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Optical characteristics of polymer-infused microstructured optical fiber using an analytical field model

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ABSTRACT

Infiltration of functional materials into the voids of microstructured optical fibers (MOFs) can provide response under different physical fields leading to tunable propagation properties of the MOFs, for the promising all-in-fiber optical components. In this article, using an analytical field model, we study the light guiding properties of MOFs with triangular lattice of voids infiltrated with polydimethylsiloxane (PDMS) elastomer, which has been selected owing to its good optical and mechanical properties. We demonstrate that infiltration of voids with PDMS can lead to tune the modal properties of MOF over the wavelength ranging from 500–1800 nm for different normalized void ratios. Further, we elucidate that the effective mode area can be tailored to any desired value between 38–264 μm^2 at the telecommunication wavelength of interest by reducing the relative void ratios, which can be useful in the domain of fiber laser applications. Comparisons with numerical simulation results based on the full vector finite-difference (FD) method and the finite-difference time-domain (FDTD) method have been included to further fine tuning of the design parameters.

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1. Introduction

The novel optical waveguide known as microstructured optical fibers (MOFs), also referred as photonic crystal fiber constitute a class of all-in-silica optical waveguides with periodic array of micrometer-scaled air-voids (or voids) running along its entire length, provide an ideal host for manipulation of the photons [1,2]. MOFs have attracted great deal of research attention worldwide and intensively studied owing to unique light confinement characteristics and their potential device applications in the domain of optical communications and the sensing technologies. In comparison to traditional optical fibers, MOFs possessed extra degrees of freedom in manipulating optical properties such as dispersion, nonlinearity and birefringence due to flexibility in engineering the opto-geometrical parameters [1–6]. Light guidance in MOF is governed by one of two principle mechanisms responsible for light trapping within the core. The first is a simple mechanism analogous to traditional optical fiber, light is guided in a higher index core by total internal reflection from a low effective index cladding. The other is known as photonic bandgap guidance (PBG) mechanism which relies on the coherent backscattering of light into the hollow-core or the low index core. Because of their novel guiding mechanism and variety in design, MOFs have a number of novel properties and significant applications [2,6]. MOFs provide a platform for the new class of optical devices

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and the number of functionalities has been demonstrated. In particular, the characteristic void pattern of MOFs can lead to strong interaction between the light and the void material while maintaining the microstructure of the optical waveguide.

Infiltration of voids with active materials such as liquid crystals and high-index liquids [7], ferrofluids [8], metals [9,10], biolayers [11] and polymers [12] leads to manipulation of light guiding characteristics and creates a new group of optical fiber termed as hybrid microstructured optical fibers [13]. The hybrid MOFs possess a new kind of guiding mechanism, based on combination of index-guiding and the bandgap-guiding simultaneously [13,14]. Thus, providing new ways to design functional fibers such as the fiber composed of semiconductor rods, silica and air-voids, in which electrons can propagate in semiconductor rods and the photons propagate in the silica core [14]. These novel hybrid all-fiber optical devices exhibit desirable properties such as the enhanced tunability, compactness and the low insertion losses.

In the last few years, hybrid devices such as optical switches/attenuators, tunable optical devices, variable optical attenuators, dispersion compensators and sensors [15–17] have been developed by infiltrating the aforementioned materials by using the selective filling technology [18]. Wang et al. [19] investigated an invertible fiber-type transformation from a photonic bandgap fiber into a non-ideal waveguide and then into an index-guiding MOF via the thermo-optic effect of the infused fluid, and concluded that such transformation could be used to develop an in-fiber optical switch/attenuator over an extremely broad wavelength range. In 2003, a low-voltage controlled broadband optical switch infiltrated with liquid crystals has been demonstrated by Larsen et al. [20]. Yu et al. [21] proposed a temperature sensor (sensitivity $\sim$ 0.315 dB/$^\circ$C) based on liquid ethanol infiltrated into the cladding of a novel MOF. In 2009, optical switches based on fluid-filled MOF Bragg grating have been reported by Wang et al. [22]. However, limited attention has been paid for infiltration of the voids with polymeric inclusions and the development of polymer infused MOF based devices and components [12].

