

Highly Nonlinear Dual Core Photonic Crystal Fiber with Low Confinement Loss at 1.55 μ m Wavelength

Vinod K. Singh and S.S. Mishra

Department of Applied Physics, Indian School of Mines, Dhanbad-826004,
Jharkhand, India

Corresponding author: singh.vk.ap@ismdhanbad.ac.in

Abstract— A novel design of Dual-Core Photonic Crystal Fiber (DC-PCF) with silica-air microstructures is proposed in this paper. Nonlinearity and confinement loss of DC-PCF are evaluated by using a Full-Vectorial Finite Element Method (FV-FEM) successfully. By optimizing the geometry of three ring DC-PCFs, a high nonlinearity ($52\text{w}^{-1}\text{km}^{-1}$) and low confinement loss (0.001dB/km) can be achieved at 1.55 μ m wavelength when diameter to pitch ratio (d/Λ) is 0.70.

KEYWORDS: Confinement loss, Full-Vectorial Finite Element Method, Nonlinearity, Photonic Crystal Fiber

I. INTRODUCTION

Recently, Photonic Crystal Fibers (PCFs) with silica-air microstructures have attracted a considerable amount of attention because of their unique properties that are not realized in conventional optical fibers [1]-[6]. PCFs are divided into two different kinds according to light guiding mechanism. The first kind is index guiding PCF, in which light is guided due to total internal reflection between a solid core and multiple air-holes in cladding region. On the other hand, light is guided in a low index core region exhibiting a photonic bandgap (PBG) effect in second kind. The nonlinearity, confinement, dispersion and birefringence of different kinds of PCF were studied by various workers [7]-[18].

In the usual index guiding PCF, there is one defect in the central region and light is guided along this defect. It has been shown that it is possible to use the PCF as an optical fiber coupler by introducing adjacent two defects or

two cores into a PCF. This type of PCF is called Dual-Core Photonic Crystal Fiber (DC-PCF). DC-PCF possesses numerous unusual properties such as high nonlinearity, negative dispersion, low transmission loss and high coupling characteristics [19]-[21]. Among all characteristics properties nonlinearity and confinement loss are important properties of DC-PCF. DC-PCFs are studied experimentally in the year 2000 by Russell *et al.* [22]. DC-PCFs are basically used as coupler, Multiplexer (MUX), De-Multiplexer (DEMUX), different gas sensor and nonlinear optics application [23]-[27]. By optimizing the air hole diameter (d) and pitch Λ , the propagation properties of DC-PCF can be characterized. The different numerical techniques are applied to calculate optical propagation properties of Photonic Crystal Fiber due to its complex structures.

The advantages and disadvantages of different numerical methods are given in Table 1. Among these methods, Full-Vectorial Finite Element Method (FV-FEM) is best suitable to calculate all fundamental propagation properties of the photonic crystal fiber. The effective refractive index, effective mode area, nonlinearity and confinement loss characteristics of dual core PCF are evaluated by using a FV-FEM technique. This mathematical technique is more advantageous to solve the characteristics of PCF than other technique such as BPM [28], EIM [29], FDTD [30], FEM [31] and FMPM [32], etc.

Table 1 Advantages and Disadvantages of Different Numerical Methods

Method	Advantage	Disadvantage
Plane Wave Expansion Method	<ul style="list-style-type: none"> • Simple • Low computation time 	<ul style="list-style-type: none"> • No polarization prop. • Inaccurate modal prop. • No PBG analysis possible
Multipole Method	<ul style="list-style-type: none"> • Describes effect of finite cladding region. • No false birefringence errors • Suited for symmetry study • Leakage loss prediction 	<ul style="list-style-type: none"> • Cannot analyze arbitrary cladding configuration
Finite Difference Time Domain Method (FDTD)	<ul style="list-style-type: none"> • Very general approach. • May describe arbitrary structures. • Well established and tested 	<ul style="list-style-type: none"> • Non modal approach. • Numerically intensive. • Requires detailed treatment of boundaries
Full-Vectorial Finite Element Method (FV-FEM)	<ul style="list-style-type: none"> • Reliable (well established) Method. • Accurate modal solution • Low computation time 	<ul style="list-style-type: none"> • Complex definition of calculation mesh

