Volume: 02, Issue: 03, Pages: 666-670 (2010)

Designing of Index-Guiding Photonic Crystal Fibre by Finite Element Method Simulation

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ABSTRACT
Different structures of Index-guiding Photonic crystal fibre are designed. The attractive vectorial Finite Element Method simulation technique is used to analyse such PCFs by taking suitable fibre parameter i.e. air hole diameter (d), pitch (Λ) and air core diameter (d´).Few important properties such as variation of refractive index with wavelength and nice confinement modal field pattern were studied. Index-guided photonic crystal fibre having inner core of radius 0.2µm, pitch 2.4µm and identical air hole of diameter d=1.38µm is suggested for which leakage of signal is almost zero at wavelength 1.55µm.

Keywords - Effective refractive index, Finite element method, Index-guided PCF, Photonic crystal fibre

Date of Submission: July 23, 2010 Date of Acceptance: October 13, 2010

I. INTRODUCTION

Now a day, PCF with a periodic transverse microstructure of air hole in its cladding region and also central air core plays significant role in optical communication and sensing application. The most effective theory were given by Joannopoulos et al. [1] and Selleri et al [2] in which they interpreted that "Photonic crystals are periodically structured electromagnetic media, generally possessing photonic band gaps: range of frequency in which light cannot propagate through the structure". Russell et al [3] had shown that PCFs guide light by confining it within a periodic array of microscopic air holes that run along the entire fiber length. According to Knight and his co-worker, Photonic crystal fiber consists of a pure silica core surrounded by a silica-air photonic crystal material with a hexagonal symmetry and it supports a single robust low loss guided mode over a very broad spectra range of at least 458-1550nm [4]. Light propagated periodically along the length of the fiber. This fiber works on the principle of photonic band gap effect. The large variety of micro-structured air holes, pitch (Λ) i.e distance between two centre of conjugative air holes, air core diameter (d´) and its arrangements demand the use of numerical method that can handle arbitrary cross-sectional shapes to analyze different kind of index-guided PCF structures. Many numerical techniques have been used to analyse the photonic crystal fibers, like Fourier transform method, plane wave expansion method, effective index method, beam propagation method, finite difference time domain method, Finite Element Method etc. Due to the complex structures and properties of photonic crystal fibers Hugo et al. derived a numerical approach based on the scalar finite element method which is applied to analyse the modal properties, dispersion and leakage loss of photonic crystal fibers having a solid core and a cladding region with either circular or non circular microstructured holes [5]. Vincetti et al has discussed a holey fiber (HF) having very complex hole geometry by means of a numerical simulator for modal analysis based on the Finite Element Method [6]. Jingyuan et al proved theoretically as well as experimentally that in Index-guided triangular PCF with air-core is introduced which guides light by total internal reflection (TIR) when the diameter of core is smaller than the diameter of holes in the cladding [7]. Uranus and his coworkers had shown the modes of a commercial endlessly single mode photonic crystal fiber (ESM-PCF) [8] that is suitable for optical communication. Here we have used finite element method (FEM), which is suitable for such analysis as it can handle complicated structure geometries.

II FINITE ELEMENT METHOD SIMULATION

The Full vector Finite element method (FEM) is an attractive mathematical tool for analysis complex geometries of hollow core photonic crystal fibre. It is a full vector implementation for both leaky modes and cavity modes for two dimensional Cartesian cross sections in cylindrical co-ordinates. First and second order interpolant basis are provided for each triangular elements. PML (perfectly matched layer) boundary conditions selected independently for each direction. We begin with the source-free time harmonic form of the vector wave equation in an arbitrary, anisotropic lossy media [9-12].

$$\nabla \times \left\{\frac{1}{\bar{s}} \cdot (\nabla \times \vec{E})\right\} - K_0^2 \, \vec{\epsilon_r} \, \vec{E} = 0 \qquad (1)$$

