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Modeling photonic crystal fiber with low birefringence using fast multipole method

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ABSTRACT: Currently fields of optics and photonics have urgent problem of fast and accurate simulation of photonic crystal fibers with different fillings. Although significant progress has been made from the time of first method founding, the rigorous analysis of light propagation remains problematic because of the large index contrast, the vectorial nature of the Maxwell equations and the complicated cross-sections of the hole geometries involved. This paper presents improved fast multipole method for low birefringence materials used in photonic crystal fiber core. Using this method, abruptly growth of modeling speed and accuracy is provided. Previously some research in the field of this method implementation in photonic crystal modeling have carried out, but suitable results for low birefringence fillings have not been reached yet. Implementation of this method for low birefringence fillings on photonic crystals is the main goal of this article. Modeling is implemented in Maple and show next results: monotonic decreasing of refraction index real part and linear character of refractive index imaginary part, attenuation has a plateau in bandwidth range and zero velocity group dispersion at 780 nm. Dissimilarity between numerical results and results presented in datasheet caused by nonideal cylindrical shape of air holes, but not by implemented theoretical method.

KEYWORDS: Photonic crystal, waveguide, simulation, numerical method, fiber optics.

1 INTRODUCTION

Photonic crystal fibers (PCF) are a new class of optical fibers using the properties of photonic crystals [1] – presence of specific energy regions photonic band gaps (PBG). In these regions no light can spread in any directions. Providing defect in fiber core leads to endlessly single mode propagation (Fig. 1). Filling core by low birefringence material makes nonlinear response of core material more predictable and has a wide usage in airspace applications.

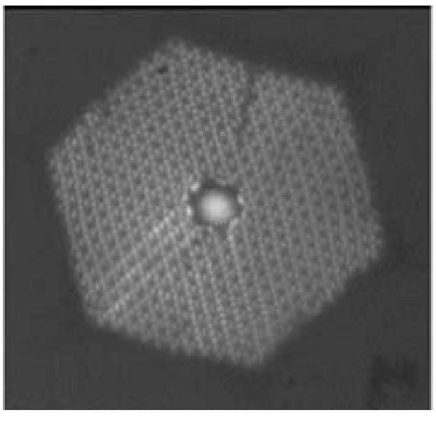

Fig. 1. Localization of electromagnetic field in photonic crystal fiber [2]

Practical interest to optical waveguides and fibers gave rise necessity to develop methods for their study. Although significant progress has been made from the time of first method founding, the rigorous analysis of light propagation in PCF remains problematic because of the large index contrast, the vectorial nature of the Maxwell equations and the complicated cross-sections of the hole geometries involved [2]. Today there are several methods to calculate optical properties of PCF. We propose to use one of the analytical approaches for modeling PCF with low birefringence – fast multipole method (FMM) [3].

Usage of this method for simulation PCF properties was proposed by T. P. White and B. T. Kuhlmey [3]. W. Song, *et al.* [4] simulated the PCF with high birefringence by using multipole method, but using multipole method for modeling PCF with low birefringence have not implemented yet.

Using this method, we can get real and imaginary parts of the effective refractive index and propagation constant [3]. Using different multipole cutoff order to meet the varied diameter of air holes and wavelength ratio, we not only guarantee the calculation precision, but also speed up the calculation.

The goal of this article is building FMM for low birefringence materials in PCF core.

2 MATHEMATICAL INTRODUCTION OF PROPOSED METHOD

For the mode analysis of PCF, we assume the longitudinal axis is the z-axis, and that the structure of the PCF is defined by its cross-section in the xy-plane. Section of PCF is shown in Fig. 2.

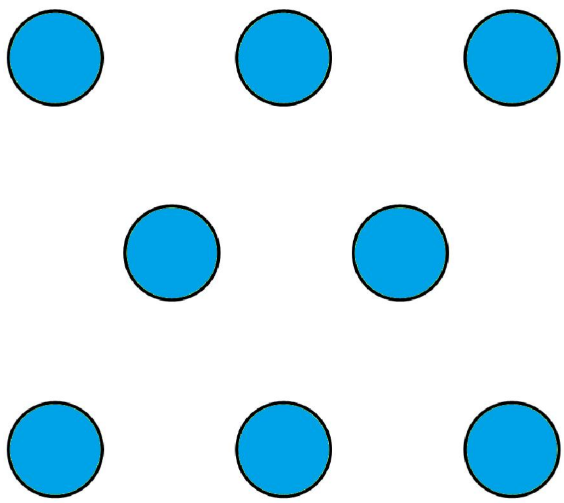

Fig. 2. Cross-section of modeled PCF

Propagation mode can be obtained as vectors of electric and magnetic field in *z* direction:

$$E(x,y,z,t) = E^{i(\beta z-\omega t)}\left(\frac{i\omega\mu}{k^2-\beta^2}\partial_y H_3^{\beta} + \frac{i\beta}{k^2-\beta^2}\times\partial_x E_3^{\beta}, \frac{-i\omega\mu}{k^2-\beta^2}\partial_x H_3^{\beta} + \frac{i\beta}{k^2-\beta^2}\partial_y E_3^{\beta}, E_3^{\beta}\right),$$