II. FULL VECTORIAL FINITE ELEMENT METHOD

It is a full vector implementation for both propagation and 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 are employed at computational domain for evaluating effective mode area and birefringence of the proposed PCF [33]. We begin with the source-free time harmonic form of the vector wave equation in an arbitrary, anisotropic lossy media [33]:

$$\nabla \times \left\{ \frac{1}{\mathbf{s}} \nabla \times \mathbf{E} \right\} - k_0^2 \epsilon_r \mathbf{E} = 0 \tag{1}$$

The complex diagonal tensors \mathbf{s} and ϵ_r represent coordinates stretching and the dielectric constant respectively. The mathematical details are given elsewhere [10].

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

$$(A - n_{eff}^2 B) \{E_{Ti}\} = \{0\} \tag{2}$$

where A and B represent global finite matrices, E_{Ti} are transverse electric field and n_{eff} represent the modal effective refractive index, $n_{eff} = \beta/k_0$. Here β is the propagation constant for guided mode and $k_0 = 2\pi/\lambda$ is the propagation constant for free space, where λ is wavelength in free space.

III. DESIGN OF DUAL CORE PHOTONIC CRYSTAL FIBER AND NUMERICAL RESULTS

The cross-section of proposed dual core photonic crystal fiber (DC-PCF) is shown in Fig.1. Here Λ is the pitch and d is the diameter of air hole. The refractive indices of air and silica are taken as 1 and 1.45, respectively.

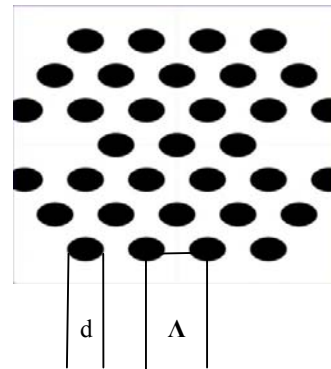


Fig. 1 Cross section of the proposed DC-PCF (Black and white regions represent air holes and silica, respectively). The structure has three dimensions of d/Λ of (i) 0.70, (ii) 0.65, and (iii) 0.60

For first simulation diameter of air hole and pitch are taken as $1.2\mu\text{m}$ and $2\mu\text{m}$, respectively and the effective refractive

indices are calculated for different wavelengths by using FV-FEM technique [33]. It is then observed that mode field pattern is leaky. The air hole diameter is then changed as $1.3\mu\text{m}$ and $1.4\mu\text{m}$ keeping pitch same in three ring fiber structures under study. The mode field pattern of one fourth part of all three structures are given in Fig. 2. It is now observed that mode field pattern becomes more confined when d is $1.4\mu\text{m}$ for which d/Λ is coming to 0.70 .

