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Microstructured optical fibers for terahertz waveguiding regime by using an analytical field model

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ABSTRACT

Microstructured optical fibres (MOFs) are seen as novel optical waveguide for the potential applications in the terahertz (THz) band as they provide a flexible route towards THz waveguiding. Using the analytical field model (Sharma et al., 2014) developed for index-guiding MOFs with hexagonal lattice of circular air-holes in the photonic crystal cladding; we aim to study the propagation characteristics such as effective index, near and the far-field radiation patterns and its evolution from near-to-far-field domain, spot size, effective mode area, and the numerical aperture at the THz regime. Further, we present an analytical field expression for the next higher-order mode of the MOF for studying the modal properties at terahertz frequencies. Also, we investigate the mode cut-off conditions for identifying the single-mode operation range at THz frequencies. Emphasis is put on studying the coupling characteristics of MOF geometries for efficient mode coupling. Comparisons with available experimental and numerical simulation results, e.g., those based on the full-vector finite element method (FEM) and the finite-difference frequency-domain (FDFD) method have been included.

1. Introduction

Terahertz (1 THz = 10^{12} Hz) radiations or THz waves, frequently referred to as T-rays, fall in the electromagnetic spectrum located in between two domains of operation and bridges the gap between the microwave and the optical frequencies. In general, this radiation band ranges from 0.1 to 10 THz (or 0.4–40 meV), corresponding to the sub millimetre wavelength range [2–7]. Recently, this domain has been extended to 40–50 THz, so-called THz gap in the frequency domain [8]. Terahertz radiation band has strong potential for applications such as biomedical sensing, noninvasive imaging and spectroscopy, astronomy, label-free detection of proteins, and the pharmaceutical drugs [9–14]. Terahertz radiation, in particular THz time-domain spectroscopy, stands on the cusp of becoming a routine research tool used by scientists in the disparate fields [10,15]. Moreover, there has been increased interest in outstanding potential of terahertz detection for imaging of concealed weapons, explosive, chemical and the biological agents [11–16]. Apart from that, T-rays are extremely useful for non-invasive medical diagnostics, tissue imaging and also in the study and better understanding of the dynamics of complex natural biological systems [17–21]. T-rays can create images and transmit information in the same way that visible light create a photograph, radio waves transmit sound and X-rays view within the human body [11–14]. Terahertz radiations are not suitable for the long distance free space communication or the ground based atmospheric monitoring but they are extremely useful for tomography and the short distance communication [22–24].

Several THz radiation emitters such as the photoconductive switch [3], free electron lasers [7] and the semiconductor surfaces [4] have been reported. The non-resonant optical rectification of ultrashot laser pulses based on nonlinear dielectric crystals facilitated by the induced polarization in the electro-optic crystals such as $LiNbO_3$, ZnTe, ZnSe and GaAs have been used for generating the broad-band THz radiation [8,25]. The frequency of T-rays is too high for electronics based operation while it is too low for dielectric-based wave guiding structures. With the need for a compact, reliable and flexible terahertz system for various applications, a low-loss THz waveguide is essential. Several innovative ideas have been made for low-loss guiding of terahertz radiations via dielectric waveguides and the metal dielectric hybrid waveguides [24,26]; moreover, a number of different fiber-based and the metal-based waveguides with various geometries have been reported such as metal tubes, parallel plate metal waveguide, sapphire fiber [3–7], polymer waveguide and the plastic ribbon waveguide [26–28]. In 2004, an interesting waveguide based on bare metal wire to guide THz pulses was presented by Wang and Mittleman [24].

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Terahertz sources are generally bulky and difficult to use because they rely on the free space to guide and manipulate the THz radiations; however, the lack of materials well suited for guided propagation at terahertz frequencies has also been shown as a barrier for increasing the number of THz applications. Materials such as glasses that work properly at optical frequencies exhibit unacceptably high absorption losses at terahertz frequencies [9,26]. Therefore, for THz applications, alternative low-loss plastic materials need to be used. Plastic materials like polytetrafluoroethylene (PTFE) (or popularly, known as Teflon), polyethylene (PE), polymethylmethacrylate (PMMA), cyclic olefin copolymer (COC) (commercially, known as Topas), polycarbonate (PC), and the high-density polyethylene (HDPE) possess low-loss absorption coefficient at the terahertz frequencies, and have been widely used as host materials for THz waveguides [9,29]. Jin et al. [30] have been carried out significant work to study the loss values of various polymer materials in the THz frequency range. The operation of dielectric fibers made of polyethylene as a waveguide for millimeter wave radiation between 70 and 110 GHz has been demonstrated by Jordens et al. [31]. Busch et al. [32] have presented THz properties of various polymer materials which can be processed by 3D printers and presented THz lenses fabricated using one of these materials. Recently, a novel low-loss and polarization-maintaining THz MOF with a triple-hole unit inside the core, embedded in the background material of Topas has been proposed by Wu et al. [33].

