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Numerical Analysis of Dispersion and Endlessly Single Mode Property of a Modified Photonic Crystal Fiber Structure

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ABSTRACT

Photonic crystal fibers(PCF) are more versatile, intriguing and promising than conventional optical fiber. PCFs are divided into two different kinds, the index-guiding PCF and the photonic band-gap (PBG) effect PCF. In conventional index-guiding PCF, there is a lattice of air holes in the silica background, which surround the core. Light in this fiber is guided through the high index solid silica core by total internal reflection mechanism. Fundamentally different from all high index core conventional photonic crystal fiber, in this paper, we propose a new type of Photonic Crystal Fiber (PCF) structure; where instead of using the air-holes in the cladding region, we use boron doped solid silica rods in order to reduce the problems associated with deformities of air-holes in the fabrication of PCF. Also, we analyze few of the properties of the proposed photonic crystal fiber structure such as Endlessly Single Mode(ESM) property and tunable dispersion, and compared with conventional photonic crystal fiber.

Keywords: Endlessly Single Mode(ESM), Photonic Band Gap(PBG), Photonic Crystal Fiber(PCF), Standard Optical Fibers (SIF)

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1.INTRODUCTION

Photonic crystals have attracted a great deal of attention in the optics community in recent years. One of the most promising applications of photonic crystals is the possibility of creating compact integrated optical devices with photonics as the carriers of information, and then the speed and bandwidth of advanced communication systems can be increased dramatically. Photonic crystal fibers (PCFs), a kind of two dimension photonic crystals, consisting of a central defect region surrounded by multiple air holes that run along the fiber length are attracting much attention in recent years because of unique properties which are not realized in conventional optical fibers. PCFs are divided into two different kinds of fibers. The first one is index-guiding PCF, guiding light by total internal reflection between a solid core and a cladding region with multiple air-holes. The second one uses a perfectly periodic structure exhibiting a photonic band-gap (PBG) effect at the operating wavelength to guide light in a low index core-region. Index-guiding PCFs, also called holey fibers or microstructure optical fibers, possess especially attractive property of great controllability in chromatic dispersion by varying the hole diameter and hole-to-hole spacing [1-4].

During the last decade, lot of research work is going on in the field of photonic crystal fiber. In fact, the technological control of the PCF characteristics is nowadays comparable to that of standard fibers: Photonic crystal fiber having attenuation loss below 0.3 dB/km has been recorded [5]. Index-guiding PCFs possess the attractive property of great controllability in chromatic dispersion by varying the hole diameter (d) and hole-to-hole spacing (Λ). So far, various PCFs with remarkable dispersion properties such as, zero dispersion wavelengths shifted to the visible and near-infrared wavelengths [6,7], ultra-flattened chromatic dispersion [8-9], and a large positive dispersion with a negative slope in the 1.55 μm wavelength range [10], have been reported. Obtaining photonic crystal fibers with required transmission characteristics is a difficult technological problem. One has to shape structures of microscopic size by controlling only macroscopic parameters such as temperature and stretching rate. [11].

In order to avoid the deformities of air-holes of the conventional PCF and to minimize the difficulties associated with fabrication process, we propose a new type of PCF structure, wherein, boron doped solid silica rods are used in the cladding region instead of air-holes. By having a structure like this, not

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only fabrication process becomes simpler but also the proposed PCFs have endlessly single mode and tuneable dispersion properties.

2. PROPOSED PHOTONIC CRYSTAL FIBER STRUCTURE

Fig.1 is of a conventional photonic crystal fiber with a triangular lattice of holes, where *d* is the hole diameter, Λ is the hole pitch, and the refractive index of silica is 1.45. In the centre, an air hole is omitted creating a central high index defect serving as the fiber core.

