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# Improved analytical model for the field of index-guiding microstructured optical fibers

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ABSTRACT

We present an improved version of our earlier developed analytical field model for the fundamental mode of index-guiding microstructured optical fibers (MOFs), to obtain better accuracy in the simulated results. Using this improved field model, we have studied the splice losses between an MOF and a traditional step-index single-mode fiber (SMF). Comparisons with available experimental and numerical simulation results have also been included.



## 1. Introduction

Novel optical fibers with very different structures from conventional single-mode fibers (SMFs) include microstructured optical fibers (MOFs) with intricate cross-sectional structures. An MOF is an all-silica dielectric optical fiber with an array of axially aligned air-holes or voids in the cladding region along the entire length of the fiber with a missing central air-hole, defining the core (localized region), and permitting the guided-wave propagation [1–5]. MOFs have been under intensive study as they offer design flexibility in controlling the mode propagation properties. Specific choices of the geometry lead to two basic light guiding mechanisms, the photonic bandgap guidance (PBG) and the effective index guidance [2,3]. In the former case, the MOFs are made by inserting an extra air-hole in a honeycomb structure or by means of hollow core, and the light is guided mainly in the low-index core region provided that the perfect periodicity exhibits a bandgap effect at the operating wavelength. Bandgap guidance has no analogue in conventional optical fibers and allows for novel features such as, light confinement to a low-index core. On the other hand the effective index-guiding mechanism is similar to that of common optical waveguide devices, where the field is trapped in a high-index defect (or solid-core) and decays in the surrounding region containing air-holes with lower average effective refractive index [6–10]. This effective index-guidance does not strictly require the periodicity of air-holes; in fact, the air-holes can even be randomly arranged [11]. Such types of waveguides are usually referred to as index-guiding MOFs and have interesting modal properties which make them attractive and quite different from standard silica fibers. The fibers operating in such a fashion also called as holey fibers (HFs), a label which includes the possibility of both periodic and non-periodic air-hole arrangements [3,9].

The first approach developed to study the propagation characteristics for the MOFs was the effective index method (EIM) [5,12], based on a simple scalar model. One can compare an MOF with an equivalent step-index fiber (SIF) by assuming a circular core whose diameter is order of twice the hole pitch and treating the cladding as a homogeneous medium whose effective index is predicted by the scalar theory [1,4]. This model predicts properties of the MOF that distinguish it from standard step-index fiber (SIF), such as single-mode operation is possible at all wavelengths [1,2], bend loss edge at short wavelengths as well as at long wavelengths [4,5], and the wavelength dependence of the beam divergence [13]. This model however averages out the significant azimuthal variation of the modal field which is an important characteristic of the MOFs.

We have recently developed an analytical field model [14–17] for index-guiding MOFs which is based on explicitly considering

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three circular rings of air-holes in the fiber structure and one ring of air-holes in the modal field (1-Ring model). This model includes the required azimuthal variation of the field. The model, though, does not consider the discontinuities in the index explicitly, the variation of the index affects the overall makeup of the field. It is like the use of the Gaussian approximation for a step-index fiber (SIF), for example. Since the relative strength of the field at the air-hole interface is small, the overall effect of this approximation is limited. Using this field model, we have studied various propagation characteristics of the MOFs such as the effective index of the fundamental mode, dispersion, near and far-field [14,15], the evolution of near-field to far-field [18] and the mode field diameters (MFDs) of different types of index-guiding MOFs [16,19], which compare well with the experimental and the numerical simulation results. We have also calculated the splice losses between two identical MOFs, and between an MOF and a conventional single-mode fiber (SMF) [15,20], which also compare well with the results obtained using full-vector finite element method (FEM), reflecting the strength of our analytical field model which is better equipped to take in to account the field asymmetries around the central missing air-hole (or core). Recently, we have studied the low-loss fusion splicing between an MOF and an SMF facilitated by expansion of the modal field of the MOF, by the controlled all air-hole collapse method [17,21]. Our results are in-line with those results that are available in the literature; hence, establishing the validity of our analytical field model approach.

In our studies, we found that the accuracy of results deteriorated for fibers with small air-holes or small pitch values. The accuracy also deteriorated as the wavelength increased. A brief analysis showed that in all the cases, the field spreads well into the air-holes lattice and the model with one ring of air-holes of field was somewhat inadequate. In this paper, we have improved our analytical field model [15–17] further, for better accuracy by adding more circular layers of air-holes in the model. We have also modified the modal field to include an additional shifted Gaussian term. Thus, we have considered five circular rings of air-holes around the central missing air-hole (or solid-core) in the fiber geometry and two rings of air-holes in the modal field (2-Ring model). Using the improved form of the analytical field model, we have studied the modal properties of index-guiding MOFs with hexagonal array of circular air-holes in the photonic crystal cladding and have shown comparison with the results obtained using 1-Ring model. For example, we have computed the splice losses between an index-guiding MOF and a conventional step-index fiber (SIF) and have compared the accuracy of results with those obtained using other methods, *e.g.*, full-vector finite element method (FEM) results which are available in the literature.

