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Evaluation of confinement losses in micro-structured optical fibers: an alternative approach

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Dedicated to Prof Anurag Sharma, FNA for his numerous contributions to Optics and Photonics

An alternative method is articulated for the prediction of confinement losses in high-index core micro-structured optical fibers (MOFs) with triangular lattice of rounded air-holes. MOF with finite number of air-holes layers is replaced by a doubly clad fiber (DCF) with a depressed index inner-cladding and then, a simple expression in combination to our optical model for confinement losses in the DCF is resuscitated for evaluation. Simulated results are in-line to those as articulated in the literature. © Anita Publications. All rights reserved.

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1 Introduction

Micro-structured optical fibers (MOFs), also referred as holey fibers are one of the most exciting recent developments in fiber optics, consisting of a hexagonal pattern of air-holes running down the length of fiber surrounding a central core of solid-silica or, in some cases, air. They exhibit numerous unique optical attributes, including zero group-velocity dispersion at the visible wavelengths and low or high effective nonlinearity. By altering the size of the air-holes and their number and position, one can also design MOFs with carefully controlled dispersive and the modal properties [1-3]. In MOFs with solid-core regions, the guidance mechanism is somewhat analogous to total internal reflection that occurs in classical optical fibers (COFs), and this analogy is easiest to observe at longer wavelengths where the modal field cannot resolve the individual air-holes and the effective cladding-index is an appropriate average of the air and silica refractive indices. Theoretical descriptions of MOFs have traditionally been based on numerical approaches because of the complex cross-sectional shape. In the course of modeling for both MOFs and COFs it is usually assumed that the cladding is of infinite extent, although this assumption furnished relevant approximation for core-mode of COFs; however, justification for the MOFs has not been established. Especially, it is difficult to evaluate confinement (or leakage) losses, α_c, peculiar to MOFs analytically and thus, different types of numerical approaches (such as those based on multipole method (MM) [4-6] and finite-element method (FEM) [7-9]) have been successfully developed; however, numerical simulations are, in general, time-consuming. Recently, an analytical approach deployed on V – parameter (i.e., normalized frequency) frequently utilized in design of COFs has been developed for high-index core MOFs [10-12]. By appropriately defining V – parameter, various unique optical attributes of MOFs can be qualitatively understood (without heavy numerical computations) within the framework of well-established COF theories. So far, the applicability of such a simple approach has been limited to MOFs with air-hole cladding region of infinite extent, resulting to no losses. In this paper, we object to explore the applicability of an alternative expression (which is easy to evaluate) in conjunction to our earlier developed optical model [13], for prediction of α_c for the finite cross-

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section MOFs [14-18] which occurs even in absence of material absorption or the scattering losses. First, an MOF with a finite number of air-holes is replaced by a DCF with a depressed index inner-cladding [14-16] and then, leakage loss formulation derived by Marcuse [15] is effectively employed to evaluate α_c for such type of fibers. In spite of that effective index models also have been practically implemented to MOFs with finite cross-section [17,18], where MOFs is replaced by the corresponding axially symmetric fibers, and α_c are numerically evaluated.

2 Doubly clad fiber (DCF) approximation

We considered an MOF with hexagonal array of circular air-holes as illustrated in Fig 1(a); where d is the air-hole diameter and Λ is termed as air-hole pitch. In order to introduce the COF theories, this MOF is now replaced by DCF with a depressed index inner-cladding, as displayed in Fig 1(b); where n_1, n_2, and n_3 are the effective indices of the core, inner-cladding, and outer-cladding, respectively. The effective core-radius is denoted by ρ, and the effective inner-cladding radius, η, is defined so that the area of inner-cladding region, Γ_N, becomes equal to that of the whole elementary cells (as displayed diagrammatically in Fig 1(a)) as follows:

$$\Gamma_N = \pi(\eta^2 - \rho^2) = \Gamma \sum_{I=1}^{N} 6I;$$

where $\Gamma = \Lambda^2 (\sqrt{3}/2)$ and N is the number of air-hole rings, and Γ denotes the area of an elementary cell [19]. Noting that the outer cladding-index is same as the core-index, $n_3 = n_1 = n_{si}$ with n_{si} being the host index of the silica and assuming that the inner cladding-index is expressed by the effective index of the so-called fundamental *space-filling* mode (FSM) in a triangular array of air-holes [11,12] (i.e., $n_2 = n_{FSM}$).

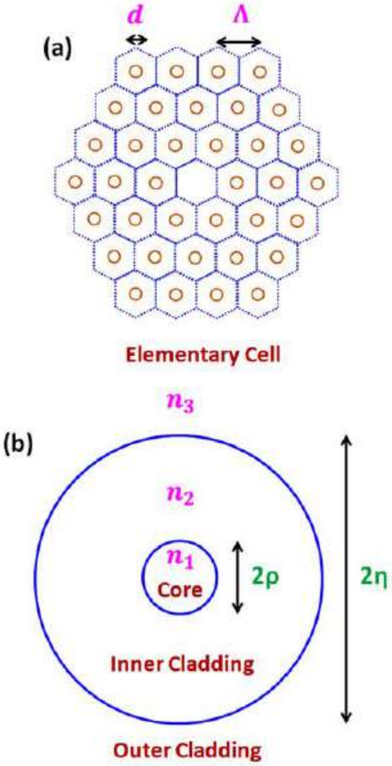


Fig 1. (a) Cross-section of a typical MOF with finite layers of circular air-holes (b) the corresponding doubly clad fiber (DCF) with a depressed index inner-cladding.

