A Comparative Analysis of Photonic Crystal Fiber at Communication Band in different Material Regime

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Abstract—*In the present work we have reported photonic crystal fiber (PCF) modeling based on effective index method. By means of effective index method; numerical investigation has been carried out for a photonic crystal fiber (PCF) in different material domain such as phosphate and crown. These materials have dissimilar refractive indices than that of conventional holey fiber i.e., silica. Moreover, the results of the two have been compared with experimental data yielding consistent results supporting our theoretical investigation. By varying the structural parameters like λ, d/Λ, d/λ, Λ within communication band the observed characteristics of phosphate has been compared with that of crown based PCF. The theoretical analysis shows that crown material based PCF has more beam quality control than phosphate material based PCF. Additionally, the dispersion shows a remarkable variation in case of crown material based PCF that indicates substantial reduction in power loss than that of phosphate material based PCF. An innovative work has been performed for modeling photonic crystal fiber in different material regime in the communication band domain.*

1. INTRODUCTION

In the year of 1992, P. Russell first invented photonic crystal fiber (PCF) using two dimensional photonic crystals. Later on in 1996 photonic crystal fiber (PCF) was reported first at the Optical Fiber Conference (OFC) [1]. PCF is composed of small air holes with diameter (d) and gap between air holes which is regarded as pitch (Λ) [1]. The design of PCFs becomes flexible with alteration of d and Λ. Additionally, refractive index of the glass and type of lattice also plays a vital role in structure modification of PCFs. Possession of flexible design parameters of PCF make them act like endlessly single mode fibers and it continues its single mode structure for a wide optical range [2]. There are certain applications in this type of fiber; which is not possible to perform by conventional fiber [3]. As mentioned earlier, tuning structural parameters of PCF lead to acquisition of some unique properties such as lower dispersion, single mode operation for a wide range of wavelength [1] [4]. It can transmit by two guiding techniques: Air-guiding and index guiding. In air-guiding mechanism the fiber uses periodic structure which guides light through the fiber using photonic-band gap effect. Light is basically confined to the core by backscattering of light into the core [5], whereas, in index-guiding light is guided through the fiber using total internal reflection (TTL) process. This technique is almost like conventional fiber [6-7]. PCF includes certain explicit characteristics such as photonic-band gap fiber (PCFs that confine light by band gap effects), holey fiber (PCFs using air holes in their cross-sections), hole-assisted fiber and Bragg fiber. PCFs can also be considered as a subgroup of a more general class of microstructured optical fibers, in which light is guided not only by refractive index differences but also by structural modifications [8-9]. It has several applications in fiber-optic communications, fiber lasers, nonlinear devices, high-power transmission, sensors and in other areas; because of its ability to confine light in hollow cores which is not possible in conventional optical fiber [10]. Along with sensing based applications; waveguide modeling and detailed analysis of modal properties can also be done of photonic crystal fiber. As mentioned earlier, this unique type of fiber has developed which has photonic band-gap structure.

Photonic crystal fiber is proposed to acquire certain properties like single mode operation over a wide wavelength range, allowing nonlinear effects for small mode area, large mode area for creating high-power optical beams, an enormous control over dispersion for variable air-hole diameter (d) and pitch (Λ) [11]. As it have the above mentioned characteristics unlike conventional fiber; it can be useful for theoretical modeling. Several numerical techniques have been established to evaluate the guiding properties of PCF such as finite difference time domain method (FDTD) [12-13], finite element method (FEM) [13], effective index method (EIM) [6]. As PCF is influenced by some dimensionless quantities like d/Λ and λ/Λ which can be used for designing purpose and also to establish certain modal property [1]. There are several methods that can be used to design PCF, but out of all the mentioned methods EIM methods are more adaptable to find out the measurable quantities and also it takes lesser time compared to other methods. Most important point is that, this technique is also suitable for deviation in refractive index of 0.01 and thus for a small change in refractive index can change the measurable parameters [3].