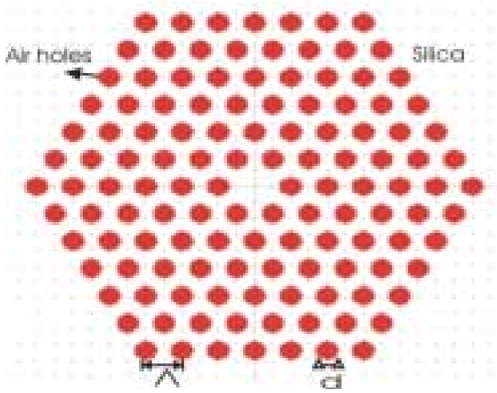

Fig.1: Conventional Photonic Crystal Fiber

The main fabrication problems in conventional photonic crystal fiber are presence of deformed air holes, emergence of additional holes, and perturbations of the structure's symmetry. Even though the photonic crystal fiber has so many advantages over conventional single mode fibers, we fail to use photonic crystal fibers practically. The main reason for this is difficulties associated with fabrication of conventional photonic crystal fibers and deformation of air-holes during fabrication.

By doping pure silica with impurity, the refractive index increases or decreases depending upon the type of impurity added. Doping of silica with materials such as fluorine/boron decreases the refractive index as the doping concentration is increased as shown in Fig. 2. [12] In our proposed PCF structure, silica is doped with boron with a concentration of f=0.135 (13.5 %). From Fig 2, it can be seen that for any given wavelength the refractive index of pure silica is decreased considerably for doping concentration of 13.5%. For light to propagate, it is required that core refractive index should be more than the refractive index of the cladding. By having an arrangement, wherein a solid pure silica rod acting as core and boron doped silica rods in the cladding region, it is possible that light will propagate by modified total internal reflection (MTIR) similar to that of conventional PCF.

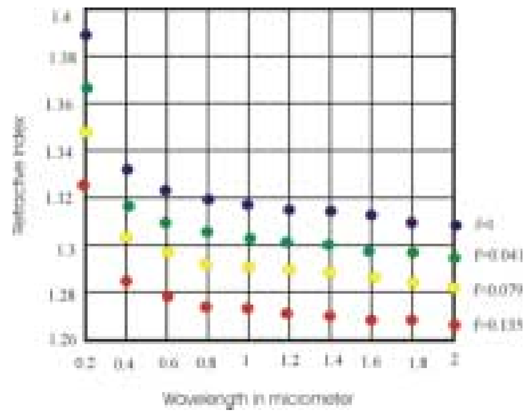

Fig.2: Effect of boron doping on refractive index of pure silica.

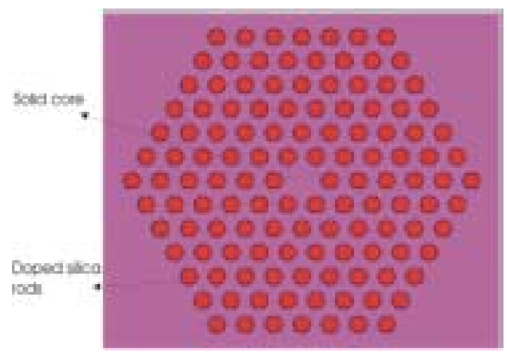

Fig. 3: Proposed PCF Structure

Fig.3 shows the proposed photonic crystal fiber having pure solid silica rod in the centre as core and boron doped solid silica rods in the cladding region instead of air-holes as in conventional PCF.

3. NUMERICAL ANALYSIS

Properties of standard optical fibers (SIF) are often parameterized by the so called V parameter (normalized frequency) and the entire concept is very close to the heart of the majority of the optical fiber community. The cut-off properties and the endlessly single-mode(ESM) phenomena of PCFs can also be qualitatively understood within this framework. For an operating wavelength, if the value of V parameter is less than or equal to 2.405, then the fiber is said to be operating in the single mode regime in standard optical fiber. The SIF is characterized by the core radius ρ, the core index n_{co}, and the cladding index n_{cl} which all enter into the parameter V_{SIF} given by, [13]

$$V_{SIF} = \frac{2\pi\rho}{\lambda}\sqrt{(n_{co}^2 - n_{cl}^2)} \quad \text{-----------------(1)}$$

The photonic crystal fiber is analyzed by eq.(2) given below [14] because there is no consideration of pitch

(Λ), and diameter (d) in eq.(1).