The guidance of the terahertz radiations with a waveguide equivalent to an optical fiber remains an unsolved problem. Several challenges must be managed, beginning with broader spectrum of terahertz radiation that one would want to guide. Optical waveguides based on polymers has led to investigation into a new class of optical fibers such as solid-core, porous-core and hollow-core microstructured optical fibers (MOFs) also, referred as photonic crystal fibers [9,26]. In view of the rapid progress in both THz and MOF technologies, the terahertz MOFs with better-controlled properties can be envisaged. The terahertz applications of MOFs depend on the types of local lattice defects. The high-index core MOF can transmit broad band THz signals while air-core MOF can be used as an ultra low-loss, narrow band THz waveguide [26,28]. Most of the plastic terahertz waveguides uses commercially available Teflon as the background material with an absorption coefficient of approximately 0.3 cm^{-1} at 1.0 THz [27,28]. Teflon MOF with metal-clad hollow defect core supporting plasmon modes have been reported by Kejalakshmy et al. [34], for the terahertz sensing applications.

Microstructured optical fiber (MOF) as a novel optical waveguide with periodic transverse cross-section exhibits enormous interest and are now extensively being studied in view of their extraordinary optical characteristics, offering a versatile platform for tailoring the effective mode area and the dispersion characteristics, to suite various linear and the nonlinear applications [35–37]. A typical high-index core (or index-guiding) MOF is a class of all-in-silica optical fiber composed of triangular lattice of circular air-holes in the dielectric cross-section running along the entire length of fiber. The core is formed by introducing a local lattice defect site (or a single omitted air-hole) into the photonic crystal structure to create a localized region with optical properties different from the surrounding cladding region. The effective refractive index of the porous (or holey) cladding relative to solid-core is reduced due to presence of air-holes; as a result guidance of light would occur via total internal reflection or index-guidance mechanism [36,37]. While in MOFs with low-index core such as air defect the light is guided by the photonic bandgap effect, and the advantage of such type of hollow-core/air-core waveguides (or optical fibers) is that the terahertz pulses propagates predominantly in the hollow-core with only a small fraction propagating in the material, resulting in low absorption losses [26]. For the basic operation, we refer to the review of Broeng et al. [38]. Han et al. [28] were the first to realize, fabricate, and experimentally demonstrate the loss and dispersion of solid-core microstructured fibers in the terahertz spectrum. In 2009, propagation loss and the dispersion characteristics of a hollow-core MOF in THz regime were investigated by Vincetti [39].

In 2006, the effective index method (EIM) was used by Li et al. [27], for analyzing and designing the high-index core triangular MOFs for the terahertz radiation. The principle of EIM establishes an analogy between the traditional step-index optical fiber and an MOF by assuming a circular symmetric core whose diameter is order of twice of the air-hole pitch and treating the cladding as a circularly symmetric homogenous medium whose effective refractive index can be predicted by using the conventional fiber optics theory. Thus, allowing the propagation characteristics of interest to be determined efficiently; however, this model averages out the significant azimuthal variation of the modal field which is an important characteristic of the MOFs.

In this paper, we have studied the light guiding characteristics of high-index core (or solid-core) triangular MOF based on considering five circular rings of air-holes in the fiber geometry and one ring of air-holes in the modal field [1] such as effective index of the fundamental core mode, the near-field (NF) and the far-field (FF) radiation profiles, evolution of the fundamental mode from near-field to far-field regime, modal spot size, effective mode area and the numerical aperture at THz frequencies with different lattice geometries without resorting to any numerical technique. Recently, we have proposed an analytical expression for the modal field of the second-order mode and present results for effective indices for the range of pitch values and the near-field intensity profile. Using the field model, we have also studied the mode cut-off conditions to identify the single-mode operation range for the solid-core triangular MOFs operating at terahertz frequency regime. Also, we have evaluated the coupling losses between two identical MOFs operating at THz frequency. The coupling losses from the THz source such as diode laser to high-index core triangular MOFs with circular air-holes in the cladding have invested in the terahertz frequency realm. For practical applications, e.g., evanescent field based sensors at terahertz frequency domain; we have evaluated the fraction of power coupled to the core of fiber, for different normalized air-hole diameter ratios. To demonstrate the accuracy of our results, we have included the results based on experimental observation, as well as the full-vector finite element method (FEM) and the full-vector finite-difference frequency-domain (FDFD) method as available in the literature.

2. Theoretical modeling

The intricate geometry of MOF with no sharp boundary between the core and the microstructured (or the holey) cladding interface makes it challenging to predict the actual functional shape of the modal field. An accurate description of the transverse modal field propagating in an optical fiber, and hence the knowledge of fundamental modal effective index is essential for studying the various fundamental propagation characteristics. In the case of traditional optical fibers, we have approximate methods like the perturbation method, WKB method and the variational method [40–45], which are easy to implement while numerical methods are computationally extensive, demanding significant computational time and memory allocations. Approximate methods have significant impact in studying the propagation properties of optical waveguides and reducing the computational time significantly. The perturbation and WKB method have limitations and they are not suitable to describe the functional form of the modal field. The variational method can be made to give an accurate description for the functional form of the modal field, and it has been widely used to report the various approximations regarding the fundamental modal field of the standard fiber [43–47]. The fundamental mode profile of MOF has complex shape and its explicit mathematical expression has not been yet reported in the literature. We intuitively choose the variational method for seeking the functional form of the mode shape with a trial field associated with set of adjustable unknown parameters.

The transverse cross-section of a typical index-guiding (or the solid-core) MOF is composed of triangular lattice of circular air-holes in the