The PCF under this study has been framed for seven missing air hole having air hole distance around 2.3μm. Since, effective refractive index of cladding and core radius of PCF influence the modal parameters; we entail effective index method (EIM) to compute the guiding aspects of Photonic Crystal Fiber. Material refractive index has a huge contribution towards modal parameter variation in the effective index method. Incorporating different materials such as phosphate, crown and silica effective index method has been carried out in S communication band. The refractive index of the materials has an enormous contribution to the variation in modal parameters. A certain specific parameters range has been considered during the analysis in which we have considered over large parameter region of d/ʌ (0.15-0.6) and λ/ʌ (0.05-0.5) primarily in the S communication band.

2. MATHEMATICAL FORMULATION

In this piece of work, some empirical relation's has been utilized to evaluate V parameter; which is basically the controlling parameter of the number of modes in case of fiber. Light propagation in a waveguide is dependent on the numerical value of V [2]. The analyzed V parameter has been used to evaluate the modal parameters PCF with two compositional elements. There are two basic tunable parameters such as air hole diameter and pitch; based on which spot size as well as the effective mode area can be altered.

The modal parameter's are defined as follows:

2.1 V parameter

The model properties of fiber can be characterized by this parameter. The modes of operation of a particular fiber can be explained using V values which has a cutoff of 2.045 for single mode operation.

$$V = \frac{2\pi}{\lambda} R \sqrt{n_{co}^2 - n_{cl}^2} \quad (1)$$

Here, n_{co} and n_{cl} are core and cladding refractive indices respectively and *R* is radius of core and is considered to be ʌ/√3 [10] for the proposed PCF.

In our proposed material based PCF; a modified expression of V parameter [1] has been used, which is given as follows:

$$V_{eff} = \frac{2\pi}{\lambda} R \sqrt{(n_{gl} + \Delta n_d)^2 - (n_{gl} - \Delta N_{gc})^2} \quad (1a)$$

Where, ngl is the cladding glass refractive index, which is related to core index and a difference parameter Δn_d, given by $\Delta n_d = n_{co} - n_{gl}$ and $\Delta N_{gc} = n_{gl} - n_{cl}$ (which is a function of d/ʌ, λ/ʌ).

2.2 Spot size

It simply represents the half of the modal intensity at 1/e point. More the spot size the intensity of the beam decay at larger interval. Also MFD is twice of the spot size. Both are the designing parameter for single mode fiber.

$$w_{eff} = R \times (0.65 + \frac{1.619}{V_{eff}^{3/2}} + \frac{2.879}{V_{eff}^{6}}) \quad (2)$$

Where, R is the radius of the air hole.

2.3 Effective Area

This parameter shows the non linearity to the system [6]:

$$A_{eff} = k_n \pi w_{eff}^2 \quad (3)$$

Where, kn =1.19 [13] is a constant term.

Out of the two proposed compositional elements, crown glass acquires a higher refractive index compared to phosphate glass.

3. RESULTS AND DISCUSSIONS

In this technique pitch ʌ we consider to be constant and different values of λ starting from 1.46 μm to 1.53 μm (S band) in specific intervals to calculate the values of V parameter and the other related parameter using this λ range using all the aforementioned Eq's as well as the fitting parameters [1]. The N_{gc} parameter as mentioned above depends on the structural parameters and based on that for three different refractive indices has been illustrated in Fig. 1 with respect to different d/ʌ values. Additionally the average values have been taken out from the N_{gc} parameter and plotted together to compare.

On comparing the results of phosphate glass PCF with that of crown glass PCF having different refractive indices, as shown in Fig 2 that crown glass PCF has high single mode range than phosphate glass PCF that are very much applicable for communication i.e. V must be less than 2.405. Also it shows that in communication band region it act as single mode fiber. Since the V parameter in the proposed PCF depends upon structural parameters such as d/ʌ and λ/ʌ; we analyse the V parameter for different values of these structural parameter in different material domain (Fig. 2 (a), 2 (b), 2 (c) & 2 (d)). As shown in Fig. 2 (c); crown based PCF shows leaner variation with respect to the change in structural parameter with low value of V. Moreover, crown based PCF has lowest possible value of V parameter which lead to single mode operation compared to other material based PCFs.

