze degree and a wider range of organic and inorganic dopants. Even though the polymer has larger absorption loss [11], it fascinating many advantages as aforementioned. Microstructured polymer optical fibers were intensively investigated and were found its wide applications in networks including fiber to the home (FTTH) and high speed connections within or between electronic consumers.

Generally, the non-uniform collapsing in the manufacture of MOFs will cause a deformation of the ideal lattice structure. The deformation in a given location and direction may result in the complexity in polarization states of guided modes. Usually the deformation occurs on a scale comparable with the wavelength of interest, which is named structural asymmetry relative to the asymmetry at the level of molecules composing the materials, such as the dielectric chirality involved in this paper.

Chirality is a geometrical concept, describing an object which cannot be superimposed on its mirror image through any translation or rotation. The materials with chirality could possess circular birefringence and circular dichroism. Chiral MOFs can be classified into dielectrical ones [15–21] and structural ones [22–30]. The former can be made by means of doping chiral molecules or synthesis of chiral monomers in the entity sections, where the scale of chiral monomer is far less than the wavelength of interest [8,9,19]. Then chiral MOFs may be fabricated like the polymer MOF that the fabrication scheme can be divided into two-step processes [11]. First, the chiral preform can be fabricated by drilling, stacking, casting/molding, modest extrusion and solvent deposition. Second, once the chiral preform is completed and it can be drawn to cane and fiber. The second method is that the common preform is firstly produced as polymer one and the chiral molecules permeate into the preform by chiral solution. Then the chiral preform can be drawn cane and fiber. In the process, the positive or negative pressure can be applied at some stage of the microstructure as required. While for the latter, the chirality may be introduced by twisting the fiber core or cladding in a scale comparable to the wavelength of interest. Investigations have indicated that circularly polarized modes are supported by chiral MOFs with circular holes [17], even for the case of an elliptical core with strong chirality [16].

Generally speaking, the squeeze of holes or lattice brings linear birefringence for achiral MOFs [33], which can be applied in linearly polarized testing and sensoring element [34–37]. Whereas for chiral MOFs, the case becomes more complicated. Without squeeze, arbitrarily weak chirality would lead to circular birefringence [17]; with the introduction of squeeze the elliptical birefringence appears, but if the chirality is strong enough, the elliptical birefringence will degenerate to circular birefringence again [15,16]. In this paper, we theoretically investigate the squeezed chiral triangular-lattice holey fiber. It mainly focuses on

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the competition and cooperation between the squeeze in structure and the chirality in medium in the modal birefringence, polarization and dispersion.

2. Model and theory

2.1. Model for chiral MOFs

The diagram of a chiral MOF is shown in Fig. 1, where the dark background (with subscript 1) and the holes (with subscript 2) denote the chiral medium and air holes, respectively. In this paper, the chiral MOFs are viewed as squeezed with the same proportion in the holes and lattice along a certain characteristic direction (for example, the six fold symmetry axis or its orthogonal direction for triangular lattice), keeping the orthogonal scale unchanged. After being squeezed, the lattice is no longer equilateral triangular and for convenience the holes may be considered as elliptical ones, whose major and minor axes a and b respectively. Where $b=ae$ and e denotes the ellipticity of holes or the squeeze degree. Note that the case of $e=1$ corresponds to a non-squeezed chiral MOF with circular holes and equilateral triangular lattice. While $0<e<1$ means the vertical squeeze, and the smaller the e, the stronger the squeeze. Similarly, $e>1$ indicates the horizontal squeeze, and a larger e implies a stronger squeeze. We only discuss the case of vertical squeeze, considering the similarity in the dispersion relation and polarization characteristics of guided modes with the case of horizontal squeeze. Thus the distance between adjacent holes in two orthogonal directions can be expressed as $Y=e\Lambda$ and $X=\Lambda\,\tan(\pi/3)$, where Λ is the lattice constant without squeeze. Through the whole article, a and Λ are fixed as 0.9167 μm and 2.2 μm.

In order to describe the dielectrically chiral background, Drude–Born–Fedorov's constitutive relations $\mathbf{D}=\varepsilon_0\varepsilon_r(\mathbf{E}+\xi\nabla\times\mathbf{E})$, $\mathbf{B}=\mu_0\mu_r(\mathbf{H}+\xi\nabla\times\mathbf{H})$ were adopted, where the chirality parameter or the strength of chirality ξ is related to the specific rotary 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 mean refractive index of chiral medium. For convenience, the strength of chirality ξ will be characterized with specific rotary power δ, and thus the air can be viewed as a chiral medium with $\delta=0$.

