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Design of the low-loss wide bandwidth hollow-core terahertz inhibited coupling fibers

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ABSTRACT

A multi-perspective numerical analysis of propagation loss in inhibited coupling fibers (ICFs) in terahertz (THz) band is presented. It is shown that the core boundary strut shape is a critical factor affecting the confinement loss. The simulation results demonstrate that the closer to a circular arc the struts, the lower the confinement loss. Furthermore, the strut thickness and the material refractive index determine the frequencies and the bandwidths of the low loss region. With the decrease of the strut thickness and material refractive index, the low loss region will be shifted toward the higher frequency, and the widths of low loss regions will be broadened. Besides, when material absorption is considered in simulation, the ICFs averaged propagation loss is still about three orders of magnitude lower than the material absorption loss itself. The conclusions could give valuable guidance for the design and fabrication of THz ICFs.

1. Introduction

THz radiation has attracted intense research interests during recent years because of its wide range of applications in biology, medical science, homeland security, information technology and environment monitoring [1,2]. In order to make these applications promising, great efforts have been made to look for low loss THz waveguide. In general, non-planar waveguides can be divided into two major categories: metallic and dielectric waveguides [3]. The metallic waveguides mainly include the circular cross-section waveguides [4], the parallel-plate waveguides [5,6], the bare metal wires [7] and the metallic slot waveguides [8]. The dielectric waveguides cover the solid-core photonic crystal fibers (PCFs) [9], the hollow-core band-gap PCFs [10], the porous fibers [11–13] and so on. Nevertheless, reducing the loss of THz waveguides and expanding the low loss region over a broad frequency range still remain challenging tasks [14].

The hollow core PCF having Kagome-like structure has been considered as a good option for THz waveguide due to its low loss and broad bandwidth. For example, a polymethyl methacrylate (PMMA) Kagome fiber (KF), which consists of a Star of David repeating unit, has exhibited a very wide transmission bandwidth, spanning from 0.6 to 1.2 THz [15]. Its obtained average power attenuation coefficient is about 260.58 dB/m, which is 20 times lower than the attenuation of PMMA material itself at 1 THz [16]. In addition, a square-lattice large-pitch hollow core PCF has also been reported in the mid-IR region [17]. The square-lattice fiber exhibits a flat attenuation spectrum less than 4 dB/m and low group velocity dispersion. The fibers with Kagome-lattice or square-lattice have been proved to be categorized as the inhibited coupling fibers (ICFs) [16,17]. In ICFs, the cladding does not support photonic band gaps, and the light in the hollow core is inhibited from coupling to the cladding. This inhibited coupling is due to the combined effects of the low cladding modes density [18,19] overlap between the cladding and core modes [20] and the mismatch in their spatial frequencies [21]. Though the propagation characteristics of the infrared light in ICFs have been extensively studied [18], the properties of ICFs working in THz band are barely known. From the perspective of the manufacture technology of fiber, the manufacture of hollow core Kagome fiber in near infrared band is limited by its tube thickness of hundreds of nanometers [22], but the fiber in THz band can be fabricated precisely because its size could be of millimeter level. Therefore, the effect of the structure of the hollow core Kagome fiber in THz band on confinement loss is worth systematic investigation.

The main purpose of this paper is to investigate the evolution of the confinement loss of the fundamental mode (FM) in THz ICFs by simulating with the change of various fiber design parameters, including the core and cladding geometry, the thickness of the cladding strut and the material refractive index. In order to analyze the propagation loss, we numerically study various ICF

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structures by using the commercial software COMSOL based on the finite element method. The obtained results reveal that the propagation loss of the investigated ICFs is about three orders of magnitude lower than that of the bulk material. According to our simulation, the transmission band width of the THz ICFs can be optimized by choosing the material with smaller refractive index and thinner strut thickness. The goal is to explore the potential of ICFs in reducing the absorption loss caused by cladding material, and we hope that some valuable guidance may be provided for the design of high performance THz ICFs in the paper.

2. The fibers

Our work starts with two types of KFs, whose transverse cross sections are shown in Fig. 1(a and b). The hollow core structure can be formed by removing seven central tubes during the fiber fabrication. The white color represents the hollow area filled with air and the gray zone is dielectric material. Both fibers consist of a periodic arrangement of hexagon dielectric tubes with maximum inner diagonal length D and maximum strut thickness t, as indicated in the inset of Fig. 1. The major difference between the two fibers is the shape of the core boundary. The first structure (S-A) is in hexagon shape (Fig. 1(a)), while the other (S-B) is characterized by a hypocycloid structure (Fig. 1(b)).