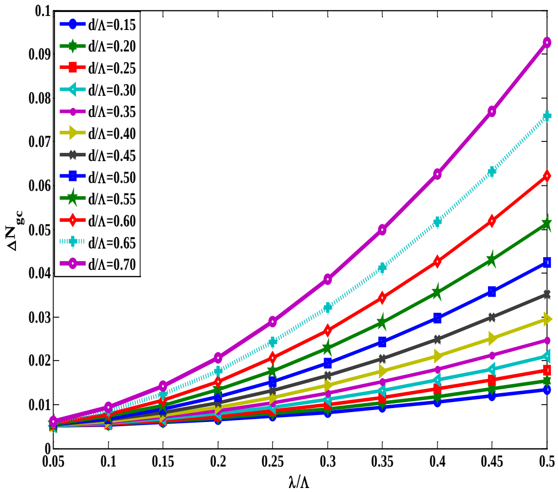

Fig. 1: (a). ΔN_{gc} vs. λ/Λ for different d/Λ (silica) at S communication band

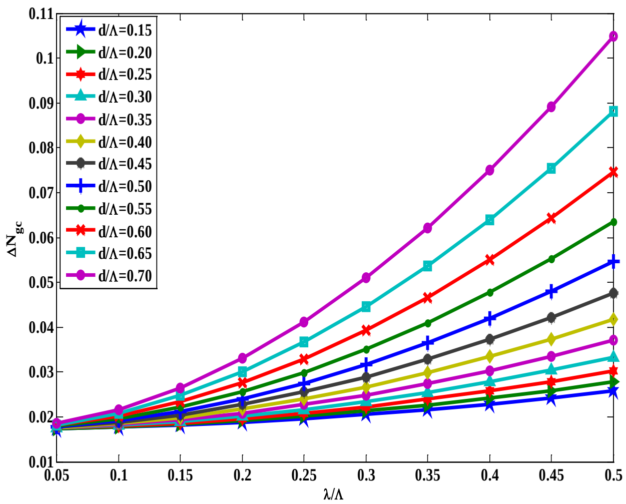

Fig. 1: (b). ΔN_{gc} vs. λ/Λ for different d/Λ (Phosphate) at S communication band

