Optics Communications 413 (2018) 242–248

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

A novel Zeonex based oligoporous-core photonic crystal fiber for polarization preserving terahertz applications

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ARTICLE INFO

Keywords:
Photonic crystal fiber
Birefringence
Dispersion
Waveguide
Effective material loss
Terahertz

ABSTRACT

A novel waveguide consisting of oligo-porous core photonic crystal fiber (PCF) with a kagome lattice cladding has been designed for highly birefringent and near zero dispersion flattened applications of terahertz waves. The wave guiding properties of the designed PCF including birefringence, dispersion, effective material loss (EML), core power fraction, confinement loss, and modal effective area are investigated using a full vector Finite Element Method (FEM) with Perfectly Matched Layer (PML) absorbing boundary condition. Simulation results demonstrate that an ultra-high birefringence of 0.079, low EML of 0.05 cm^{-1}, higher core power fraction of 44% and negligible confinement loss of 7.24×10^{-7} cm^{-1} can be achieved at 1 THz. Furthermore, for the y-polarization mode a near zero flattened dispersion of 0.49 ± 0.05 ps/THz/cm is achieved within a broad frequency range of 0.8–1.7 THz. The fabrication of the proposed fiber is feasible using the existing fabrication technology. Due to favorable wave-guiding properties, the proposed fiber has potential for terahertz imaging, sensing and polarization maintaining applications in the terahertz frequency range.

1. Introduction

In the electromagnetic frequency spectrum, the 0.1–10 THz frequency range is commonly known as the terahertz band [1]. The terahertz band bridges the gap between the microwave and infrared frequencies making it a potential candidate for applications in the field of sensing [2,3], pharmaceutical drug testing [4], spectroscopy [5–7], biomedical engineering [8], DNA hybridization detection and biotechnologies [9] and so on. Devices such as terahertz couplers [10], splitters [11] and gratings [12,13] are also attracting significant attention. Emerging terahertz applications require highly birefringent, dispersion flattened and low loss terahertz waveguides [14,15]. The main function of waveguides is to transmit electromagnetic waves as well as information with near zero dispersion [16]. Over the last decade, a number of waveguide structures in the terahertz regime have been designed and studied for efficient and reliable transmission of terahertz waves. Firstly, electromagnetic waves in the terahertz spectrum were guided by metallic waveguides [17]. There are various types of metallic waveguide such as metallic circular wave guide [18], parallel plate waveguide [19], bare metal wire [20] and slit waveguides [21]. In metallic waveguides terahertz pulses face a number of problems. For example, Ohmic losses occur due to metal strips, dielectric losses occur in the substrate of circular metallic waveguides, divergence losses in parallel plate waveguides occur due to beam spreading in the unguided medium, radiative losses in bare metallic waveguide occurs due to weak confinement of the mode to the structure and attenuation loss occurs due to larger metal area of the metallic slotted waveguide. Another key waveguide for the terahertz regime is a fiber dielectric waveguide. These terahertz fibers can have either (i) a solid core, (ii) a hollow core, or (iii) porous core. In a hollow core fiber, terahertz waves are limited to a short propagation distance. Furthermore, the bending losses are significant as they are inversely proportional to the diameter and bending radius of the fiber. These deleterious features have slowed down the acceptance of hollow core waveguides and restricted their use today to applications in chemical sensing, thermometry, and laser power delivery [22–25]. Solid core fibers were also proposed earlier but disregarded due to their higher material absorption loss as the core is based on solid material.

Porous core photonic crystal fiber [26–30] have attracted significant interest due to the ability to readily determine optical properties through design, due to their dependence on geometric features. In a PCF, the designer can control the structure by adjusting the number of air holes, the air hole diameter, pitch size, core radius etc. In a PCF, the birefringence is one or two orders greater than conventional polarization

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https://doi.org/10.1016/j.optcom.2017.12.061
Received 11 October 2017; Received in revised form 29 November 2017; Accepted 21 December 2017

maintaining terahertz fibers that can be achieved by introducing an anisotropic structure both in the core and cladding regions [31].

Several types of highly birefringent and low loss terahertz PCFs were proposed earlier for the purpose of polarization maintaining terahertz applications. In 2008, Atakaramians et al. proposed a porous core PCF for polarization maintaining applications of terahertz waves [32]. Using asymmetrical sub-wavelength air-holes within the core they obtained a low birefringence of 0.026. Later, to obtain a high birefringence Chen et al. proposed a super cell structure but failed to increase the birefringence [33]. In 2015, a slotted core photonic crystal fiber was proposed by Raonaqul [34] et al. They showed a higher birefringence of 0.075 but failed to reduce the loss and flatten the dispersion properties. Later, a dual air hole unit based PCF [35] was proposed obtaining a moderate birefringence of 0.033 with a low EML of 0.043 dB/cm. However, the dispersion properties of their proposed dual air hole unit based fiber was not reported. Next, to improve the birefringence and reduce the EML with improved flattening of the dispersion, Hasan and coworkers [36] proposed a new type of polarization maintaining spiral PCF. They were able to increase the birefringence to 0.0483 but with a higher value of EML of 0.085 cm^{-1} with higher dispersion variation of 0.97 ps/THz/cm in the x-polarization mode and 1.42 ps/THz/cm in the y-polarization mode. A dual asymmetrical terahertz PCF [37] with a birefringence of 0.045 was then proposed. Recently, a new type of PCF named the oligo-porous core PCF was proposed by Wu and coworkers [31]. They obtained a birefringence value of 0.03 with a high value of EML of 20%–40% using Topas as the bulk material. The same research group then proposed a triple-hole core [38] based PCF and obtained a birefringence value of the order of 10^{-2} with a higher EML value of 0.07 cm^{-1}. Moreover, an elliptical air hole based hexagonal structure in the core surrounded by a circular air hole based hexagonal cladding was proposed by Ahmed [39] et al. They obtained a lower value of birefringence of 0.0119 and higher value of EML of 0.0689 cm^{-1}. So, from the discussed literature review of terahertz PCF it can be concluded that there is scope for PCF improvement in terms of birefringence, dispersion, and loss etc. In practice, the trade-offs between high birefringence, flattened dispersion, low loss, high power confinement and low confinement loss based terahertz fiber are challenging.