Previous work has shown that beyond two layers, the number of hole-layers has a weak influence on the confinement loss [23–25]. Therefore, the hollow-core inhibited coupling fibers surrounded by two-ring-cladding layers are studied in our study. Moreover, the perfectly matched layer (PML), whose thickness is about 2 mm, is placed at the outermost layer to absorb the radiation mode. No significant change of the results could be found when using thicker of PML or setting PML further.

Recently, it has been demonstrated that the guiding mechanism of ICFs, such as Kagome and square lattice hollow-core fibers [26], could be modeled as an antiresonant reflecting optical waveguide (arrow) [27,28], in which the resonance between core modes and cladding modes in ICFs will lead to high loss. The resonance condition is given by

$$k_{0m} t\sqrt{n^2-1} = m\pi. \tag{1}$$

with t being the cladding strut thickness, n the material refractive index and m an integer, $k_{0m}=2\pi f_m/c$ being the propagation constant in vacuum of the m-order resonance frequency f_m. Therefore, the resonance frequencies can be predicted by

$$f_m = \frac{mc}{2t\sqrt{n^2-1}}. \tag{2}$$

And the interval of adjacent resonance frequencies is written as

$$\Delta f = f_{m+1} - f_m = \frac{c}{2t\sqrt{n^2-1}}. \tag{3}$$

The Eqs. (2) and (3) can be used to approximately estimate the high-loss frequency region and the transmission bandwidth of the ICFs.

3. Influence of geometrical parameters

In the analysis of Section 3, the dielectric material of the tubes has been assumed to be polytetrafluoroethylene (Teflon) with a refractive index $n=1.4$ [23] and the material absorption loss is ignored.

3.1. Influence of the shape of core boundary

The shape of core boundary is considered as the major variable geometrical parameter in this part. By using COMSOL, the effective complex refractive index, namely, $n=n_{eff}-ib$, of FM supported by ICFs can be obtained. Hence, the propagation loss can be given by the imaginary part via $\alpha_{dB}\approx 8.686\omega b/c$ (dB/m), where ω represents the angular frequency of terahertz wave and c indicates the light speed [29]. The obtained confinement losses and effective refractive index n_{eff} of FMs as a function of the frequency in both fibers shown in Fig. 1 are indicated in Fig. 2. As shown in Fig. 2(a), the transmission spectra of S-A and S-B fibers both exhibit an alternation of high loss and low loss band, and show some fluctuation. The fluctuations of the of ICFs' confinement loss have been frequently observed in previous works [22,30,31]. It might be attributed to the weak interactions between the core modes and the cladding modes [25]. Due to the same reason, weak fluctuation also appears in the refractive index plot except for high loss regions frequencies as highlighted in the inset of Fig. 2(b) [25]. Moreover, one may notice the discontinuity in the refractive index plots in Fig. 2(b). They correspond to the high loss regions indicated in Fig. 2(a) which are induced by the strong resonances between guided modes and struts cladding modes [25]. It is more important to notice that the average value of the confinement loss of S-B fiber is at least 10 times lower than that of S-A fiber. In addition, its high transmission frequencies shift to lower frequency side when compared with S-A fiber, though the transmission bandwidths are nearly unchanged. The shift of high loss frequencies may be understood by the difference of the averaged thickness of the boundary struts of S-A and S-B fibers. In our design, the boundary strut thickness is defined at the nodes. In the case of the hypocycloid structure (S-B) fiber, the thickness of the boundary strut is uniform. Whereas in the case of the hexagon structure (S-A) fiber, the boundary strut thickness would be slightly smaller than t except for the nodes. Accordingly, the averaged thickness of the boundary strut of S-A fiber is smaller than that of S-B fiber. Since the resonance of core and cladding

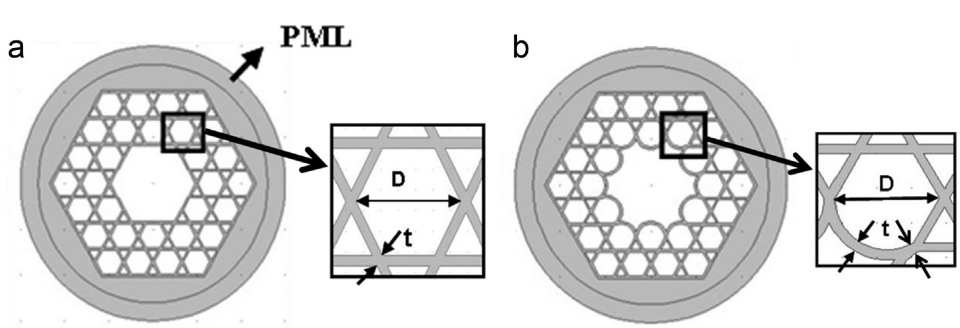

Fig. 1. Cross sections of Kagome fibers with two different shapes of core boundary struts: (a) hexagon (S-A) and (b) hypocycloid (S-B).