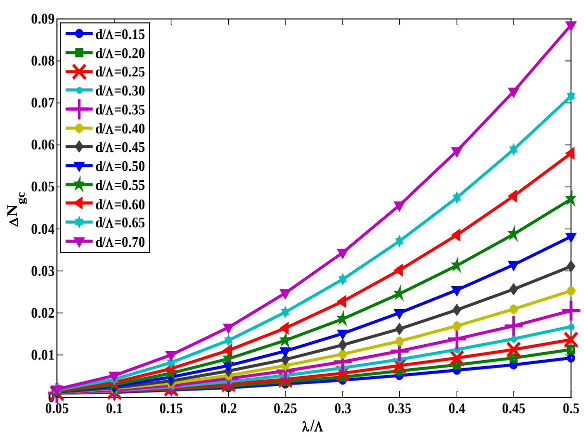

Fig. 1: (c). ΔN_{gc} vs. λ/Λ for different d/Λ (Crown) at S communication band

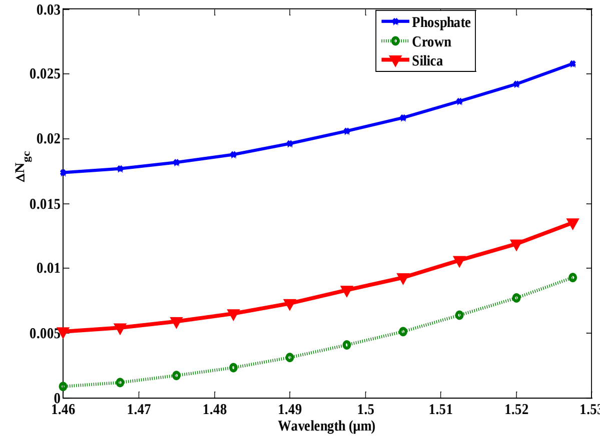

Fig. 1: (d). ΔN_{gc} vs. wavelength at S communication band

On comparing the results of crown glass PCF with phosphate glass PCF crown glass shows more towards the single mode region than phosphate glass PCF (Fig. 2). Crown glass PCF shows that for larger λ the spot size decreases which means that it has more beam quality control than phosphate PCF (Fig. 3). The values are compared with experimental value for silica based PCF.

Effective area for the two glass material shows lower value at higher λ side which is applicable in communication band (Fig. 4). Moreover, decrease in effective area with wavelength give rise to low loss which is a vital factor for long distance communication.

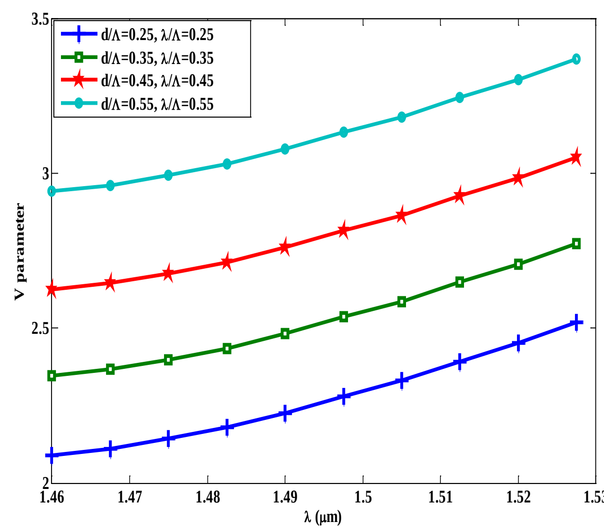

Fig. 2: (a). V parameter vs. wavelength for different values of d/Λ and λ/Λ at S communication band (silicon)

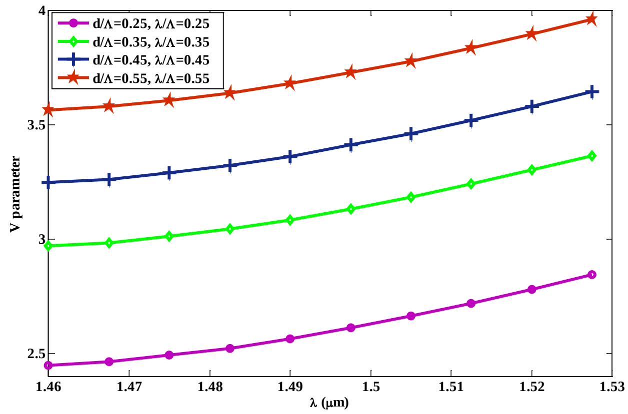

Fig. 2: (b). V parameter vs. wavelength for different values of d/ʌ and λ/ʌ at S communication band (phosphate)

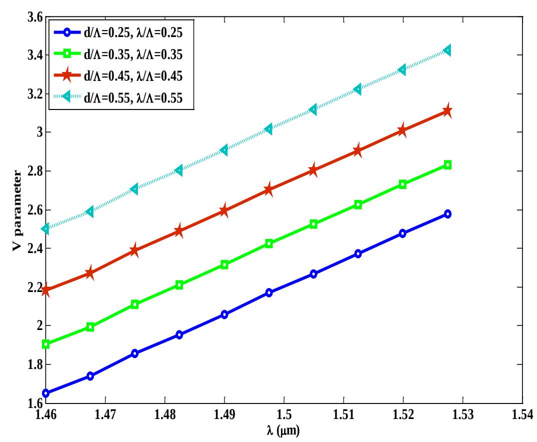

Fig. 2: (c). V parameter vs. wavelength for different values of d/ʌ and λ/ʌ at S band (Crown)

