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Thermo-optic characteristics of hybrid polymer/silica microstructured optical fiber: An analytical approach

Dinesh Kumar Sharma [a], [*], Anurag Sharma [b], Saurabh Mani Tripathi [c]

[a] Department of Applied Science, Ajay Kumar Garg Engineering College, Adhyatmik Nagar, Ghaziabad, 201009, India
[b] Department of Physics, Indian Institute of Technology Delhi, New Delhi, 110016, India
[c] Department of Physics and Center for Lasers & Photonics, Indian Institute of Technology Kanpur, Kanpur, 208016, India

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ABSTRACT

Microstructured optical fibers (MOFs) allow a variety of advanced materials to be infiltrated in their air-voids for obtaining the increased fiber functionality, and offering a new versatile platform for developing the compact sensors devices. We aim to investigate the thermal characteristics of high-index core triangular hybrid polymer/silica MOFs with circular air-voids infused with polymer by using the analytical field model [1]. We demonstrate that infiltration of air-voids with polymer, e.g., polydimethylsiloxane (PDMS) can facilitate to tune the fundamental modal properties of MOF such as effective index of the mode, near and the far-field profiles, effective mode area and the numerical aperture over the temperature ranging from 0 °C to 100 °C, for different values of relative air-void ratios. The evolution of the mode shape for a given temperature has been investigated in transition from near-field to far-field regime. We have studied the thermal dependence of splice losses between hybrid MOF and the standard step-index single-mode optical fiber in combination with Fresnel losses. For enhancing the evanescent field interactions, we have evaluated fraction of power associated with fundamental mode of hybrid MOF. We have compared the accuracy of our results with those based on full-vector finite-difference (FD) method, as available in the literature.

1. Introduction

The appearance of novel optical waveguide known as microstructured optical fibers (MOFs) (often, referred as photonic crystal fibers or "holey" fibers) is a breakthrough in the fiber optic technology, possessing many distinguished optical properties compared to traditional optical fibers [1–5]. Light guidance in standard optical fibers is based on two concentric regions (i.e., core and cladding) with different doping levels and limited by the small and well-controlled refractive index step between the core and cladding. On the other hand, MOF technology is based on subtle variations in refractive index by means of corralling light within a microscopic and periodic array of air-voids in the cladding [2]. MOFs are the air/silica microstructured optical waveguides and have attracted great deal of attention owing to their unique light confinement properties and the potential device applications. In contrast to traditional optical fibers, MOFs have large degrees of freedom due to their flexibility in opto-geometrical parameters for manipulating the optical characteristics, to the anticipated values [3–8]. MOFs were first imagined with the aim of guiding light through photonic bandgap effects in the hollow-core. The first MOF, however, had a solid-silica core surrounded by a regular hexagonal array of circular air-voids. Such MOFs have an overall lower refractive index in their cladding than in their core, it was soon realized that their guidance mechanism is analogous to that found in standard step-index optical fibers, known as total internal reflection rather than to Bragg reflection or the photonic bandgap effect [9]. The guiding mechanism of a bandgap MOF can be predicted by the photonic bandgap theory [10]. MOFs comprise all-in-silica optical waveguide with periodic array of micrometre-scaled air-voids running down the entire length of the fiber. The size and location of these air-voids opens up for large degree of design freedom within optical waveguides design. Further, the existence of air-voids in MOFs [11–16] provides access close to the fiber core while maintaining the microstructure of the optical waveguide. Filling the air-voids of MOFs with functional materials such as gases [17], colloids [18], high-index liquids [11,12], ferrofluids [13], metals

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[*] Corresponding author.
E-mail addresses: dk81.dineshkumar@gmail.com (D.K. Sharma), asharma@physics.iitd.ac.in (A. Sharma), smt@iitk.ac.in (S.M. Tripathi).

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[14,15], biolayers [16], polymers [17] and the glasses [19,20] lead to manipulate the guiding characteristics of MOFs according to the required applications and thus, creating a new group of optical fibers termed as hybrid microstructured optical fibers [21,22], which is the modified structure of the unfilled conventional MOFs.

To create a fluid-filled solid-core hybrid MOF, the air-voids of an MOF can be infused by virtually any functional materials/fluids [11–20] to have interesting optical properties. For the resulting hybrid MOF, fluid absorption should be small at operating wavelengths, should allow tuning, and have surface affinity with fiber material, facilitating the infusion and avoid subsequent spilling of fluid [9,22–25]. Depending on the fluid and MOF material, infiltrating fluids into air-voids can simply be achieved by submerging one MOF end-facet into a liquid reservoir while leaving the other end-facet open to atmospheric pressure [17,25]. If the fluid (or polymer) has surface affinity with fiber material [9,26], capillary forces [12,26–33] will dominate, and a strand of polymer will rise up the walls of microscopic channels in typically a few minutes for short filling lengths (e.g., <5 cm). It is worth noting that the infiltrated fiber length is directly related with viscosity of material, size of air-voids, and the applied pressure to the sample [23,26–28]. In 2014, the nanocolloidal solution was infiltrated inside the air-voids of MOF using the capillarity action [27,29] where for an infused length of around 5 cm, the infiltration time was ~10 min [20]. For fabricating the functional MOFs a unique method by selectively filling air-voids with liquid phase materials has been proposed by Huang et al. [31], where they utilize the dependence of filling speed on the size of air-voids. The filling-time can be significantly reduced, for long fluid lengths (e.g., >10 cm) by increasing the pressure difference between the MOF end-facets [27,34], either by applying vacuum to one end of the fiber or by applying pressure to the fluid, using a syringe pump or a pressure chamber [9,18]. The time required for capillaries to be infiltrated primarily depends on capillary diameter, viscosity and surface tension of the fluid (or polymer) [18,26]. Surface treatments enhancing the wetting characteristics can reduce the filling time [29,30]. Nielsen et al. [26] proposed a model that can qualitatively predict the infusion time of a specific liquid into one or more specific micro-sized air-voids in MOFs, which is verified for water, and its enabling potential is illustrated by the polymer application.