$$H(x,y,z,t) = H^{i(\beta z-\omega t)}\left(\frac{-i\omega n^2\varepsilon}{k^2-\beta^2}\partial_y E_3^{\beta} + \frac{i\beta}{k^2-\beta^2}\times\times\partial_x H_3^{\beta}, \frac{i\omega n^2\varepsilon}{k^2-\beta^2}\partial_x E_3^{\beta} + \frac{i\beta}{k^2-\beta^2}\partial_y H_3^{\beta}, H_3^{\beta}\right),$$

where ω is a frequency, β – propagation constant, ε, μ – electrical permittivity and magnetic permeability of free-space.

Assuming above mentioned and continuity of tangential components of the *E* and *H* fields we can summarize the eigenvalue problem which determines a mode with propagation constant β as follows:

$$\nabla^2 E + (k^2 - \beta^2)E = 0$$
$$\nabla^2 E + (k^2 - \beta^2)E = 0$$
$$[E] = 0$$
$$[H] = 0$$
$$\left[\frac{\beta}{k^2 - \beta^2}\frac{\partial H}{\partial t}\right] = -\left[\frac{k^2 / k_v}{k^2 - \beta^2}\frac{\partial E}{\partial n}\right]$$

Remember FMM approach shown in [3], edge of each hole in PCF structure is source of radiation inside and outside the hole. This is caused by division fundamental fields at the edge of hole boundary in two parts: transmitted through the boundary and reflected from the boundary [4].

Due to cylindrical geometry of the air holes, polar coordinates can be used to describe the fields inside and outside the holes:

$$E_z = \sum_{m=-\infty}^{\infty} a_m^{(l)} J_m(k_\perp^i r_l)\exp(im\phi_e)\exp(i\beta z)$$
$$E_z = \sum_{m=-\infty}^{\infty} (b_m^{(l)} J_m k_\perp^e r_l + c_m^{(l)} H_m^1 k_\perp^e r_l) \times \exp(im\phi_e)\exp(i\beta z)$$

$k_T = \sqrt{k_0^2 n_i^2 - \beta^2}$, $k_\perp = \sqrt{k_0^2 n_e^2 - \beta^2}$, refractive index of air n_i = 1, n_e is the refractive index of quartz material, k_0 is the wave vector in free space, r_l and J_m are coordinate of regional coordinate system $\vec{r}_l(r_l, \phi_l) = \vec{r} - \vec{c}_l$, c_l is the center of the air hole. The expression of magnetic field part k is similar to the electric field.

We can easily obtain $a_m^{(l)}$, $b_m^{(l)}$ and $c_m^{(l)}$ using boundary conditions of cylindrical inclusions. Calculating optical properties we choose proper cutoff value corresponding to the air hole diameter and the wavelength ratio M. Goal of this procedure is to optimize speed and precision of the calculation. The effective refractive index of the mode n_{eff} can be obtained by results of propagation constant β calculation.

Then, the imaginary part of the n_{eff} can be used to get the fiber confinement loss (the unit is dB/m):

$$L = \frac{40\pi}{\lambda \ln(10)} \mathrm{Im}(n_{eff}) \times 10^6$$

The unit of L is nanometer (nm), dispersion can be derived from the real part:

$$D = -\frac{\lambda d^2 \,\mathrm{Re}(n_{eff})}{dx^2}.$$

3 NUMERICAL RESULTS

To ensure the most accurate and actual results the parameters have been chosen one of the most well-known fiber Thorlabs HC-800B [5]: center wavelength: 820 nm, attenuation: <0.3 dB/m, bandwidth: 770 – 870 nm. The time and frequency discretization points are chosen to be 2^{10}, core diameter – 8 microns, fiber length – 1 m. Pump power 500 mW.

Light effectively coupled in PCF core. Localization of electromagnetic radiation in the fiber core is associated with a significant difference between the refractive index of core and effective refractive index of PCF coating. This corresponds to presence of defect mode in PBG.

Consider mentioned above about field localization, we can start calculation of dispersion and nonlinear properties. Simulating results for main mode and slight mode are shown on Fig. 3 and Fig. 4.

Monotonic decreasing of refraction index real part can be explained using Sellmeier law for quartz glass. Linear character of refractive index imaginary part correspond to low confinement loss (<4 mdB/km). To decrease these losses is necessary to increase number of holes in PCF. This will lead to increase nonlinearity of dispersion curve (greater efficiency of nonlinear processes).

Dispersion properties and attenuation (Fig. 5) can be compared with corresponding in datasheet [5]. Both figures show zero group velocity dispersion ZGVD near 780 nm. Group velocity dispersion have double zero points but in datasheet only one. This can be explained by interpolation mistake during numerical calculation. Dissimilarity between numerical results and results presented in datasheet caused by nonideal cylindrical shape of air holes, but not choosing and implementation of theoretical method. Attenuation in PCF has a plateau in bandwidth range. This confirm high field localization in PCF core and matches data in datasheet.