Subject to vanishing field boundary conditions at the domain edges

$$\hat{n} \times \vec{E} = 0 \qquad (2)$$

The complex diagonal tensors s and ϵ_r represent co-ordinates stretching and the dielectric material respectively. Throughout the domain s is the identity tensor, but in the boundary layer, it has the following form

$$\vec{s} = \left(\frac{s_y s_z}{s_x}\right)\hat{x}\hat{x} + \left(\frac{s_x s_z}{s_y}\right)\hat{y}\hat{y} + \left(\frac{s_x s_y}{s_z}\right)\hat{z}\hat{z} \qquad (3)$$

$$s_{\alpha=x,y,z} = 1 - \left(\frac{\alpha - L}{L}\right)^2 \delta_{max}$$

δ_{max} is the loss tangent, α is the distance from the edge and L is the thickness of the layer, known as the perfect matched layer (PML). The tensor elements in the PML are matched to those in the rest of the domain according the prescription, $\vec{\epsilon_2} = \epsilon_1 \vec{s}$ to produce arbitrarily small reflection at the PML interface for all frequencies and angle of incidence. The PML is terminated with a perfect electric conductor (PEC) boundary condition (3).

This functional in two dimensions over domain A is given by

$$F(\vec{E}) = \iint_A \left[(\nabla \times \vec{E}) \cdot \frac{1}{\bar{s}} \cdot (\nabla \times \vec{E}) - \vec{\epsilon} \cdot \vec{E}\right] dA \qquad (4)$$

For propagating and leaky modes [13], a separable electric field becomes

$$E(x,y,z) = E(x,y)\exp(-j\beta z)$$

Where, $\boldsymbol{\beta}$ is the modal propagation constant along z.

Instead of finding an expansion basis over the entire domain, which can be difficult in general, the finite element method, sub-divides the domain into a collection of elements for which a simple basis can be defined. This basis vanishes outside the element, so that the final solution is just a summation over the solution of all the elements.

For hybrid node/edge FEM, the transverse components are expanded in a vector (edge element) basis.

$$\vec{E_T}(x,y)e^{-j\beta z} = \sum_{i=1}^{n} \vec{N_i} E_{Ti} = \sum_{i=1}^{n} \{U\hat{x} + V\hat{y}\} E_{Ti} \qquad (5)$$

Where, E_{Ti} are the values of the field along each edge. The longitudinal component (perpendicular to the plane of the element) is represented by a scalar (node element) basis.

$$E_z(x,y)e^{-j\beta z} = \sum_{i=1}^{n} N_i E_{zi} \qquad (6)$$

Where, E_{zi} are the values of the field and N_i are the basis at each node. The basis dimension n' depends on the geometry of the element and the order of the interpolation. Since the Euler Langrangian equations of the functional correspond to original wave equations the solution of latter equations can be approximated by extremization of the functional. The functionals are approximated using interpolation of polynomial basis functions and functional are discretized in a finite no. of element within the computational domain [14-19].

$$\frac{\partial F}{\partial E_i} = 0 \qquad (7)$$

Finally, we will get matrix generalized eigen-value equation of the form

$$\nabla F = \left(A - n_{eff}^2 B\right)\{E_{Ti}\} = \{0\} \qquad (8)$$

Where A and B represent global finite matrices and n_{eff} represents the modal effective refractive index.

III. RESULTS AND DISCUSSIONS

At first 3-different structures of index-guided PCF with a triangular lattice of air holes are shown in Fig 1. A missing air hole at the centre of fibre acts as the fibre core. The diameter of the air holes of inner most ring is largest and it goes on decreasing gradually from inner ring to outer ring. Three such structures were studied. For all three structures pitch remains same e.g 2.4µm and three ring hole diameters are (a) d_1 = 1.5µm, d_2 = 1µm, d_3 = 0.5µm(b) d_1 = 1.2µm, d_2=1µm and d_3= 0.8µm (c) d_1 = 1µm, d_2= 0.8µm and d_3 = 0.6µm respectively.