In this context, we propose a new type of Zeonex based terahertz photonic crystal fiber named oligo-porous core fiber using elliptical structured air holes in the core surrounded by kagome cladding. Several types of core structure [40–43] inside a kagome cladding have been proposed earlier but to the best of our knowledge an oligo-porous core structure inside a kagome cladding has not been proposed for terahertz wave propagation. The anisotropic structure of elliptical air holes inside the core simultaneously offers high birefringence and low effective material loss. Furthermore, the compact geometry of the kagome cladding directs most of the useful power throughout the core region. The fabrication of the PCF is readily possible using the existing fabrication techniques. We anticipate that the fiber will have applications in the fields of polarization maintaining transmission systems and dispersion compensation applications.

2. Modeling of the proposed terahertz PCF

Fig. 1 shows the full cross sectional view of the proposed oligo-porous core PCF. We used kagome lattice structure because it offers a very low confinement loss in a broad frequency range [43]. The core is designed using three elliptical air holes to enhance the asymmetry between the polarization modes. The elliptical air-hole arrangements in the core can be structured as dual-hole, triple-hole or other anisotropic structures, and are referred to as oligo-porous cores [31].

In Fig. 1 the symbol D_{core} denotes the length of the core which is twice the circumradius of the hexagon. Also, L and L_1 denote the major axis length of center ellipse and ellipses either side of the center ellipse respectively. It is well known that, during standard fabrication ±2%

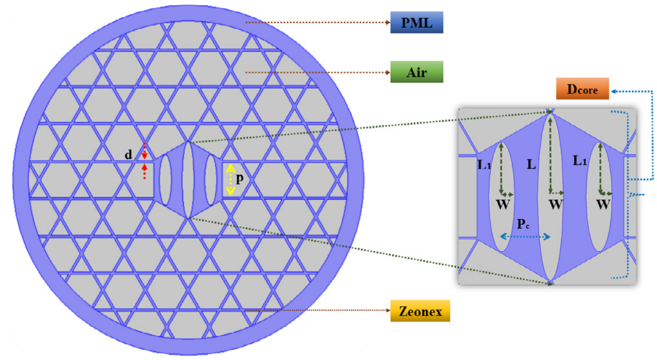

Fig. 1. Cross section of the proposed kagome lattice PCF.

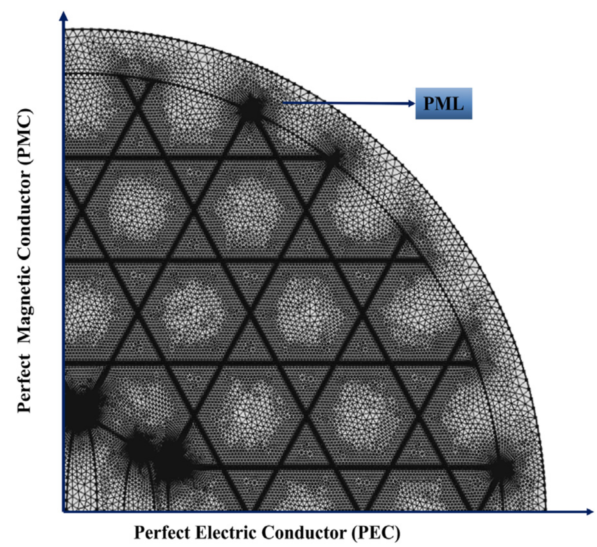

Fig. 2. FEM mesh and boundary conditions for characteristic computation of the proposed Zeonex based PCF.

variation in global parameters of a PCF can occur [3] and considering that fact we choose a maximum major axis length of $L = 0.49D_{core}$ and $L_1 = 0.32D_{core}$ respectively. Here, W indicates the length of minor axis of each elliptical air holes and considering the fabrication fact the maximum possible value of W is $0.143D_{core}$. The center to center distance between the elliptical air holes is denoted by P_c whose maximum value of $P_c = 0.205D_{core}$. Further reduction of P_c may result in overlap of the air holes with one another and that may create fabrication difficulties. In the cladding region the distance between parallel struts is defined by P which changes with D_{core} whereas the strut width is defined as d.

There are several polymer materials such as PMMA, Teflon, Silica, Topas and Zeonex that can be used as the background material of a terahertz PCF. Among them Cyclo Olefin Polymer (COP) commercially known as Zeonex is used as the base material of the proposed fiber because of its flat refractive index at terahertz, lower bulk absorption loss (0.2 cm^{-1} at terahertz range), low water absorption, high transparency, high glass transition temperature and excellent optical stability after humidity and heat exposure [44–46].

Commercially available software COMSOL $v4.3b$ is used for designing the structure and simulating the result. A finite element method is used to calculate the modal characteristics of the fiber. To improve the accuracy of calculation using COMSOL we used *extremely fine* mesh element to characterize the PCF. The elements and boundary conditions for an *extremely fine* mesh is shown in Fig. 2. During simulation the