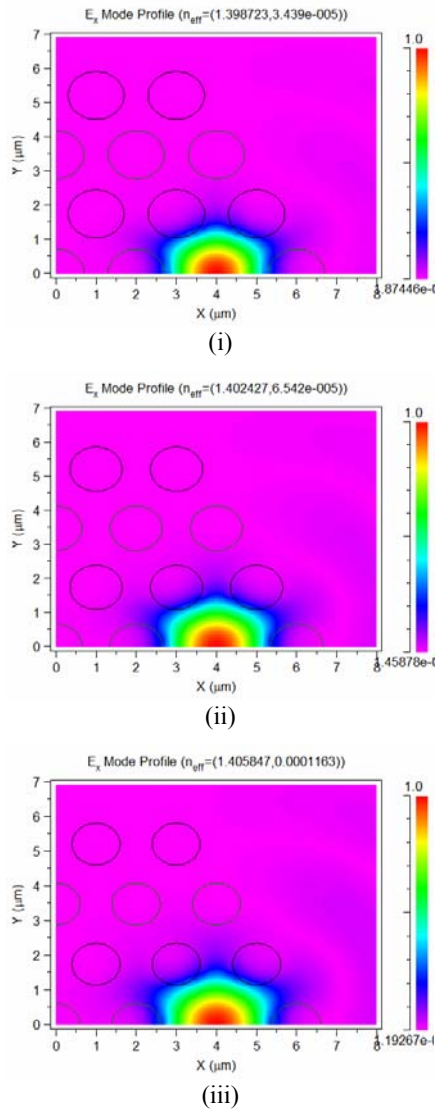


Fig. 2 Simulated Mode Field Pattern of DC-PCF for d/Λ equal to (i) 0.70 , (ii) 0.65 , and (iii) 0.60 Effective Refractive Index

The variation of effective refractive index with wavelength is shown in Fig. 3. It is clear from

Fig.3 that effective refractive index decreases with increase of wavelength for all three structures. The effective refractive index for structure (i), (ii) and (iii) are found as 1.398 , 1.402 and 1.406 respectively, at wavelength $1.55\mu\text{m}$. The effective refractive index is maximum for structure (iii) at wavelength $1.55\mu\text{m}$ which means mode field pattern is very strong and more confined for third structure in comparison to other two structures. This shows that light is guided in this fiber due to index guiding mechanism in dual core region of PCF.

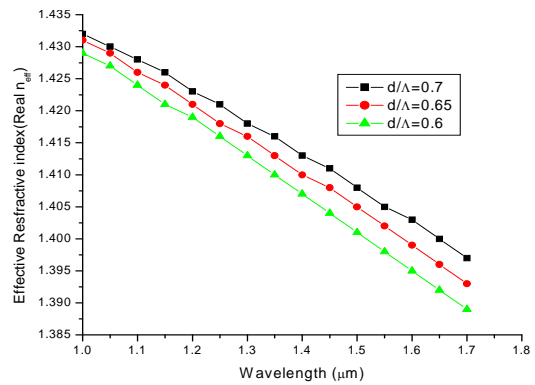


Fig. 3 Variations of effective refractive index spectra for three structures with different d/Λ .

A. Effective Mode Area and Nonlinearity

Effective mode area parameter of DC-PCF is important parameter for the calculation of nonlinearity. By using FV-FEM, Effective mode area, A_{eff} , and nonlinear coefficient, γ for DC-PCF can also be calculated by using following formula [10]:

$$A_{eff} = \frac{\left(\int_{-\infty}^{+\infty} |E|^2 dx dy \right)^2}{\int_{-\infty}^{+\infty} |E|^4 dx dy} \quad (3)$$

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \times 10^3 \text{ W}^{-1} \text{ km}^{-1} \quad (4)$$

where, E is the electric field, λ is the wavelength and n_2 is the nonlinear refractive index.

Once effective mode area is calculated using Eq. (3), the nonlinear coefficient of DC-PCF

can be known very easily by using Eq. (4). Fig.4 shows variation of effective mode area with wavelength. It is clear that effective mode area increases with increasing wavelength for all three structures. The effective mode area is found to be $2.34\mu\text{m}^2$ at wavelength $1.55\mu\text{m}$ for structure (iii) which is minimum compared to other structures. Fig.5 shows the variation of nonlinear coefficient with wavelength in near infrared region. It is clear from Fig.5 that nonlinear coefficient decreases with increasing wavelength for all three structures. The nonlinearity is also maximum $52\text{ w}^{-1}\text{km}^{-1}$ for structure (iii) at wavelength $1.55\mu\text{m}$.

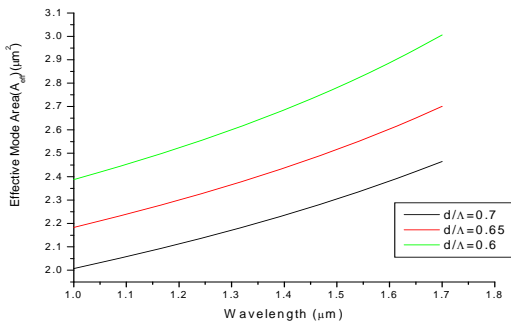


Fig. 4 Variations of Effective Mode Area spectra for three structures with different d/Λ .