## 2. The field model

The dielectric cross-section of an index-guiding MOF is formed by triangular lattice of circular air-holes in the silica matrix which repeats itself throughout the entire structure. In such type of array system, each lattice point has six nearest neighbors at a distance of pitch, $\Lambda$ (center-to-center separation between adjacent air-holes) and six next-nearest neighbors at a distance of $\Lambda\sqrt{3}$ followed by another six neighbors at a distance of $2\Lambda$ and so on [14,22]. Thus, the defect site (the solid silica core) can be considered to be surrounded by successive circular rings of radii $\Lambda$, $\Lambda\sqrt{3}$, $2\Lambda$, $\Lambda\sqrt{7}$, … etc., each ring containing air-holes placed symmetrically with six-fold rotational symmetry is schematically shown in Fig. 1. The air-holes of first, third and fifth circular ring are arranged at the same angular position. In second circular ring air-holes are shifted by an angle of $\pi/6$, while in fourth ring they are shifted by an angle of

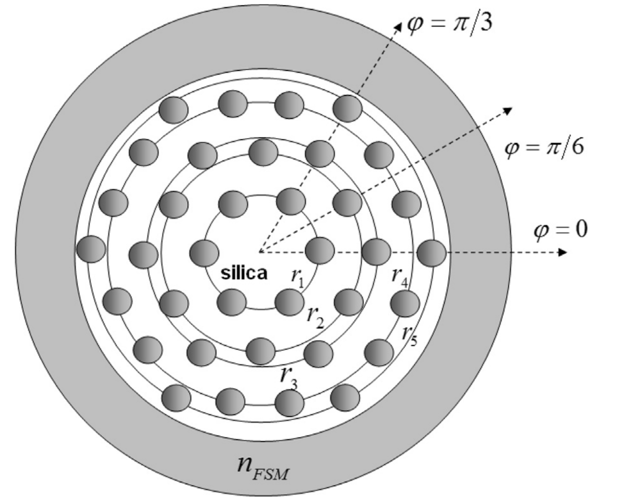


**Fig. 1.** Transverse cross-section (shown schematically) of an index-guiding microstructured optical fiber with $N$=5 rings of circular voids or air-holes in the photonic crystal cladding surrounding the core. The photonic crystal cladding comprises air-holes of diameter $d$ arranged in a triangular array of lattice constant $\Lambda$.

$\pi/12$. There are 12 air-holes in this circular ring. The first circular ring has a radius of $r_1 = \Lambda$ while the next circular rings have radii, $r_2 = \Lambda\sqrt{3}$, $r_3 = 2\Lambda$, $r_4 = \Lambda\sqrt{7}$, and $r_5 = 3\Lambda$ respectively. The entire microstructured cladding beyond fifth circular ring, *i.e.*, $r > (3\Lambda + a)$, where $a$ is the radius of air-hole, are taken into account in an average fashion by considering the fundamental space-filling mode (FSFM). The propagation constant of the fundamental space-filling mode (FSFM) is used to define the effective cladding index which is defined as the effective index of an infinite cladding material, if the core (or local lattice defect) were absent [1,23].

It may be noted that in a single mode MOF structure the mode field is $\varphi$-dependent and therefore the simple Gaussian function approximation is not adequate to approximate this field, although it is still a good approximation to represent the mode field of a well guided mode as the modal field is mainly confined in the central local defect region. In other cases, as the field spreads beyond the central core, the low amplitude tail of the Gaussian function gets modified due to presence of air-holes placed symmetrically around the core. We have used, in our field model, the modal field (or trial field) based on the Gaussian function, which is well equipped to take into account the field asymmetries around the air-holes of the photonic crystal cladding. We consider the field distribution (or trial field) which mainly consists of two types of Gaussian terms: simple Gaussian that controls the field variation along radial direction $(r)$ and the shifted Gaussian which controls the azimuthal $(\varphi)$ variation of the field.

We have modified the field distribution of our earlier model [14–17] by adding an additional shifted Gaussian term in order to take into account the effect of air-holes of second ring which become important in the cases where the modal field spreads more into the holey cladding. The trial field for the fundamental mode of index-guiding MOF with the required six-fold azimuthal symmetry is thus modeled by the following expression (2-Ring model);

$$\Psi(r,\varphi) = \exp\left(-\alpha r^2\right) - \left[A\exp\left(-\alpha_1(r-\sigma\Lambda)^2\right)(1+\cos 6\varphi)\right] - \left[B\exp\left(-\alpha_2\left(r-\eta\sqrt{3}\Lambda\right)^2\right)(1-\cos 6\varphi)\right] \quad (1)$$

where $A, \alpha, \alpha_1, \sigma, \beta, \alpha_2$ and $\eta$ are the unknown model parameters. The field parameters $\sigma$ and $\eta$ determine positions of the maxima of second and third term, respectively. Aforementioned field distribution