Polymers have attracted a significant scientific interest during the last decades as they are flexible materials and have good thermal and the mechanical properties, which can be available through an appropriate choice of polymer material as well as the dopants. Moreover, polymers have low processing temperatures facilitating organic and inorganic dopants to be used, and have relatively low cost and often suitable for photonic applications [23–25]. The first polymer-based MOF was made of polymethylmethacrylate (PMMA); a common material used for manufacturing of the polymer optical fiber [25], and the use of polymer for MOFs facilitates a wide variety of fiber structures to be considered. Moreover, combining polymers with microstructure extends their potential to more exotic applications. Polymer-silica fiber with large air-filling fraction, simplify the process of polymer infusion into the voids to produce hybrid optical waveguides further, it reduces fabrication constraints over traditional fiber designs. Polymer-silica MOFs have enhanced tunability for propagation characteristics and multitude applications of these waveguides have been demonstrated by Cerqueira et al. [13]. A tunable birefringence MOF facilitating to tune the guiding properties and creating the strong waveguide asymmetry has been reported by Kerbage et al. [26,27]. However, the proposed device required post-processing to enhance the efficient interaction of the evanescent field with the infused polymer. In addition, polymers can exhibit shrinkage during the process of polymerization and can create stress which often causes cracks. Therefore, the choice of "active polymer" has a crucial role in the development of tunable optical devices.

Polydimethylsiloxane (PDMS) is a well-known soft, deformable elastomer material and has been used as stamp resin; moreover, it play significant role in the research areas of photonics and micro/optofluidics [28]. It has good mechanical and the optical properties; moreover, the PDMS elastomer, exhibits almost highly linear, and the negative thermo-optic coefficient, $dn/dT = -4.5 \times 10^{-4}/^\circ C$ [28,29]. The PDMS exhibit unique capability to operate over a wide range of wavelengths as compared to polymer or liquids, bearing a potential for developing thermally tuned all-in-fiber devices [28–30]. The mature technology of MOF in combination with the extraordinary optical properties of the PDMS can constitute an efficient and alternative route for developing the compact, cost-effective tunable optical devices and the sensors. Infiltration of PDMS elastomer can convert a multimode fiber to endlessly single mode depending upon the normalized void ratio for the range of wavelength, which is crucial for developing tunable devices [28]. For an example, PDMS/silica MOF with normalized void ratio, $d/\Lambda = 0.55$, exhibits the single mode behavior above the wavelength of 800 nm while fiber configurations with $d/\Lambda = 0.65$ and 0.75 above the wavelength of 1100 nm and 1300 nm, respectively. The corresponding conventional unfilled MOF (i.e., air/silica MOF) possesses multimode operation over the entire range of wavelength [28].

Using the analytical field model, we have studied various propagation properties of index-guiding (or the solid-core) air/silica MOFs such as effective index of the fundamental core mode, the group-velocity dispersion (GVD), the near and the far-field patterns, and the evolution of near-field to far-field domain, the mode field diameters (MFDs), splice losses between identical solid-core MOFs, and between an MOF and a traditional step-index single mode fiber [31–34], which compared well with those experimental and the theoretical results (e.g., those based on the full vector finite element method (FEM)), as available in the literature, reflecting the strength of our analytical field model. We have also used the field model to study the modal characteristics of air/tellurite glass based MOFs [35], matching well to those based on the multipole method (MM) [36], and the MOFs operating at terahertz regime [37]. Also, we have studied the characteristics of long-period gratings imprinted in MOF by using the field model [38] and achieved appreciable accuracy with experimental data, as reported in the literature.

In this article, we study the optical properties of the PDMS/silica MOF with circular voids in the cladding arranged in a regular hexagonal geometry around the central missing void (or the solid-core) by using the analytical field model [31–34]. We evaluate effective index of the fundamental core mode, the effective mode area and the numerical aperture for different configuration of the PDMS/silica MOF over a wide range of wavelength. Also, we demonstrate that the PDMS infusion can

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