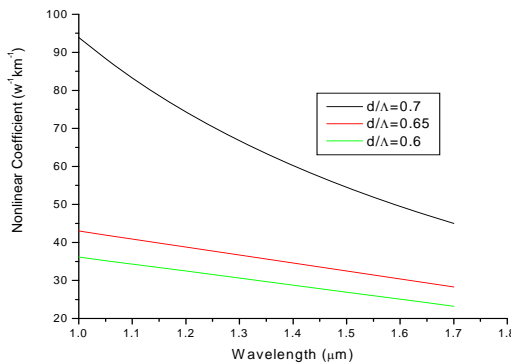


Fig. 5 Variations of Nonlinear coefficient spectra for three structures with different d/Λ .

Table 2 Calculated values of Effective refractive index (n_{eff}), Effective mode area (A_{eff}), nonlinearity and confinement loss of proposed DC-PCF at wavelength of $1.55\mu\text{m}$

DC-PCF				
Structure Parameter d/Λ	n_{eff} (Real)	A_{eff} (μm^2)	Nonlinearity ($\text{w}^{-1}\text{km}^{-1}$)	Confinement Loss (dB/km)
0.60	1.398	2.83	26	0.004
0.65	1.402	2.55	31	0.002
0.70	1.406	2.34	52	0.001

B. Confinement Loss

The confinement loss is an important property of PCF. Once the imaginary part of effective refractive index is calculated using FV-FEM, confinement loss (dB/km) can be easily calculated by using following formula:

$$\text{Confinement loss} = 8.686k_0 \text{Im}[n_{eff}] \quad (5)$$

where $k_0 = 2\pi/\lambda$, λ is the propagation wavelength.

Figure 6 shows that the confinement loss increases with increasing wavelength. It is observed from Table 2 that the confinement loss is minimum (0.001dB/km) for structure (iii) at wavelength $1.55\mu\text{m}$ in comparison to other structures of proposed DC-PCF.

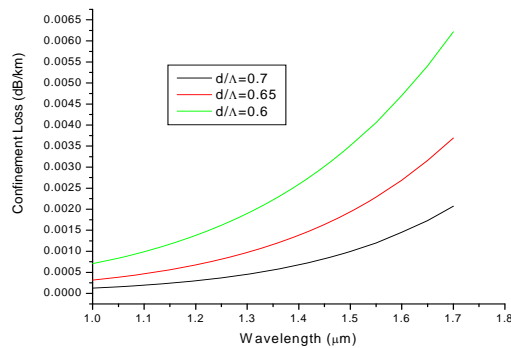


Fig. 6 Variations of effective refractive index spectra for three structures with different d/Λ .

IV. CONCLUSION

A Dual Core PCF with an effective refractive index of 1.405 and effective mode area of $2.34\mu\text{m}^2$ was proposed at wavelength $1.55\mu\text{m}$ when diameter to pitch ratio was 0.70 and thereby both high nonlinearity ($52\text{ w}^{-1}\text{km}^{-1}$) and low confinement loss (0.001dB/km) were achieved. This kind of PCF may be used as fiber coupler, fiber laser and different gas sensing purposes.

REFERENCES

- [1] S.G. Johnson and J.D. Joannopoulos, *Photonic Crystals: the road from theory to practice*, Kluwer Academic Publishers, 1973.
- [2] P. Russell, "Photonic Crystal Fibers," *Rev. Appl. Phys.* Vol. 299, pp. 358-362, 2003.
- [3] J.C. Knight, "Photonic crystal fiber," *Nature* Vol. 424, pp. 847-851, 2003.

