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Low loss and flat dispersion Kagome photonic crystal fiber in the terahertz regime

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ABSTRACT

A novel fiber design based on hexagonal shaped holes incorporated within the core of a Kagome lattice photonic crystal fiber (PCF) is presented. The modal properties of the proposed fiber are evaluated by using a finite element method (FEM) with a perfectly matched layer as boundary condition. Simulation results exhibit an ultra-low effective material loss (EML) of 0.029 cm^{-1} at an operating frequency of 1.3 THz with an optimized core diameter of 300 μm. A positive, low, and flat dispersion of 0.49 ± 0.06 ps/THz/cm is obtained within a broad frequency range from 1.00 to 1.76 THz. Other essential guiding features of the designed fiber such as power fraction and confinement loss are studied. The fabrication possibilities are also investigated to demonstrate feasibility for a wide range of terahertz applications.

1. Introduction

The emerging terahertz band is gaining substantial attention due to its ability to allow significant applications, ranging from basic science through to applications in biosensing, imaging, security, spectroscopy [1,2] and biomedical engineering [3]. The terahertz band corresponds to wavelengths from 3 to 0.03 mm of the electromagnetic (EM) spectrum with corresponding photon energies between 1–100 meV. Terahertz radiation bridges the gap between microwave and optical bands. A lack of components and systems that perform in the terahertz range led to this band being called the 'last frontier of the electromagnetic spectrum'. To date, both metallic waveguides as well as dielectric waveguides have been explored both theoretically and experimentally for the propagation of THz radiation [4–18]. However, until recently designing low loss waveguides in the terahertz band is still a challenge. Due to high material losses in the terahertz regime, waveguides similar to metal waveguides for microwaves or to dielectric fibers for visible and far-infrared are not suitable for guiding terahertz waves.

Searching for a low absorption material to reduce the loss is an area of significant focus. As a result, a number of waveguides such as polystyrene foam [19,20], hollow core fibers [8,10,20–30] were proposed in the literature. However, each of them displays at least one of the limitations such as high absorption loss, larger dimension, narrow bandwidth etc.

To realize low EML and low confinement loss simultaneously porous-core waveguides have been introduced. A number of smaller air holes instead of solid material or one larger air hole within the core is the basis of porous fibers. The guiding mechanism in these waveguides is based on total internal reflection. The term *porosity,* which is closely related to the EML of a porous fiber, is a measure of the amount of holes in the material, and is the portion of the volume of holes over the entire volume. It is determined by the distribution, shape, and size of the holes. Notable research has been carried out based on porous fibers [12,13,17,18,31–49] in order to attain low absorption loss and comparatively wide bandwidth. Tight confinement and consequently

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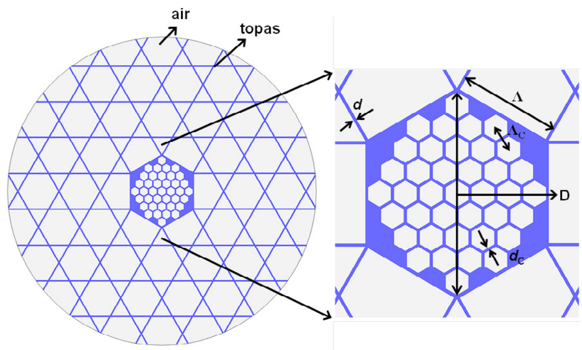

Fig. 1. Kagome structure and porous core of the designed fiber.

lower bending losses [12] of porous fibers have attracted significant attention. Moreover, in comparison to microwires, porous fibers result in reduced distortion of terahertz pulses [31].

Additionally, several porous fibers have been investigated by researchers utilizing the mechanism of modified total internal reflection. Among them, a hexagonal porous core showed an absorption loss of 0.12 cm^{-1} [17]. The authors used the polymer Teflon as background material for their fiber. Kaijage et al. presented an octagonal porous core [18] to reduce the absorption loss further, and was able to reduce the absorption loss to 0.076 cm^{-1} which is about 60% of its bulk material Topas. Using the same kind of design as Kaijage, Sohel et al. [34] was able to reduce loss further by 9% by optimizing the parameters. Authors in [35] also reported an octagonal porous fiber with a small change of geometric structure in the core and were able to reduce the absorption loss to 0.056 cm^{-1}. All of these studies led the way to guide terahertz waves with minimal absorption loss and a number of novel designs were consequently reported with improved absorption loss to some extent. While all of these designs result in fairly low absorption losses, in an attempt to reduce the absorption loss even further a novel type of Kagome structure for porous fiber [39] was presented and this design showed a loss of 0.035 cm^{-1} at f = 1 THz.