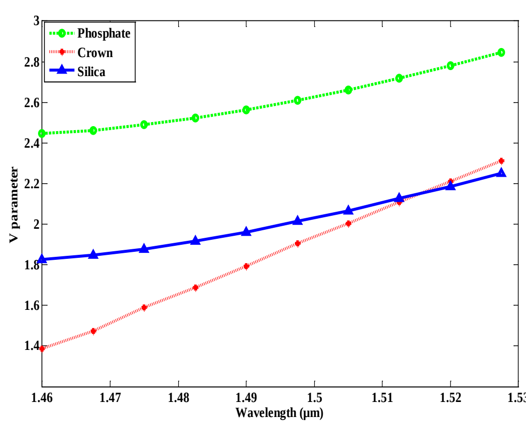

Fig. 2: (d). V parameter vs. wavelength for different values of d/ʌ and λ/ʌ at S band

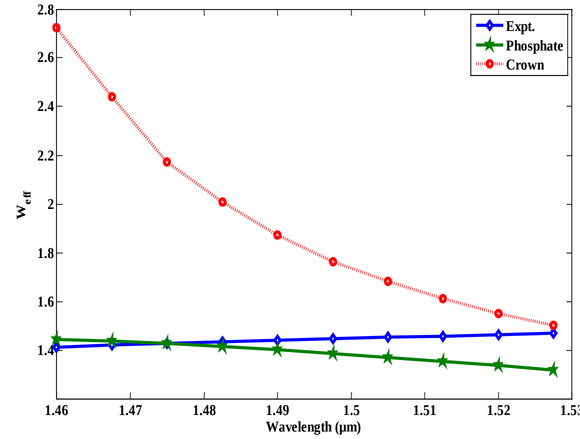

Fig. 3: Spot size vs. wavelength in S band

Effective index method has been carried out to highlight on the fact that crown glass core PCF has low loss than that of phosphate glass. Moreover, we arrived in a situation where we have got a focused beam on the use of crown glass rather than using phosphate glass PCF as we have taken up the refractive index range beyond the range of conventional material based PCF that has been used till date. Since a vast difference can be arrived on the use of different refractive index fiber. Thus while computing we get a difference in our results than the previous results and also with the experimental results.

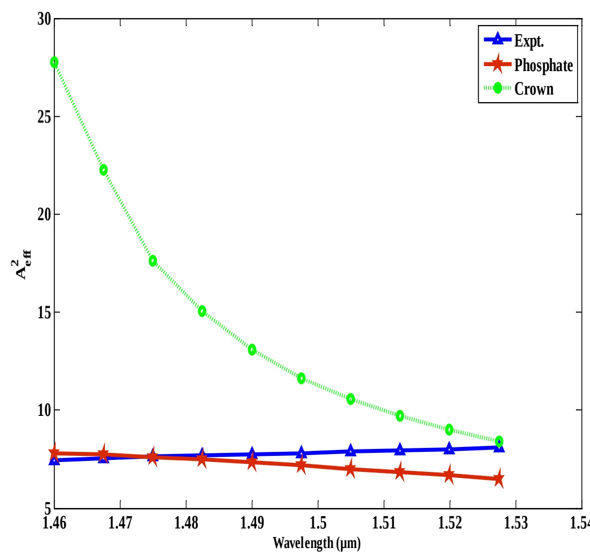

Fig. 4: Effective area vs. wavelength in S band

We accomplish this process over S communication band and with constant pitch, ʌ (2.3μm) via some additional constants to structure a comparative analysis between crown and phosphate glass PCF and also compare their results with silica based PCF.

4. CONCLUSION

Using EIM technique we can easily incorporated different material core PCF which can be used for communication purposes. Crown glass based PCF can be tuned for experimental purposes. Also we can go for the single mode operation as well as long distance communication purposes as it shows good behaviour to the change in modal parameters. Beam quality can be control easily using EIM technique for crown glass PCF as it shows very low effective area with respect to λ. Moreover, the proposed material based PCFs can be utilized for practical purposes too.

5. ACKNOWLEDGEMENTS

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