- [4] J.C. Knight, J. Broeng, T.A. Birks and P.S.J. Russell "Photonic band gap guidance in optical fiber," *Science*, Vol. 282, pp. 1476–1478, 1998.
- [5] G.P. Agrawal, *Nonlinear Fiber Optics*, Academic press (San Diego, CA) 2nd Ed. 1995.
- [6] A.K. Ghatak and K. Thyagarajan, *Introduction to Fiber Optics*, Cambridge University Press, 2002.
- [7] P. St. J. Russell, "Photonic-crystal fibers," *IEEE J. Lightwave Technol.* Vol. 24, pp. 4729-4749, 2006.
- [8] F. Luan, A.K. George, T.D. Hedley, G.J. Pearce, D.M. Bird, J.C. Knight, and P. St. J. Russell, "All-solid photonic bandgap fiber," *Opt. Lett.* Vol. 29, pp. 2369–2371, 2004.
- [9] S.S. Mishra and V.K. Singh "Study of Dispersion properties of Hollow-core Photonic Crystal Fiber by Finite Element Method," *J. Optoelectronics and Advance Materials-Rapid Commun.* Vol. 3, pp. 874-878, 2009.
- [10] S.S. Mishra and V. K. Singh "Study of Fundamental Propagation Properties of Solid Core Holey Photonic Crystal Fiber in Telecommunication window", *Chin. J. Phys.* Vol. 48, pp. 592-606, 2010.
- [11] S.S. Mishra and V.K. Singh "Highly Birefringent Photonic Crystal Fiber with Low Confinement Loss at Wavelength 1.55 μm ," *J. Light, Electron and Optics, OPTIK*, Vol. 122, pp. 1975-1977, 2011.
- [12] S.S. Mishra and V.K. Singh, "Comparative Study of Fundamental Properties of Honey Comb Photonic Crystal Fiber at 1.55 μm Wavelength," *J. Microwave Optoelectronics Electromagnetic Research*, Vol. 10, pp. 343-354, 2011.
- [13] Y. Xu and A. Yariv, "Loss analysis of air-core Photonic Crystal fibers," *Opt. Lett.* Vol. 28, pp. 1885-1887, 2003.
- [14] M. Ji, Z. Shi, and J. Lin, "Observation and Explanation of bending Characteristics in solid core photonic crystal fibers," *Microwave and Optical Technol. Lett.* Vol. 50, pp. 1178-1180, 2008.
- [15] T. Hong-da, Y. Zhong-Yuan, H. Li-hong, and L. Yu-min, "Effect of the structural parameters of photonic crystal fibers on propagation characteristics," *J. China University of posts and Telecommun.* Vol. 16, pp. 89-93, 2009.
- [16] X. Sang, C. Yu, M.K. Islam, and N.G. Lu, "Generation of Photon pairs in highly nonlinear photonic crystal fiber for quantum information processing," *J. Optoelectronics and advanced materials*, Vol. 8, pp. 1895-1900, 2006.
- [17] K. Saitoh, N.J. Florous and M. Koshiba, "Ultra-flattened chromatic dispersion controllability using a defected core photonic crystal fiber with low confinement losses," *Opt. Express*, Vol. 13, pp. 8365-8371, 2005.
- [18] F. Poli, A. Cucinotta, S. Selleri, and A.H. Bouk, "Tailoring of flattened dispersion in highly nonlinear photonic crystal fibers," *IEEE Photon. Technol. Lett.* Vol. 16, pp. 1065-1067, 2004.
- [19] Y. Ni, L. Zhang, L. An, J. Peng, and C. Fam "Dual core photonic Crystal Fiber for Dispersion Compensation," *IEEE Photon. Technol. Lett.* Vol. 16, pp. 1516-1518, 2004.
- [20] K. Saitoh, Y. Sato, and M. Koshiba "Coupling Characteristics of dual-core Photonic Crystal Fiber," *Opt. Express* Vol. 11, pp. 3188-3195, 2003.
- [21] R. Jha, J. Villatoro, and G. Badenes, "Ultrastable in reflection photonic crystal fiber modal interferometer for accurate refractive index sensing," *Appl. Phys. Lett.* Vol. 93, pp. 191106 (1-3), 2008.
- [22] D. Chen, G. Hu, and L. Chen, "Dual-Core Photonic Crystal Fiber for Hydrostatic Pressure sensing," *IEEE Photon. Technol. Lett.* Vol. 23, pp. 1851-1853, 2011.
- [23] M.F.O. Hameed and S.S.A. Obaya, "Coupling Characteristics of Dual Liquid Crystal Core Soft Glass Photonic Crystal Fiber," *IEEE Quantum Electron.* Vol. 48, pp. 1283-1290, 2011.
- [24] D. Monzon-Hernandez, V.P. Minkovich, J. Villatoro, M.P. Kreuzer, and G. Badenes, "Photonic crystal fiber microtaper supporting two selective higher-order modes with high sensitivity to gas molecules," *Appl. Phys. Lett.* Vol. 93, pp. 081106 (1-3), 2008.
- [25] J. Villatoro, M.P. Kreuzer, and R. Jha, "Photonic crystal fiber interferometer for chemical vapor detection with high sensitivity," *Opt. Express*, Vol. 17, pp. 1447–1453, 2009.
- [26] H.Y. Choi, K.S. Park, and B.H. Lee, "Photonic crystal fiber interferometer composed of a long