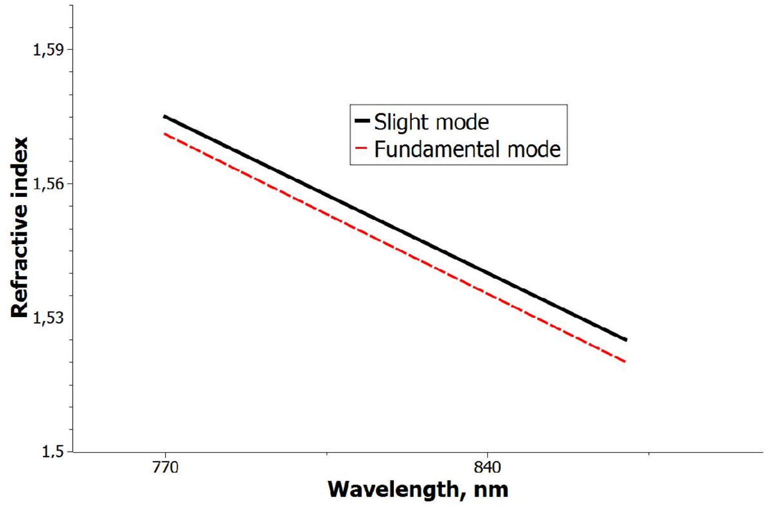

Fig. 3. Dispersion curves of low birefrigence PCF (real part of refractive index)

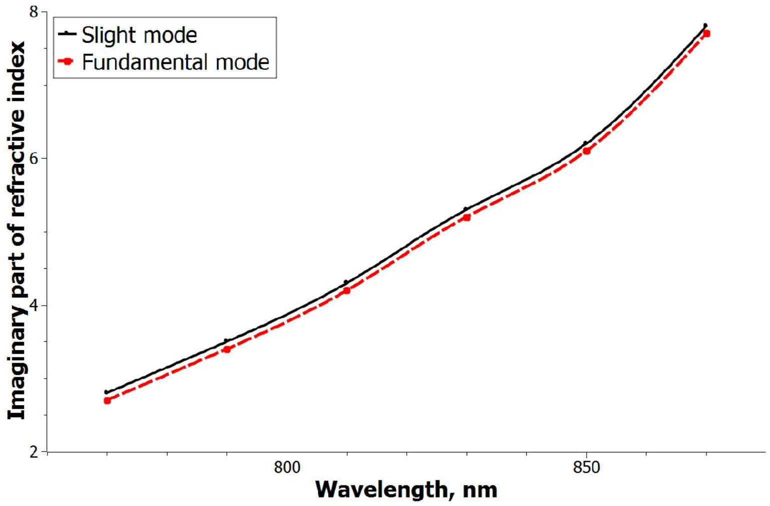

Fig. 4. Nonlinear curves of low birefringence PCF (imaginary part of refractive index)

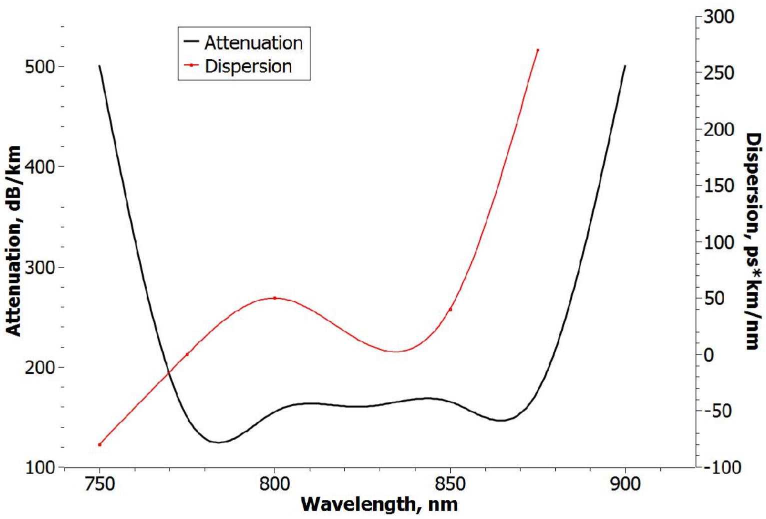

Fig. 5. Dispersion properties of hollow core PCF ant its attenuation [6]

4 CONCLUSIONS

Approach presented in paper provides fast and accurate simulation of PCF with low birefringence. Results can be used for modeling fiber devices in space applications. Linear character of refractive index imaginary part correspond to low confinement loss (<4 mdB/km). To decrease these losses is necessary to increase number of holes in PCF. This will lead to increase nonlinearity of dispersion curve (greater efficiency of nonlinear processes). Figures provided by modeling and data sheet show ZGVD near 780 nm. Dissimilarity between them caused by nonideal cylindrical shape of air holes, but not by used theoretical method.

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