In this paper, we propose of a novel type of Kagome lattice PCF having hexagonal shaped air holes within the core. The advantage of this design is that the terahertz field mostly propagates inside the air holes, which effectively reduces the loss caused by absorption of the fiber material. Furthermore, the Kagome structure offers a low propagation loss over a broad frequency range. At first, the structure of the proposed fiber is discussed. Then, investigations of the modal characteristics including the power fraction, confinement loss, dispersion, etc. are presented. The proposed design exhibits an extremely low EML of 0.029 cm^{-1} for a core diameter of 300 μm and at an operating frequency of 1.3 THz.

2. Geometry of the Fiber

The hexagonal structure surrounded by a Kagome cladding is shown in Fig. 1. The Kagome cladding consists of equilateral triangles and regular hexagons, organized in such a way that each hexagon is surrounded by triangles and vice versa. The core diameter of the proposed structure is denoted by D. The center-to-center distance between two adjacent hexagonal shaped air holes (i.e. the pitch) is indicated by Λ_C. The symbol d_C depicts the wall thickness between two air holes in the core. The distance between two parallel struts in the cladding is denoted as Λ of the cladding and the strut thickness is d.

It is crucial to select an appropriate material to design a waveguide in terahertz regime. Several polymers such as polymethyl methacrylate (PMMA) and polycarbonate (PC), high-density polyethylene (HDPE) polytetrafluoroethylene (PTFE), cyclic olefin copolymer (COC) would be suitable for our waveguides as they show relatively low absorption losses in terahertz region. We have chosen to use Topas (trade name of a certain COC) as it has some advantages compared to others: an approximately constant refractive index, n = 1.53 between 0.1 and 2 THz [29], lowest material absorption of 0.2 cm^{-1} at f = 1 THz [37] and a high glass transition temperature that is advantageous for production [50].

3. Results and discussions

The finite-element method (FEM) based on COMSOL software, a practical and extremely precise computational technique for describing the interaction between EM waves and matter, is used to compute the guiding properties of the fiber. A perfectly matched layer (PML) is applied to the outer structure of the PCF in order to limit the computational domain. The E-field distributions of the proposed fiber at different frequencies are shown in Fig. 2. As clearly depicted from the figure that E-fields are bounded by the porous core region and extend little into the cladding. The distributions also indicate that especially for higher frequencies the maximum for the E-field is not right at the center of the core but at the core-cladding interface. As can be clearly seen in Fig. 1, the filling factor and therefore the effective refractive index at a radial region around this interface are higher than at the center of the core. While this effect will lead to a slight mismatch with a Gaussian input beam, it does not influence the guiding properties of the waveguide.

When a guided mode propagates along a fiber with specific mode field profile, it experiences a loss mechanism called effective material loss which is quantified by [29]

$$\alpha_{\text{eff}} = \sqrt{\frac{\varepsilon_0}{\mu_0}}\left(\frac{\int_{\text{mat}} n_{\text{mat}}|E|^2\alpha_{\text{mat}}\,\mathrm{d}A}{\left|\int_{\text{all}} S_z \mathrm{d}A\right|}\right) \tag{1}$$

where the permittivity and permeability of vacuum are expressed by ε_o and μ_o respectively, n_{mat} is the refractive index of Topas for our design, E is the modal electric field, α_{mat} is the bulk material absorption loss, and S_z is the Poynting vector in the direction of propagation. Figs. 3 and 4 show the behavior of EML when the core diameter and the frequency are changed, respectively. The amount of solid material within the core increases when D increases, and consequently the EML increases as depicted in Fig. 3. At higher frequencies, EM waves are more confined and therefore interact more with the bulk material Topas; therefore, as shown in Fig. 4, the EML increases with frequency. Both Fig. 3 and Fig. 4 reveal that a low EML of 0.029 cm^{-1} is obtained at f = 1.3 THz and D = 300 μm which is clearly better than previous works in this field [17,18,31–49]. Moreover, we provide improved dispersion over a wider frequency range as compared to [39] while maintaining low loss. One notable point is that, for the first time, the proposed fiber exhibits an ultralow EML at a high frequency of 1.3 THz in porous core fibers. Waveguides with low absorption loss at higher frequency would be a good candidate for the application in broadband transmission in terahertz regime.

The fraction of guided mode power that is confined within different areas of the fiber is called the power fraction. In this design, we consider three different regions such as the subwavelength air holes in the core, the air holes in the cladding, and the solid material to calculate the fraction of mode power and it is can be calculated by [12]

$$\eta' = \frac{\int_X S_z dA}{\int_{\text{all}} S_z dA}, \tag{2}$$

Where X represents the all integral regions mentioned above.

Figs. 5 and 6 represent the mode power in the different regions, and unveil that about 33% of mode power is transmitted through core air holes at f = 1.3 THz and D = 300 μm. Increasing the frequency aids the fiber for tighter confinement, and as a result the fraction of power within the core air holes increases.

We also observe the variation of the EML and the power inside the air holes of the core when d_C and d are changed. Figs. 7 and 8 demonstrate