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Characteristics of solid-core square-lattice microstructured optical fibers using an analytical field model

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ABSTRACT

The excellent propagation properties of square-lattice microstructured optical fibers (MOFs) have been widely recognized. We generalized our recently developed analytical field model (Sharma and Sharma, 2016), for index-guiding MOFs with square-lattice of circular air-holes in the photonic crystal cladding. Using the field model, we have studied the propagation properties of the fundamental mode of index-guiding square-lattice MOFs with different hole-to-hole spacing and the air-hole diameter. Results for the modal effective index, near and the far-field patterns and the group-velocity dispersion have been included. The evolution of the mode shape has been investigated in transition from the near to the far-field domain. We have also studied the splice losses between two identical square-lattice MOFs and also between an MOF and a traditional step-index single-mode fiber. Comparisons with available numerical simulation results, e.g., those based on the full-vector finite element method have also been included.

1. Introduction

Microstructured optical fibers (MOFs) are characterized by the regular stack of hollow silica capillary tubes running along the entire fiber length, and have been in practical existence as low-loss optical waveguide since early 1996. MOFs present a new way to trap the light in a holey structure; moreover, air-holes (or voids) in transverse cross-section act as the cladding and provide much more flexibility in design, in comparison to traditional optical fibers. Owing to huge variety of air-holes arrangements, MOFs offer new possibilities for controlling the refractive index contrast between the core and the microstructured cladding; as a consequence they offer novel optical properties [2–4]. Air-filled holey cladding leads to extraordinary light guidance properties that are difficult to achieve in case of traditional fibers such as photonic band gaps at optical wavelengths, large core with endlessly guidance, high nonlinearity, supercontinuum generation and the soliton effects, polarization maintenance and the dispersion management [5–9]. Classical optical fiber performs very well in the telecom and non telecom applications but there is series of fundamental limits related to their geometries. MOFs possessed more degrees of freedom as there are several structural parameters to manipulate like lattice spacing, air-hole shape and size, refractive index of glass and type of lattice pattern, for tailoring the fundamental modal characteristics. One of the most appealing properties of MOFs is the dispersion management over traditional fibers. The periodic cladding consisting of micrometer sized voids, allows desirable engineering of the dispersion curves; moreover, task of controlling dispersion play a crucial role in designing optical communication and nonlinear systems [5,6].

MOFs are produced using a variety of different techniques but the versatile technique, the stack-and-draw technique, involves fabrication by stacking and fusing arrays of hollow capillary tubes into the preform, that are drawn at high temperature. By appropriately designing the stacked preform, capillary voids within a single MOF can have wide range of shapes and sizes in precisely engineered periodic or non-periodic configurations [10,11]. Typically, the most common type of MOF have all-silica cross-section consisting of multiple layers of air-holes arranged in hexagonal fashion with a single missing air-hole at the centre that acts as the core of the fiber [2–4]. These longitudinal air-holes reduce the cladding effective index below that of the background material. Therefore, light is guided by a mechanism analogous to total internal reflection, as in case of traditional step-index fibers (SIFs) [3,10].

In MOF designing, it is difficult to control the dispersion and achieving low confinement losses over a wider wavelength range. To overcome this problem several type of designs have been proposed, out of them square-lattice MOFs play a vital role in achieving nearly zero ultra-flattened chromatic dispersion and in

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supercontinuum generation [12,13]. Recently, MOFs with solid-core in silica matrix and square-lattice of circular air-holes in transverse cross-section have been investigated intuitively by Bouk et al. [12]. They studied the guiding and dispersion characteristics of index-guiding square-lattice MOFs as a function of opto-geometrical parameters. MOFs with square-lattice compared to triangular lattice with same pitch and air-hole diameter, offers larger effective mode area for all considered wavelengths due to different air-hole location around the core, leading to higher power accumulation in the core needed for high power broadband generation [12,13]. A square-lattice MOF preform has been recently realized by Russell et al. [14] with standard fabrication process, in order to study localization and control of high frequency sound by introducing two solid defects in the periodic distribution of air-holes. Poli et al. [15] studied the modal cut-off of square-lattice MOFs and obtained a phase diagram describing regions of single-mode and multimode operation as well as the endlessly single-mode regime. It has been demonstrated by them that square-lattice MOFs have larger endlessly single-mode operation region compared with the one for triangular MOFs. In 2009, Tan et al. [16] proposed a new type of square-lattice MOF with two different air-hole diameters in the cladding and investigated their modal properties at the wavelength of 1.55 μm. The negative as well as the zero dispersion properties, and the modal effective area of MOF based on the selenide glass with hexagonal and square-lattice of air-holes has been studied by Dabas and Sinha [17]. A simple index-guiding square array MOF design has been proposed by Begum et al. [18], and they simulated to achieve nearly the zero ultra-flattened dispersion in the wavelength range of 1.38–1.89 μm. Inci and Ozsoy [19] investigated theoretically the large solid-core fiber designs constructed by omitting nine air-holes at the center of square-lattice silica photonic crystals with square shaped air-holes, and compared their modal characteristics with those of circular ones.