2.2. Plane wave expansion method

In order to simulate the chiral MOFs, a modified plane-wave expansion (PWE) method is employed and the wave equation for the vectors of magnetic field is [16]

$$\nabla\times\left(\frac{1}{\varepsilon_r}\nabla\times\mathbf{H}\right)=k_0^2\,[\nabla\times(\xi^2\nabla\times\mathbf{H})+\nabla\xi\times\mathbf{H}+2\xi\nabla\times\mathbf{H}+\mathbf{H}],\tag{1}$$

where the material is considered as non-magnetic. $\mathbf{H}$ and the electromagnetic parameters including the $\boldsymbol{\varepsilon}_r$ and ξ are expanded in the reciprocal space as

$$\begin{aligned}\mathbf{H}(\mathbf{r})&=\sum_{\mathbf{G}}\mathbf{H}(\mathbf{G})\exp\left((i\mathbf{k}+\mathbf{G})\cdot\mathbf{r}\right)\\ \xi(\mathbf{r})&=\sum_{\mathbf{G}}\xi(\mathbf{G})\exp\left(i\mathbf{G}\cdot\mathbf{r}\right)1/\varepsilon(\mathbf{r})\\ &=\sum_{\mathbf{G}}\varepsilon^{-1}(\mathbf{G})\exp\left(i\mathbf{G}\cdot\mathbf{r}\right)\\ \xi^2(\mathbf{r})&=\sum_{\mathbf{G}}\kappa(\mathbf{G})\exp\left(i\mathbf{G}\cdot\mathbf{r}\right),\end{aligned}\tag{2}$$

In a MOF, wave vector $\mathbf{k}$ corresponds to propagation constant β, thus the wave equation becomes an eigen-equation about the propagation constant β

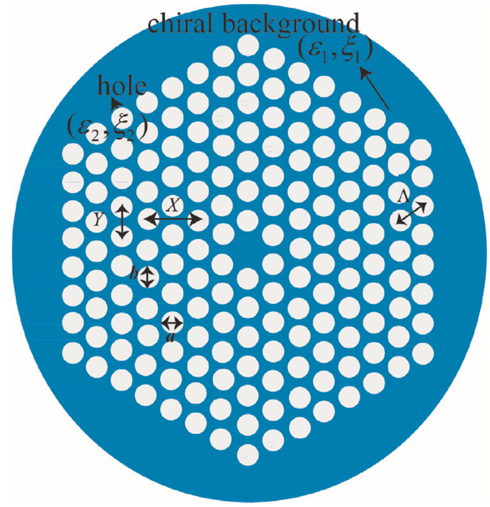

Fig. 1. Schematic diagram of a squeezed chiral MOF.

$$\begin{aligned}&\beta^2\sum_{n,v}A_{mn}^{uv}h_n^v+\beta\sum_{n,v}B_{mn}^{uv}h_n^v+\sum_{n,v}C_{mn}^{uv}h_n^v=0\\ &u,\ v=x,\ y,\ z\\ &m,\ n=1,\ 2,\ 3\ldots,\ s,\end{aligned}\tag{3}$$

where s is the number of plane-waves, h denotes a Cartesian component of the nth Fourier component of magnetic field $\mathbf{H}(\mathrm{G}_n)$, and coefficient A, B and C are related to the basis vectors and reciprocal space vectors [17].

In the simulation, we choose polymethyl methacrylate (PMMA) doped griseofulvin as the background of chiral MOFs. The more dilute dopant can hardly affect the material dispersion of PMMA [32], so without loss of generality, we describe the material dispersion of n with the formula for the pure PMMA. For instance, $n^2-1=\Sigma_{i=1}^{3}A_i\lambda^2/(\lambda^2-l_i^2)$, where $A_1=0.4963$, $l_1=71.8$ nm, $A_2=0.6965$, $l_2=117.4$ nm, $A_3=0.3223$ and $l_3=9237$ nm [32]. Chirality is introduced by griseofulvin with solution doping technology, 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 [31]. Here we employ $B_1=1.46\times10^{4\circ}$ nm^2/mm and $B_2=1.82\times10^{10\circ}$ nm^4/mm as in the literature [31].

2.3. Description of polarization

Generally, the distributions of intensity and polarization of a guided mode in chiral MOFs are not uniform on the cross section. However, the polarization distribution in the core represents the main characteristics of a guided mode, since the intensity is mainly confined in the core. As an example, Fig. 2 shows the distributions of intensity and polarization for the paired fundamental modes in a squeezed chiral MOF, where the localized and normalized third Stokes parameter s_3 is employed to characterize the modal polarization. One can see that the light intensity is mainly confined in the core, in which the polarization is rather uniform. Thereby we may introduce a single number

$$S_3=\iint_{core}s_3|E|^2dS\Big/\iint_{core}|E|^2dS\tag{4}$$

which ranges from -1 to $+1$ to characterize the modal polarization. Negative and positive values of S_3 respectively indicate left-