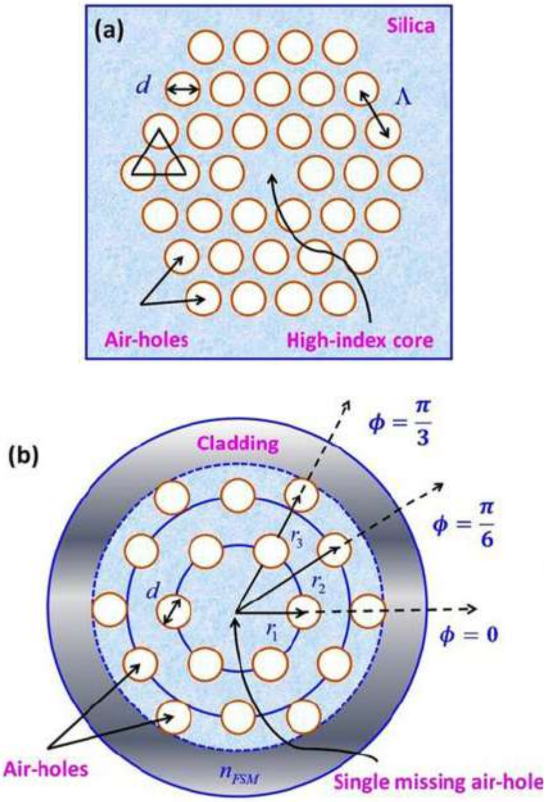
The power leakage formula is quantified in terms of effective V– parameter $\left(V = (2\pi/\lambda)\rho\sqrt{n_{si}^2 - n_{FSM}^2}\right)$ and the effective normalized transverse phase and the attenuation constants, i.e., $U\left(= (2\pi/\lambda)\rho\sqrt{n_{si}^2 - n_{eff}^2}\right)$ and $W\left(= (2\pi/\lambda)\rho\sqrt{n_{eff}^2 - n_{FSM}^2}\right)$, are defined in the same manner as in the case of COFs and satisfy the under-mentioned well-known relation,

$$2\alpha_c = (2\lambda U^3 W/n_{eff}\rho^2\, V^4\, K_1^2(W))\,\exp(-2\eta W/\rho) \tag{1}$$

where λ is the wavelength (in µm), n_{eff} is the effective index of the principal core-mode propagating in MOF with air-hole cladding region of infinite extent, and K_1 is the first-order modified Bessel function of the second-kind.

3 Results and Discussion

The MOF first considered in the present analysis with typical example of its opto-geometrical cross-section is displayed in Fig 2(a) in the case of three rings of air-holes. For evaluating the values of effective V– parameter (U– parameter and the W– parameter) we employed our optical model with $\rho = 0.65\Lambda$ [13]. The background index of the silica is assumed to be 1.45. The fabrication defects contributing to loss are not taken into account during simulation. It is noticeable that due to symmetry attributes of the optical model (as displayed schematically in Fig 2 (b)) just a sector of the cross-section can be presumed for analysis. The hexagonal symmetry as well as the leakage due to interruption of lattice is evident; moreover, the field confinement and its decay rate play a cardinal role in leakage attributes depending on d, Λ and on the number of rings, N in the cross-section.