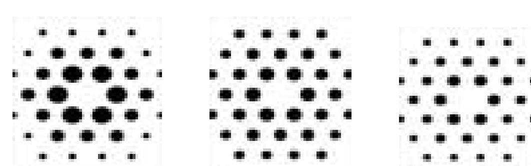

Fig. 1 (a) (b) (c)

For 1(a) d_1 = 1.5 µm, d_2 = 1µm, d_3 = 0.5 µm and Λ = 2.4 µm
For 1 (b) d_1 = 1.2 µm, d_2 =1µm and d_3 = 0.8 µm and Λ =2.4 µm
For 1(c) d_1 = 1 µm, d_2 = 0.8 µm and d_3 = 0.6 µm and Λ = 2.4µm

The refractive indices of the air hole and fibre silica are 1 and 1.45 respectively. After FEMSIM simulation [20] for all 3-structures of PCF Fig.1, it is observed that the effective refractive index decreases with increase in wavelength Fig 2. A confined mode field pattern at wavelength 0.6µm was observed for all three structures but it is almost non-lossy for structure 1(c) as shown in Fig 3.It might be mentioned here that above PCF is not suitable for 1.55 µm as mode field pattern in above structure [Fig.1(c)] is completely leaky for 1.55 µm.

Another structures of 3-different index-guided PCFs as shown in Fig 4(a), 4(b) and 4(c) suitable for 1.55µm have been taken and simulated by FEMSIM. The diameter of air core d′ was first chosen as 0.2µm and diameters of 1st, 2nd and 3rd ring in the cladding region of holey PCF were 0.6µm, 1.1µm and 1.6µm respectively. The separation between two consecutive holes in any ring were kept constant equal to 2.4µm. In remaining two structures central core diameter were taken as 0.3 µm and 0.4µm respectively keeping all other parameters the same. It was ovserved that effective refractive index decreases with increase of wavelength as shown in Fig 5 and modal pattern was better (effective index is maximum) in 1st case i.e. d′ = 0.2 µm which clearly indicates that loss of propagated light is less in 1st structure as shown in Fig 6. It might be mentioned here that no modal pattern was found by taking the core diameter as below 0.2µm and above 0.4µm.

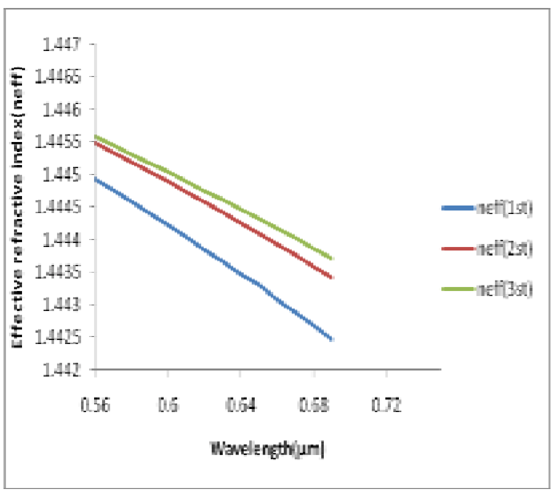

Fig. 2 Simulated effective refractive index of the PCF with corresponding wavelength fixed pitch and different ring holes diameter are

For 2(a) d_1 = 1.5 µm, d_2 = 1 µm, d_3 = 0.5 µm and Λ = 2.4 µm
For 2(b) d_1 = 1.2 µm, d_2 =1 µm , d_3= 0.8 µm and Λ = 2.4 µm
For 2(c) d_1 = 1 µm, d_2= 0.8 µm, d_3 = 0.6 µm and Λ = 2.4µm

