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

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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 ($52w^{-1}km^{-1}$) and low confinement loss (0.001dB/km) can be achieved at 1.55μm 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	• Simple • Low computation time	• No polarization prop. • Inaccurate modal prop. • No PBG analysis possible
Multipole Method	• Describes effect of finite cladding region. • No false birefringence errors • Suited for symmetry study • Leakage loss prediction	Cannot analyze arbitrary cladding configuration
Finite Difference Time Domain Method (FDTD)	• Very general approach. • May describe arbitrary structures. • Well established and tested	• Non modal approach. • Numerically intensive. • Requires detailed treatment of boundaries
Full-Vectorial Finite Element Method (FV-FEM)	• Reliable (well established) Method. • Accurate modal solution • Low computation time	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]:

$$\nabla \times \left\{ \frac{1}{\mathbf{s}} \nabla \times \mathbf{E} \right\} - k_0^2 \varepsilon_r \mathbf{E} = 0 \qquad (1)$$

The complex diagonal tensors **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:

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

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.

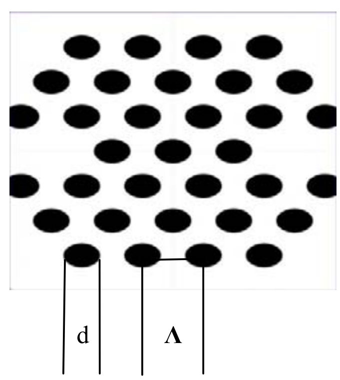

Fig. 1 Cross section of the proposed DC-PCF (Black and white regions represent air holes and silica, respectively). The structure has three dimensions of *d/Λ* of (i) 0.70, (ii) 0.65, and (iii) 0.60

For first simulation diameter of air hole and pitch are taken as 1.2μm and 2μm, 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 1.3µm and 1.4µm 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 µm for which *d/Λ* is coming to 0.70.

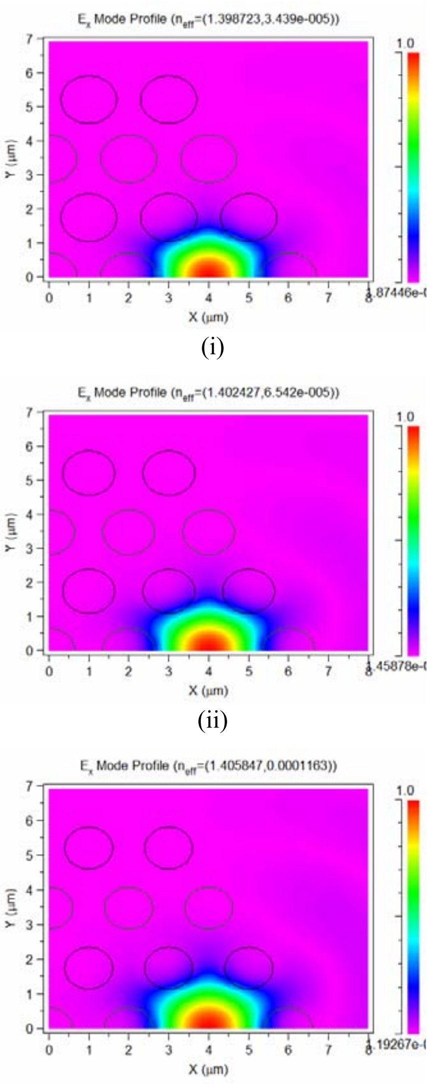

Fig. 2 Simulated Mode Field Pattern of DC-PCF for d/Λ equal to (i) 0.70, (ii) 0.65, and (iii) 0.60 Effective Refractive Index

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 1.55µm. The effective refractive index is maximum for structure (iii) at wavelength 1.55µm 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.