Hybrid MOFs are the novel all-in-fiber optical devices exhibit desirable characteristics such as enhanced tunability, compactness and the low insertion losses; moreover, they provide much longer interaction lengths between the material and the light, and allowing the filled MOFs to be used as the light sources and the sensors [2,19]. Light could be guided in a hybrid MOF (e.g., a half-filled MOF; where half of the air-voids were selectively filled by using the micromachining system consisting of a femtosecond laser and a microscope) by the index-guiding or bandgap guiding mechanisms, depending on which of the two guiding mechanisms is predominate in the fiber [2,31]. The perspectives of design and active control of optical waveguides can be further widened, if we introduce the idea of self-organized material components into the action. A very interesting candidate is the use of liquid crystals, which according to theoretical work by Busch and John [35] may be used to obtain tunable light localization. In 2014, photo-structural changes in a hybrid chalcogenide/silica MOF with chalcogenide nanofilms inside the inner surface of the cladding holes were experimentally demonstrated by Marko [20]. A new type of hybrid MOFs, infiltrated with liquid crystals has been demonstrated by Larsen et al. [36], and they studied the thermo-optic fiber switching by utilizing the phase transitions of a thermo-chromic liquid crystal inside an MOF.

Hybrid devices such as optical switches, attenuators, tunable optical devices, laser sources, dispersion compensators and the variable optical attenuators [32–40] have been developed by infiltrating the functional (or advanced) materials by using a versatile technique, to fill selectively a fluid into the desired air-voids in MOFs. A promising selective-filling technique was demonstrated by Nielsen et al. [26], based on carving a fan-shaped groove on MOF to expose selected air-voids to atmosphere by using a micromachining system consisting of a femtosecond infrared laser. The work by Kerbage and Eggleton [41] is particularly interesting, because it demonstrates the possibility of realizing the active waveguide control, by dynamic positioning of a micro-fluid inside the MOF. Further, Yablonovitch [42] states that a combination of liquid and the photonic crystals may hold new potential for 3-dimensional waveguide structures. An invertible fiber-type transformation from a photonic bandgap fiber into a non-ideal waveguide and then into an index-guiding MOF via thermo-optic effect of the infused fluid have been investigated by Wang et al. [33]. A low-voltage controlled broadband optical switch infiltrated with liquid crystals has been demonstrated by Larsen et al. [43]. Yu et al. [44] proposed a temperature sensor based on liquid ethanol infused 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. [45]. In 2006, Wang et al. [19] described an effective method for integrating a liquid-core MOF with conventional fiber pigtails for all-in-fiber applications. However, limited attention has been paid for infusion of air-voids with polymeric inclusions and the development of polymer infused hybrid MOF devices.

In last few decades, polymers have attracted a significant scientific research interest as they are flexible and have good thermal and the mechanical characteristics [18]. By combining polymers with MOFs extend their potential to more exotic applications; moreover, they have low processing temperatures facilitating organic and inorganic dopants to be used, and have relatively low cost and suitable for photonic applications [46–48]. The polymethylmethacrylate (PMMA) is the most common polymer material, which is used for manufacturing the polymer based microstructured optical fiber [48]. Polymer/silica fiber with large air-filling fraction, simplify the process of polymer infusion into the air-voids for producing the hybrid optical waveguides further, it reduces the fabrication constraints over the traditional fiber designs. Polymer/silica MOFs have enhanced tunability for propagation characteristics and the tunable birefringence. MOF facilitating to tune guiding properties and creating the strong waveguide asymmetry has been reported by Kerbage et al. [25,49]. However, proposed device requires post-processing for enhancing 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. An in-fiber magnetic field sensor based on magneto-driven optical loss effects, while being implemented in a ferrofluid infiltrated microstructured polymer optical fiber has been presented by Candiani et al. [50].

Polydimethylsiloxane (PDMS) is a well-known polymeric silicon material which is a very versatile, soft and deformable elastomer material, and has been used as stamp resin; moreover, it has good optical properties such as low absorption, high transparency with a refractive index lower than that of silica and the low young's modulus [51–57]. The mechanical properties of PDMS enable the realization of pneumatic, electromagnetic and the thermal actuators [51,52]. PDMS exhibits high elasto-optic coefficient, and highly linear and the negative thermo-optic coefficient; it also possess biocompatibility for cell behavior studies and unique capability to operate over the wide range of wavelength [53,54]. The negatively high linear thermo-optic coefficient of the elastomeric inclusions has advantage of partially reconstructing fundamental guiding