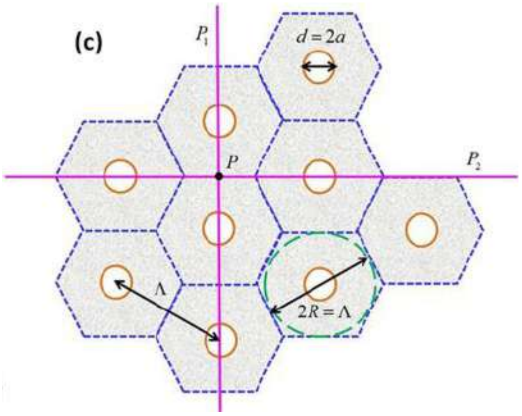
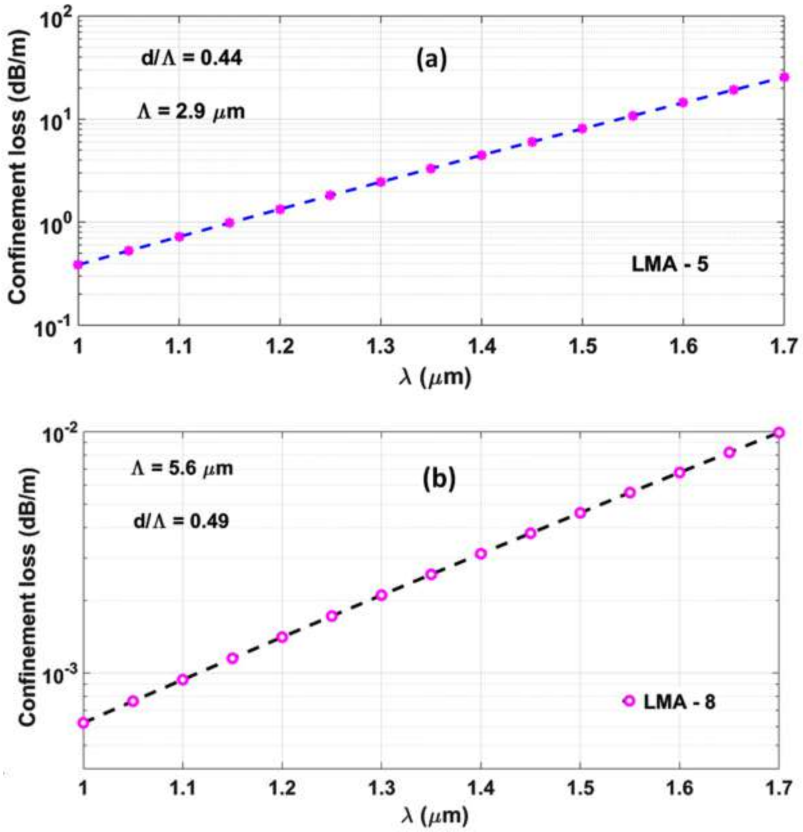


Fig 2. (a) Diagrammatic representation of high-index core MOF (b) illustrative diagram of optical model employed for simulation (c) schematic sketch of MOF cladding with commensurate circular unit cell and the planes of symmetry are displayed by P_1 and P_2.

Figure 3 demonstrates that α_c for the solid-core large-mode area (LMA) MOFs ((e.g., LMA-5 (Λ= 2.9 μm & $d/\Lambda = 0.44$), LMA-8 (Λ= 5.6 μm & $d/\Lambda = 0.49$) and LMA-10 (Λ = 7.14 μm & $d/\Lambda = 0.46$)) against wavelength (spanning from 1.0 μm to 1.7 μm) evaluated from utilizing Eq (1) in combination to our model by taking the normalized air-hole diameter, d/Λ and the pitch as the geometrical parameters; where $\lambda = 1.55$ μm.



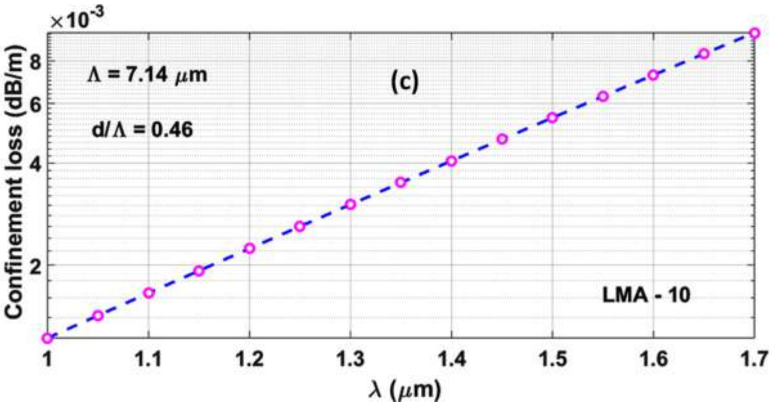


Fig 3. Confinement loss (dB/m) against wavelength (μm) for all-in-silica (a) LMA-5 (b) LMA-8, and (c) LMA-10 MOFs of hexagonally packed rings of air-holes.

Results are plotted for elementary mode on logarithmic scale. We anticipated that simulated results (based on DCF approximation incorporated to optical model) follow the same trend (increasing smoothly with increment in wavelength for fixed value of N as the field confinement decreases) as narrated (for finite cross-section MOFs) in the literature, and hence, demonstrating the applicability of easy to evaluate methodology, as proposed in this article. Evidently greater pitches (see Fig 3(c)) correspond to larger cores and thus, more tightly confined optical fields. As a consequence, the wavelength increment corresponds to a little improvement of the confinement with a small reduction of the losses.

4 Conclusion

We have explored an elegant approach based on simplified expression for the prediction of confinement losses, α_c, for the high-index core LMA-MOFs with rounded air-holes in the cladding region of finite extent. The present approach offers an alternative route to evaluate losses for solid-core MOFs with hexagonal symmetry of air-holes. If appropriate empirical expressions for the effective indices (or the effective V, U, and W parameters) are found the strength of our auxiliary approach would be further enhanced. Using the aforementioned relation in combination to our optical model α_c for the LMA-MOFs can be easily estimated without any requirement for numerical computations. In this article, only the impact of wavelength is dictated on confinement losses.

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