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Experimental verification of improved effective index method for endlessly single mode photonic crystal fiber

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ABSTRACT

We report the experimental verification of Improved Effective Index Method (IEIM) for Endlessly Single Mode Photonic Crystal Fibers (ESM PCFs) from far field intensity measurements. In this paper all the key parameters i.e. *V*-Number, effective refractive index of the cladding, radius of the core and numerical aperture have been obtained from the experimentally measured far-field intensity pattern of ESM-PCFs. It is shown that the transmission characteristics of ESM-PCFs match with the simulation result obtained using IEIM and also with the core diameter of PCF obtained from scanning electron microscope (SEM) within the experimental limit.

1. Introduction

Photonic crystal materials are the prime focus area in the past few years with the number of publications and patents increasing exponentially. It is now the critical phase of their development as they move fast from the realm of fundamental studies to the manufacturing of photonic devices and commercial deployment of photonic crystal fibers in optical communication network.

Photonic crystals are patterned materials with a well defined periodicity in dielectric constant. Photonic Crystal Fibers (PCFs) are one of the most important applications of photonic crystal materials. PCFs have given a new dimension in the field of optical communication. PCF has the ability to confine light with the confinement characteristics, not possible in conventional optical fiber due to its high degree of design flexibility [1–5]. PCF is an optical fibers made up of single material with an arrangement of periodic air holes across the cross-section running down its entire length. A localized region of higher refractive index is formed by leaving a single lattice site without an air hole. Light can be trapped along the axis of the fiber in this localized region, which acts as a waveguide core. PCFs are now finding applications in fiber-optic communications, fiber lasers, nonlinear devices, high-power transmission, highly sensitive gas sensors, super-continuum generation and other areas. With its high degree of design flexibility and wavelength dependent refractive index of cladding, PCFs can be optimized for single mode operation over a very long range of wavelengths. Due to this property it is also named as Endlessly Single Mode PCF (ESM PCF), first coined by Birks et al. [1]. Extensive numerical calculation for the transmission characteristics of ESM PCF have been reported in the recent past [6–11]. Many numerical modeling techniques have been applied to study its propagation and transmission characteristics, which include the effective index method (EIM) [9,11–13], scalar effective index method (SEIM) [13], full vectorial effective index method (FVEIM) [13], plane wave expansion method [14–16], localized basis function method [12,17,18], finite element method [19,20], finite difference time domain method [21,22] and multipole method [23–25], etc.

The basic of all these methods is to calculate the effective cladding index and then compute the propagation characteristics of the PCFs. Among the above mentioned methods, the FVEIM requires less computation time and less computer memory. However FVEIM does not provide very accurate results at higher wavelength values. This has led to development of Improved Effective Index method (IEIM) by Park and Lee (2005) [8] in which they empirically expressed the optimized value of core radius of PCF in terms of air hole spacing (Λ) and air hole diameter (d). The implementation of the core radius in terms of air hole diameter and air hole spacing substantially improved the accuracy of the results of effective index method. Although IEIM has been extensively used to estimate propagation characteristics of PCFs, yet no effort has been done to experimentally test this method.

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Mortensen and Folkenberg have investigated the transition of the fundamental mode radiating out of a PCF, from near field to the far field [28] for endlessly single mode PCF. Further, implication of six fold rotational symmetry in the far field intensity pattern measurement of PCF is also analyzed by Dabirian et al. [29]. However, the geometrical and waveguiding parameters of PCFs had not been explicitly obtained using far field measurements for experimental characterization of ESM PCFs.

In this paper, we report the experimental verification of IEIM for ESM PCF from far field intensity measurements. From the experimental measurements of the far field intensity pattern, we obtained the transmission characteristics of ESM PCF in terms of *V*-number, effective refractive index of the cladding, radius of the core, numerical aperture, etc. The experimental values of the waveguiding and geometrical parameters are found to be in agreement with the simulation results obtained using IEIM and Scanning Electron Microscope (SEM) data. This paper is supported with experimental as well as simulation results and confirms the validity of IEIM for estimation of transmission characteristics of ESM PCFs.

2. Theory

In this paper, the geometrical and wave guiding parameters of ESM PCF are obtained from the far field intensity measurements. It is also referred as the Fraunhofer region intensity measurement; the region where the angular field distribution is essentially independent of distance from the source.

Far field intensity expression of the cylindrical waveguide is obtained. The far-field radiation pattern $\Psi(r,\theta,\Phi)$ is the inverse Fourier transform of the aperture or near fields.