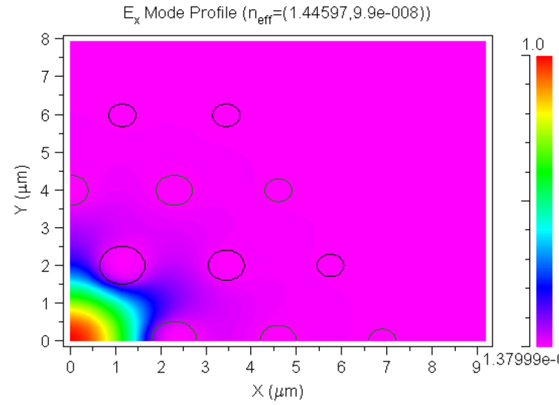

Fig. 3 Simulated mode field (one fourth) part of PCF at wavelength 0.6µm and effective refractive index 1.44597 having three ring hole diameter from inner to outer e.g d_1=1 µm, d_2= 0.8 µm , d_3 = 0.6 µm and pitch Λ=2.4 µm.

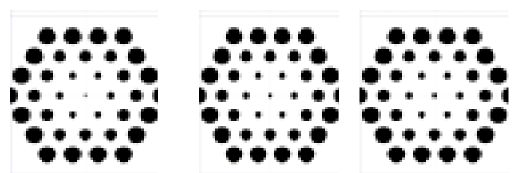

Fig. 4 (a) (b) (c)

For 4 (a) d1= 0.6µm, d2=1.1µm, d3=1.6µm, Λ=2.4µm and d′= 0.2µm.
For 4 (b) d1= 0.6µm, d2=1.1µm, d3=1.6µm, Λ=2.4µm and d′= 0.3µm.
For 4 (c) d1= 0.6µm, d2=1.1µm, d3=1.6µm, Λ=2.4µm and d′= 0.4µm.

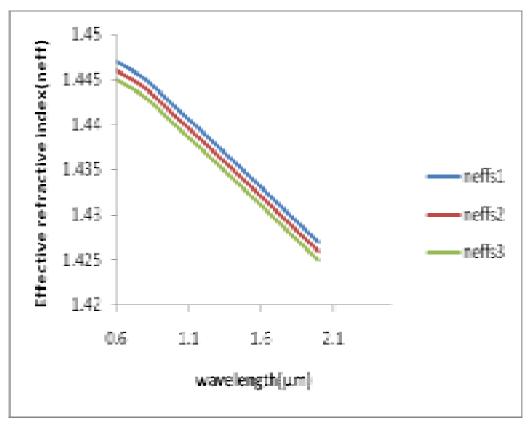

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Fig. 5 Simulated effective index of the PCF with Λ= 2.4µm, d_1= 0.6 µm, d_2=1.1 µm, d_3=1.6 µm and core diameter d′= 0.2 µm, 0.3 µm, 0.4 µm

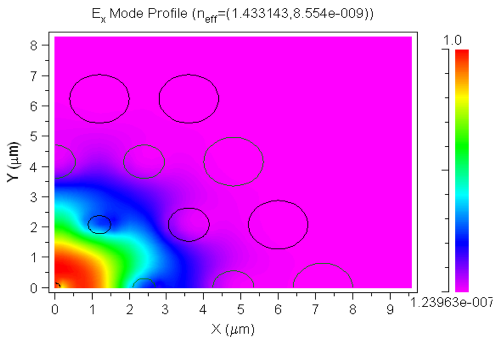

Fig. 6 Simulated mode field of the index-guided(one fourth) part of PCF at wavelength 1.55µm and effective refractive index 1.433143 having three ring hole diameter from outer to inner e. g d_1= 0.6µm,d_2= 0.8µm,d_3=1µm with pitch Λ=2.4µm and core diameter d′=0.2µm.

To find completely non-leaky PCF at 1.55µm three more structures were studied in which diameter of all ring air holes were kept identical (1.38µm).The pitch taken were also same as earlier (2.4µm) and the inner core diameter taken for three structures were 0.2 µm, 0.3µm and 0.4µm respectively as shown in Fig.7.