Aiming to generalize our analytical field model [1] based on the variational principle for index-guiding (or solid-core) MOFs with hexagonal lattice of circular air-holes in the cladding; we extend our analysis to index-guiding square-lattice MOFs as well. As the propagation properties of MOFs are strictly related to geometric characteristics of air-holes in the cladding, so it is interesting to analyze how a regular air-hole pattern different from the more common hexagonal lattice structure affects the light guidance properties of the fundamental mode.

In the present work, we used an analytical field model associated with 4-fold rotational symmetry of square-lattice geometry, for studying the propagation characteristics of solid-core MOFs with square-lattice of air-holes in the holey cladding without resorting to any intensive numerical computation. We approximated the mode shape of the fundamental core mode as a Gaussian function consisting of a simple Gaussian and shifted Gaussian terms. Using the field model, we have evaluated the effective index of the mode and the group-velocity dispersion for different configurations of square-lattice MOFs. We present results on the near and the far-field profiles, and evolution of the fundamental mode from near-field to far-field domain. We have used the field model to study the splice losses between two identical index-guiding square-lattice MOFs, and also between an MOF and a conventional step-index fiber, e.g., SMF-28 fiber. Comparisons with available modelling results have been included, as reported in the literature.

2. The field model

The dielectric cross-section of an index-guiding MOF with square-lattice of air-holes in the background of host material is shown schematically in Fig. 1. In such type of array system, each lattice point has four nearest neighbors at a distance of Λ (center-to-center distance between adjacent air-holes, known as pitch) and the four next-nearest neighbors at a distance of $\Lambda\sqrt{2}$ followed by another four neighbors at a distance of 2Λ and so on [20]. Thus, the opto-geometrical local lattice defect site (or core) can be considered to be surrounded by successive circular rings of following radii: Λ, $\Lambda\sqrt{2}$, 2Λ, etc., each circular ring containing air-holes placed symmetrically with 4-fold rotational symmetry is shown schematically in Fig. 1. In the first and third circular ring air-holes are arranged such that one of the holes is at the angular position of $\varphi = 0$, while in the second and fifth ring the positions are shifted by an angle of $\pi/4$.

Air-holes in the fourth circular ring are shifted by an angle of $\pi/8$ (see, Fig. 1) [21]. The entire air/silica microstructured cladding region beyond the fifth circular ring is taken into account in an average fashion by considering the fundamental space-filling mode (FSFM) or the lowest order cladding mode. The propagation constant ($\beta_{FSFM} = n_{FSFM} \times k_0$; where k_0 is the free-space wave vector) of the FSFM is used to define the effective cladding index which is obtained as the effective index of an infinite photonic crystal cladding material, if the core or local lattice defect site is absent [3,11].

The cladding effective index is an important design parameter for MOFs and its value determines wavelength range for which a particular MOF configuration is single-moded [5]. Computation for cladding effective index has been done both by the numerical [22] and the analytical methods [23,24]. The numerical methods give accurate results but require large computation time and memory allocations while the scalar analytical techniques significantly reduce the computational time. The cladding index for equivalent step-index profile of MOF at different wavelengths is obtained by using the scalar effective index method (S-EIM), where the wave equation is solved for a unit cell of microstructured region using the appropriate boundary conditions [23]. For the determination of effective index of the fundamental space-filling mode, n_{FSFM} for square-lattice MOFs the modal analysis remains the same as in case of hexagonal lattice except for expression of the radius of equivalent circular unit cell. By adopting the methodology, as reported in the Ref. [22,23] for hexagonal lattice, the radius of

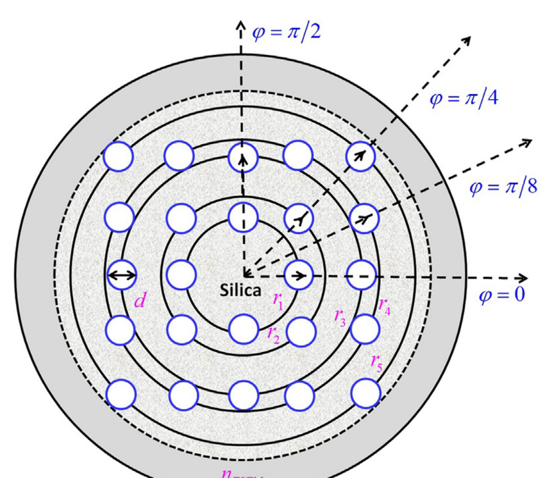

Fig. 1. Transverse cross-section of the microstructured optical fiber with five circular rings ($N = 5$) of air-holes (shown schematically) in the photonic crystal cladding surrounded by the core defect, formed by the omission of single air-hole in the lattice structure. The cladding consisting of air-holes of diameter, d arranged in square array of pitch, Λ possessing 4-fold rotational symmetry.