$$V = \frac{2\pi a_{eff}}{\lambda}\sqrt{(n_{co}^2 - n_{FSM}^2)} = \sqrt{(U^2 + W^2)}$$
--------------------------------------(2)

where U & W are known as normalized transverse phase and attenuation constants, given by eq. (3). Where a_{eff} is the effective core radius and is given by $a_{eff} = \frac{\Lambda}{\sqrt{3}}$, n_{co} is core refractive index, n_{FSM} is cladding index, n_{eff} is the index of the fundamental guided mode, λ is operating wavelength.

$$U = \frac{2\pi a_{eff}}{\lambda}\sqrt{(n_{co}^2 - n_{eff}^2)} \quad \text{and}$$

$$W = \frac{2\pi a_{eff}}{\lambda}\sqrt{(n_{eff}^2 - n_{FSM}^2)} \quad \text{--------------(3)}$$

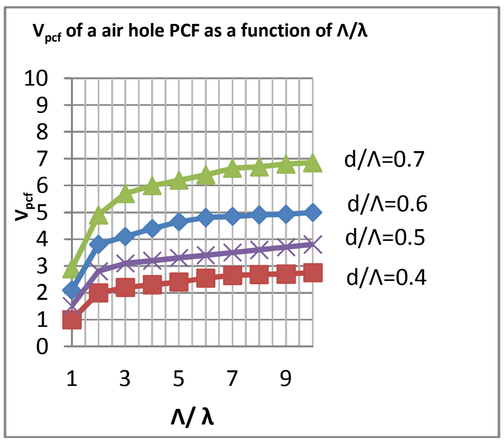

Fig.4(a): Effective V parameter for different values of d/Λ in Air-Hole PCF

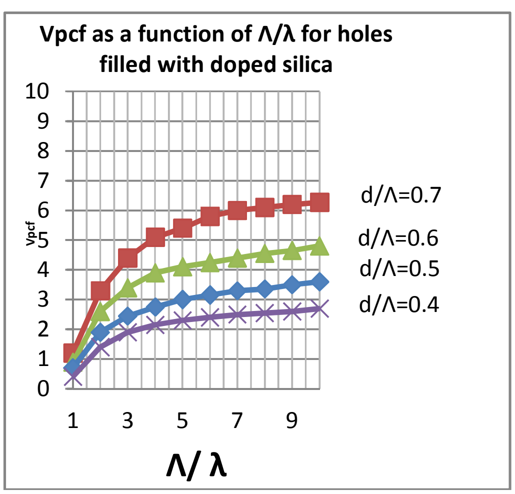

Fig.4(b): Effective V parameter for different values of d/Λ in proposed PCF

A full-vector finite element method (FEM) can be used to analyze the chromatic dispersion property. Alternately, we can also use empirical relations [14] for the analysis of dispersion property of photonic crystal fiber. By trial and error method, we get the values of V and W parameters comparable with the values obtained from finite element method (FEM). Then, the values of n_{FSM} for different wavelengths are determined using eq.(2). Once we have the values of V, W, and n_{FSM}, we can easily find out the effective refractive index from eq. (2) and eq.(3).

4. RESULTS AND DISCUSSION

The proposed photonic crystal fiber structure also shows the cut-off property. It has the advantage of having the cut- off V parameter less than π for a higher value of d/Λ, i.e., 0.46 whereas conventional PCF has cut-off at d/Λ of 0.425. A higher value of d/Λ simplifies the fabrication process. At the same time, the proposed photonic crystal fiber shows endlessly single mode property. For our proposed new structure, the value of the effective V parameter should be less than that of the air hole PCF as there is a low refractive index contrast between core and cladding for the same value of d/Λ. Fig.4(b) shows the effective V parameter of proposed PCF for different values of d/Λ. We can examine the above said low values of V parameter for same value of d/Λ for air-hole PCF and proposed PCF by comparing Fig.4(a) and Fig.4(b). For d/Λ of 0.4, the value of V parameter is 2.6 for proposed PCF whereas for air-hole PCF it is 2.8 for a value Λ/λ of 10.