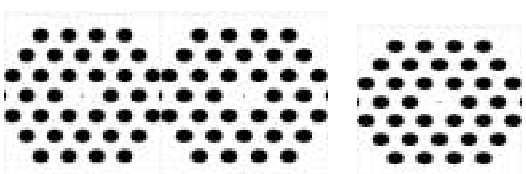

Fig.7 (a) (b) (c)

For 7 (a) d_1= d_2= d_3= 1.38 µm and d′=0.2 µm
For 7 (b) d_1= d_2= d_3 = 1.38 µm and d′=0.3 µm
For 7 (c)d_1= d_2= d_3=1.38 µm and d′=0.4 µm

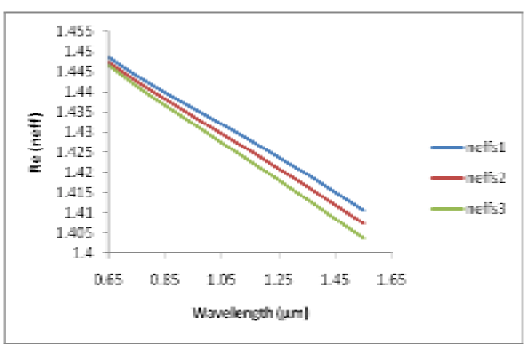

Fig.8 Simulated effective index of the PCF with fixed pitch Λ=2.4µm and three ring holes diameter are 1.38µm for core diameter d′=0.2µm,d′=0.3µm and d′=0. 4µm respectively.

The variation of effective indices with wavelength for above PCFs of identical diameter is shown in Fig 8. It is clear that effective index n_{eff} decreases as d′ increases which also indicates that by increasing the diameter of the air core ability to confine light in core region in PCF weakens. The nature of plot of effective index versus wavelength is very much identical with the conventional fiber.

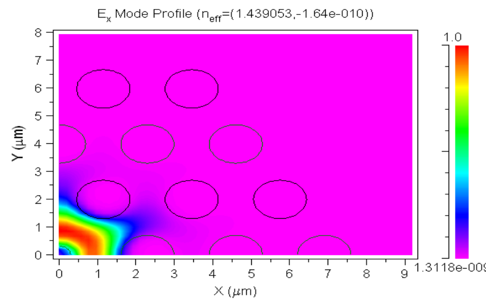

Fig. 9 Simulated mode field (one fourth) of the PCF having all three ring hole diameter d=1.38µm with pitch Λ=2.4µm and core diameter d′=0.2µm at 1.55µm wavelength .

This structure 7(a) gave a surprising result of mode pattern at wavelength 1.55µm as shown in Fig 9. The mode pattern was far better than earlier suggested structure. It shows that this structure is almost non leaky. This structure may be very much useful in communication because loss is minimum at wavelength 1.55µm.

IV CONCLUSIONS

Thus, PCF of particular structure of different 3-ring air hole diameter e.g. d_1 = 1µm, d_2= 0.8µm and d_3 = 0.6µm and same pitch 2.4µm loss of propagated light of wavelength 0.6µm is minimum. The loss increases with increasing the diameters of air ring hole. Then one more index-guided photonic crystal fibre having inner core 0.2µm, pitch 2.4µm and 3-ring air hole diameter d_1= 0.6µm, d_2= 0.8µm and d_3=1µm is also simulated which is bit lossy for light of wavelength 1.55µm. At last the structure is modified and air hole diameter is taken identical having diameter d=1.38µm where as inner core diameter and pitch were taken same as earlier (0.2µm and 2.4µm respectively). In this newly designed PCF, leakage of signal of wavelength 1.55µm is almost non lossy. This PCF is best suitable for communication purpose.