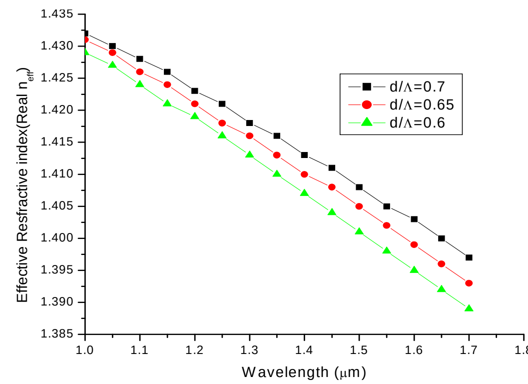

Fig. 3 Variations of effective refractive index spectra for three structures with different *d/Λ*.

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]:

$$A_{eff} = \frac{\left(\int_{-\infty}^{+\infty} |E|^2 \, dxdy \right)^2}{\int_{-\infty}^{+\infty} |E|^4 \, dxdy} \tag{3}$$

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \times 10^3 \ \mathrm{W^{-1}km^{-1}} \tag{4}$$

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 2.34μm^2 at wavelength 1.55μm 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 w^{-1}km^{-1} for structure (iii) at wavelength 1.55 μm.

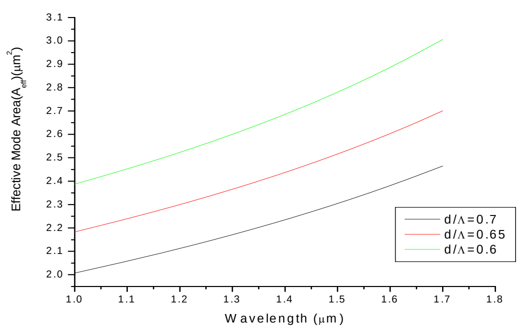

Fig. 4 Variations of Effective Mode Area spectra for three structures with different d/Λ.

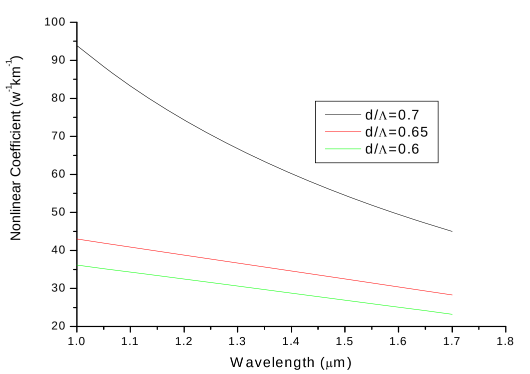

Fig. 5 Variations of Nonlinear coefficient spectra for three structures with different d/Λ.

Table 2 Calculated values of Effective refractive index (neff), Effective mode area (Aeff), nonlinearity and confinement loss of proposed DC-PCF at wavelength of 1.55μm

DC-PCF Structure Parameter d/Λ	n_{eff} (Real)	A_{eff} (μm^2)	Nonlinearity (w^{-1}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:

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

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 1.55μm in comparison to other structures of proposed DC-PCF.

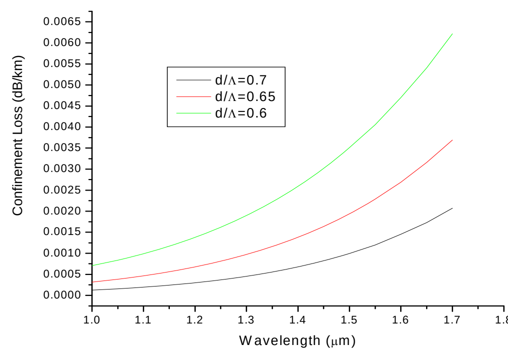

Fig. 6 Variations of effective refractive index spectra for three structures with different d/Λ.

IV. Conclusion

A Dual Core PCF with an effective refractive index of 1.405 and effective mode area of 2.34μm^2 was proposed at wavelength 1.55 μm when diameter to pitch ratio was 0.70 and thereby both high nonlinearity (52 w^{-1}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.

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