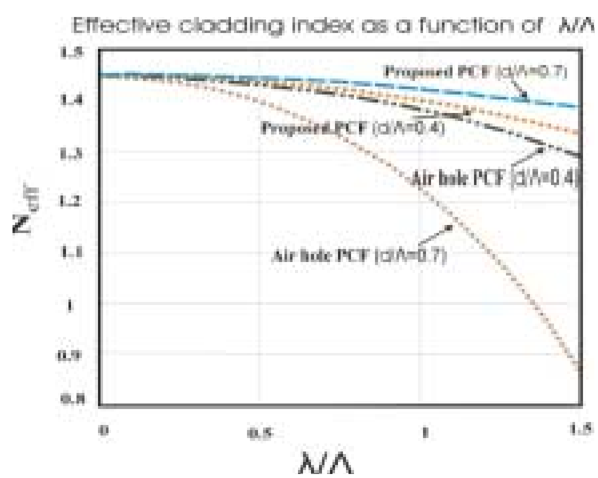

Fig.5:Effective refractive index of conventional PCF and proposed (doped silica rods in cladding region)PCF for different values of d/Λ.

Fig.5 shows the variation in the effective refractive index in conventional photonic crystal fiber and proposed photonic crystal fiber structure for the same value of d/Λ. The waveguide dispersion D_{WG} of a PCF for a particular wavelength is easily calculated from the n_{eff} value using the following equation.

$$D_{WG} = -\frac{\lambda}{c}\frac{d^2 \,\mathrm{Re}(n_{eff})}{d\lambda^2} \qquad \text{---------------(4)}$$

where c is the velocity of light in a vacuum and Re (n_{eff}) stands for the real part n_{eff}. The material dispersion is given by Sellmeier formula and to get chromatic dispersion we have to add it to waveguide dispersion

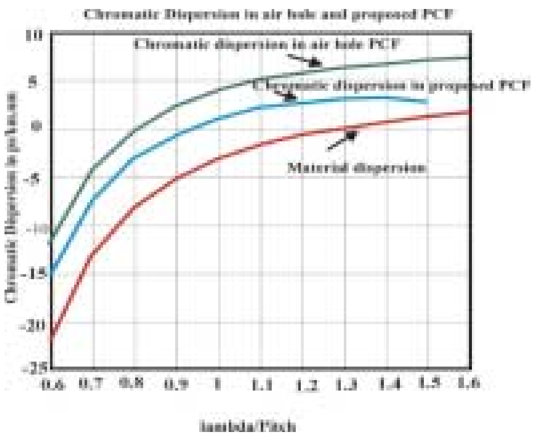

Fig.6: Chromatic dispersion in air hole and proposed PCF for d/ Λ value of 0.4

Fig.6 shows the chromatic dispersion in the conventional and proposed photonic crystal fiber. Using photonic crystal fiber, it is possible to shift zero dispersion wavelength below 1.3 µm, as shown in Fig.6. This property is not possible in single mode fiber. The zero dispersion wavelength is shifted from 1.3 µm to 0.8 µm and 0.9 µm for conventional and proposed photonic crystal fiber respectively.

5. CONCLUSIONS

In this paper a pure solid silica rod in the centre as core and boron doped solid silica rods in the cladding region instead of air-holes as in conventional PCF is proposed. This new proposed PCF will potentially overcome the fabrication challenge. All though Photonic Crystal Fibers are more versatile, intriguing and promising than conventional fibers, we are not able to use photonic crystal fibers practically for communication applications. This is due to non availability of long length photonic crystal fiber, as its fabrication is difficult, and in addition to this, there is a problems with deformities of air holes. The proposed fiber is free from the problems associated with deformities of air holes, as boron doped silica rods are used in the cladding region instead of air holes. Few properties of the proposed PCF such as endlessly single mode and chromatic dispersion are analysed. These properties are compared with that of conventional air hole photonic crystal fiber and found to be in close agreement.

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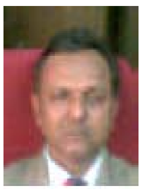

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