- period fiber grating and one point collapsing of air holes,” *Opt. Lett.* Vol. 33, pp. 812–814, 2008.
- [27] G. P. Agrawal, *Fiber-Optic Communications Systems*, New York: Wiley, 1997.
- [28] F. Fogli, L. Saccomandi, P. Bassi, G. Bellanca, and S. Trillo, “Full vectorial BPM modeling of indexguiding photonic crystal fibers and couplers,” *Opt. Express* Vol. 10, pp. 54-59, 2002.
- [29] A.D. Varshney and R.K. Sinha “Nonlinear Properties of photonic crystal fiber: Improved Effective index Method,” *Chin. J. Phys.* Vol. 47, pp. 184-191, 2009.
- [30] M. Qiu “Analysis of guided modes in photonic crystal fibers using the Finite-Difference Time-Domain Method,” *Microwave and Optical Technol. Lett.* Vol. 30, pp. 327-30 2001.
- [31] L. Zhao-lun, H. Lan-tian, and W. Wei “Tailoring Nonlinearity and Dispersion of Photonic crystal Fibers using Hybrid cladding,” *Brazilian J. Phys.* Vol. 39, pp. 50-54, 2009.
- [32] W. Song, Y. Zhao, Y. Bao, S. Li, Z. Zhang, and T. Xu, “Numerical Simulation and Analysis on mode property of photonic crystal Fiber with high birefringence by Fast Multipole Method,” *PIERS online*, Vol. 3, pp. 836-841, 2007.
- [33] FEMSIM Rsoft Design Group, Ossining, NY 10562, 1. 3. 2007.



Vinod Kumar Singh was born in Bihar, India on January 02, 1964. He received the M.Sc.

degree in Physics with Electronics as specialization from Bhagalpur University, Bihar. After getting M. Phil. and Ph.D. degrees from I. S. M., Dhanbad, Jharkhand, India, he joined as Senior Lecturer in the Department of Applied Physics, I. S. M. He is now Assistant Professor in the same Department. His areas of research are Fiber Optics and Design, Fabrication and Characterization of PCFs. He has published more than 33 papers so far in different Journals and Conferences.



S. S. Mishra was born in Orissa, India on December 9, 1982. He received the M.Sc. degree in physics from North Orissa University, Baripada, Orissa, India in 2005. He has completed his Ph.D. from Department of Applied Physics, ISM Dhanbad under the guidance of Dr. Vinod K. Singh. Presently, he is Post Doctorate fellow in Optical communication Lab. of Hoseo University, South Korea. The area of research interests of Dr. Mishra are design, fabrication and characterization of PCFs for new optical applications including nonlinear optics.