The normalized (wrt $\theta=0$) far-field intensity distribution $I(\theta)$ for the fundamental mode of PCF [6,27] with normalized radiation angle (α) is given as

$$\mathrm{I}(\theta) = |\Psi|^2 \tag{1a}$$

$$|\Psi|^2 = \left[\frac{U^2W^2}{(U^2-\alpha^2)(W^2+\alpha^2)}\left\{J_0(\alpha)-\alpha J_1(\alpha)\frac{J_0(U)}{UJ_1(U)}\right\}\right]^2 \quad \text{for } U\neq\alpha \tag{1b}$$

$$|\Psi|^2 = \left[\frac{U^2W^2}{(2V^2)(UJ_1(U))}\left\{J_0^2(\alpha)+J_1^2(\alpha)\right\}\right]^2 \quad \text{for } U\neq\alpha \tag{1c}$$

where $V^2=U^2+W^2$; $\alpha=ka\sin\theta$; $k=2\pi/\lambda_0$; λ_0 is the free-space wavelength and '*a*' is the optimized radius of the core. With the help of above equations the universal curve (Fig. 1) for the step index photonic crystal fiber is plotted, which is used for the characterization of ESM PCF from the far-field measurement.

It is noted that α_{10} and α_{50} are the values of $\alpha(=ka\sin\theta)$, which correspond to angles in the far field intensity pattern at which the intensity has dropped to 10% and 50% of its maximum value (at $\theta=0$). The intensities are measured at θ_{10} because it is practically very difficult to measure the first minimum intensity position accurately in far field intensity pattern [26,27].

2.1. Improved effective index method

The development of IEIM was led by Park and Lee [8] and later used by subsequent authors [30–32]. In IEIM the core radius (r_c) is optimized in terms of pitch (Λ) and air hole diameter (d), which substantially improved the accuracy of the results of the effective index method [9–11]. As the core radius of a PCF with a fixed pitch should decrease when air hole diameter becomes large, whereas the core radius of a PCF with a fixed air hole size increases when the pitch increases. Therefore the core radius has been optimized using empirical formula given as

$$\frac{r_c}{\Lambda} = c_1\Big/\left\{1+\exp\left[\left(\frac{d}{\Lambda}-c_3\right)\Big/c_2\right]\right\} \tag{2}$$

where $c_1=0.686064$, $c_2=0.265366$ and $c_3=1.291080$

The tolerance of this formula is 1e−6.

The analysis of fully vectorial effective index method begins with Maxwell's equations. The homogeneous vector wave equations for the electrical field '*E*' and magnetic field '*H*' in cylindrical coordinates, since the refractive index profile of the PCFs are cylindrically symmetric can be rewritten as,

$$\frac{\partial^2\boldsymbol{\psi}}{\partial\mathbf{r}^2}+\frac{1}{r}\frac{\partial\boldsymbol{\psi}}{\partial\mathbf{r}}+\frac{1}{r^2}\frac{\partial\boldsymbol{\psi}}{\partial\boldsymbol{\phi}}+(k^2n^2-\beta^2)\boldsymbol{\psi}=0 \tag{3}$$

where n is the refractive index of the material, β is the propagation constant, k is the wave vector and $\boldsymbol{\psi}$ can represent either the E_z or H_z. By applying boundary conditions, dispersion equation has been obtained

$$\left(\frac{P_l'(\gamma a)}{\gamma aP_l(\gamma a)}+\frac{I_l'(\kappa a)}{\kappa aP_l(\kappa a)}\right)\left(\frac{n_{silica}^2P_l'(\gamma a)}{\gamma aP_l(\gamma a)}+\frac{n_{air}^2I_l'(\kappa a)}{\kappa aP_l(\kappa a)}\right) = l^2\left[\left(\frac{1}{\gamma a}\right)^2+\left(\frac{1}{\kappa a}\right)^2\right]^2\left(\frac{\beta}{k}\right)^2 \tag{4}$$

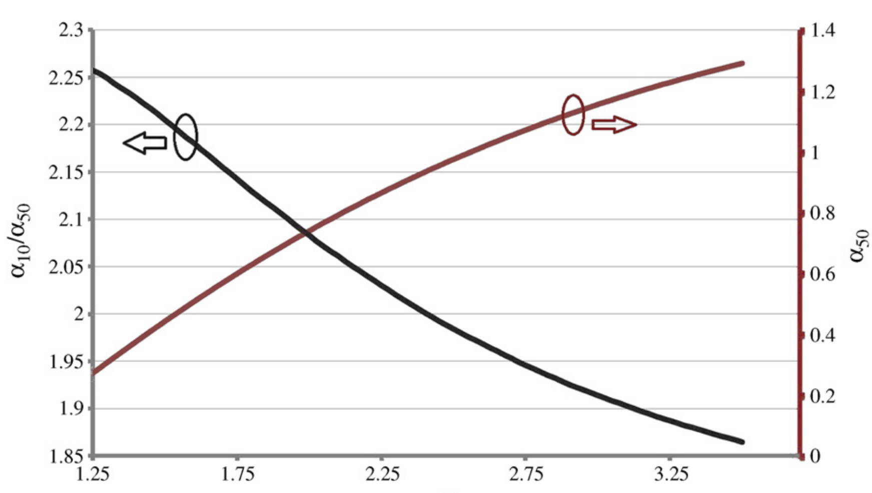

Fig. 1. Variation of the ratio α_{10}/α_{50} (black) and α_{50} (red) with *V* parameter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)