REFERENCES

[1] S. G. Johnson, and John D. Joannopoulos, *Photonic crystals: the road from theory to practice* (Kluwer Academic Publishers 1973).
[2] F. Poli, A. Cucinotta, S. Selleri, Photonic crystal fibers Properties and Apllications, (Springer series in material science, vol.102,First edition 2007).
[3] P. Russell, Photonic Crystal Fibers, *Applied Physics Review* 299 Science,17 January 2003.

[4] J.C. Knight, T.A. Birks, P.St.J. Russell, and D.M. Atkin, All-silica Single –mode optical fiber with Photonic crystal cladding, *Optics letters*, *21*(19) *1996* ,1547.

[5] V. Hugo, A. Velez, F. Javier and T. Pedro, Analysis of Photonic Crystal Fibers:Scalar solution and polarization correction, *Optics Express 14*(11850),27 November 2006.

[6] A. Cucinotta, S. Selleri, L. Vincetti and M. Zoboli, "Holey Fiber Analysis Through the Finite Element Method" *IEEE Photonics Technology Letters*,Vol.14,No.11, November (2002).

[7] J.G. Wang, C. Jiang, W. Hu, and M. Gao, Properties of index-guided PCF with air-core, *Optics & Laser Technology* 39 ,2007,317-321.

[8] H.P. Uranus, H.J.W.M Hoekstra and E.Van Groesen, "Modes of an endlessly single-mode photonic crystal fiber: a finite element investigation. *Proceeding Symposium IEEE/LEOS Benelux Chapter*, 2004.

[9] J. Jin, *The, Finite Element Method in Electromagnetics*(2nd Ed.,John Wiley & Sons, New York,2002).

[10] S. Saitoh and M. Koshiba, Full-Vectorial Imaginary-Distance Beam propagation Method based on a finite element scheme: Application to photonic crystal fiber, *IEEE JQE*, *38*(7),2002,927().

[11] D.Schulz, C. Glingener, M.Bludszuweit and E. Voges, Mixed Finite element Beam Propagation Method, *IEEE JLT*, *16*(7), 1998,1336.

[12] Q. Zhou, X.Q. Lu, D.P. Chen, C.S. Zhu and J.R. Qiu, A new method of modeling cladding band structure of air-guiding photonic crystal fibers, *Journal of Non-Crystalline solids*, *354*, (12)13,2008,1201-1204.

[13] Y.Tsuji, M.Koshiba and T.Shiraishi, Finite Element Beam Propagation Method for three-dimensional optical waveguide structures, *IEEE JLT*,*15*(9), 1997,1728.

[14] M. Koshiba & Y.Tsuji, Curvilinear Hybrid Edge/Nodal Elements with triangular shape for for guided wave problems, *IEEE JLT*, *18*(5), 2000,737.

[15] A.F. Peterson, Vector Finite Element Formulation for scattering from two dimensional Heterogeneous Bodies, *IEEE Trans.on Antennas and propagation*,*43*,(3) 1994,357.

[16] J.C. Nedelec, Mixed finite Element in R^3, *Numerische Mathematik*,*35*, 1980, 315.

[17] H.P. Uranus and J.W.Hoekstr, Modelling of micro structured waveguides using finite element–based vectorial mode solver with transparent boundary conditions,*Opt.Express*,*12*,(12), 2004,2795-2809.

[18] S. Mishra, V. K. Singh & V. Priye, Single Mode Property of Solid-Core Photonic Crystal Fiber by Finite Element Method, *Proceeding of National Seminar held at I.S.M. University, Dhanbad* , 13-15 Oct. 2008,95.

[19] S. Mishra & V. K. Singh, Photonic Crystal Fiber Analysis by Finite Element Method, *Proceeding International* conference, Photonics *2008*, *held at IIT Delhi*, 15-18 Dec. 2008,242.

[20] FEMSIM. *Rsoft Design Group, Ossining*, NY 10562. 1.3.2003.

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