Modal parameter analysis for crown glass and phosphate glass photonic crystal fiber

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SHORT RESEARCH COMMUNICATION

Modal parameter analysis for crown glass and phosphate glass photonic crystal fiber

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Abstract: The dependence of modal parameter on different photonic crystal fiber has been taken into consideration for a comparative analysis. We consider here phosphate glass and crown glass photonic crystal fiber for our modal analysis for seven air-hole missing photonic crystal fiber. By the use of effective index method, the analysis has been put forwarded for *L* and *C* communication bands. Crown glass is found to be a good candidate for spot size and single mode application. Also most importantly, it is very much reliable for low loss and dispersion in comparison with theoretically computed phosphate glass and experimental results of silica core photonic crystal fiber.

Keywords: Photonic crystal fiber; Effective index method; Crown; V parameter

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1. Introduction

Photonic crystal fibers with an array of air holes arranged periodically within the structure of the fiber, as shown in Fig. 1, have been under intensive study as they offer design flexibility in controlling the modal properties [1, 2]. Tunable single mode wavelength range, low loss and nonlinearity make them better candidate, compared to conventional fibers [3]. Single mode behavior of photonic crystal fiber can be explained by *V* parameter with a cut-off value of 2.405 [4].

Several methods [1, 4] have been reported to measure guiding mechanism of photonic crystal fiber till now. Analytical method [4] has been proposed for designing photonic crystal fiber at telecommunication bands (L and C), through empirical relations, related to designing parameters as a function of some dimensionless variables such as d/Λ and λ/Λ, where d, Λ and λ are the diameter, pitch and wavelength respectively [4]. Numerically calculated *V* parameter is exploited to evaluate modal properties such as dispersion [5], effective area, mode field diameter and spot size. Various modeling methods have been deployed such as finite difference time domain method [1], finite element method [3], effective index method (EIM) [1]. Among them, modal parameters can be estimated more efficiently through EIM. Additionally, effective index approach is applicable for the cases, where refractive index variation of 0.01 makes a huge difference in the parameters for different photonic crystal fiber materials. So far extensive theoretical studies [1, 4, 5] have been executed using photonic crystal fiber in the context of controlled parameter.

In this paper, we highlight issues related to refractive index of composition materials core radius and *V* parameter of photonic crystal fibers and compare the enumerated results in terms of composites so that better control on modal parameters can be achieved. The observed findings render crown glass as a better candidate for photonic crystal fiber material in the context of controlled parameter. Apart from this, we check for consistency of numerically computed values with experimental values.

2. Theoretical consideration

We entail a computationally efficient effective index approach for photonic crystal fibers with seven missing air holes by systematic study of effective refractive index and core radius of photonic crystal fiber. This approach has been extended for phosphate as well as crown glass. The crown glass possesses higher refractive index than the phosphate glass. Without resorting to expensive computational tool

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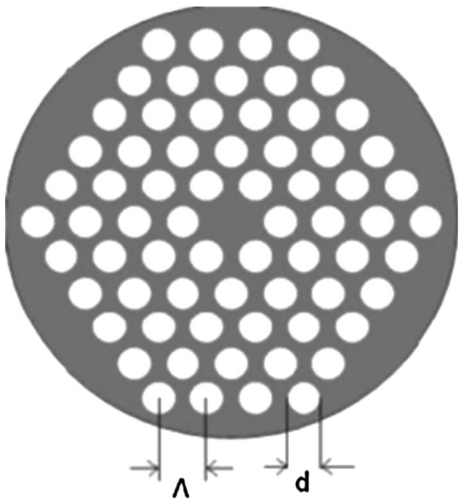

Fig. 1 Schematic representation of PCF

such as finite element method, we adopt empirical equations with three parameters to approximate fairly for effective cladding index over large parameter region of d/Λ's (0.15–0.6) and λ/Λ's (0.05–0.5), chiefly in L and C communication band with fair accuracy. As this approach does not suffer from any recalibration of refractive index variation, we introduce crown based photonic crystal fiber in same domain of parameter within the exact range of varying parameters, although refractive index has been changed to a great extent with respect to phosphate based photonic crystal fibers.

Apart from this, we estimate mode field diameter [3], beam divergence using relations among effective spot size (w_{eff}) and V parameter and dispersion of photonic crystal fiber. We accomplish this over a large parameter region of d/Λ (0.15–0.6), λ/Λ (0.05–0.5) [3] and Λ (2.3 µm), using some additional constants to carry out a comparative analysis between crown and phosphate glass photonic crystal fibers and see how modal parameter varies for crown glass photonic crystal fiber [1, 6, 7]. Additionally, we analyze these compositionally variant photonic crystal fibers on the basis of their inherent properties, by the variation of the parameters related to the communication field.

The modal properties of fiber can be characterized by V parameter [4, 8], which is defined as follows

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

where n_{co} and n_{cl} are refractive indices of core and cladding respectively and R is radius of core, which is considered to be $\Lambda/\sqrt{3}$ [9] for photonic crystal fiber and λ denotes wavelength under consideration for this study. As observed in previously established results [4], refractive index of cladding is slightly smaller than that of core, justifying scalar approximation used in earlier techniques [1, 4]. We use modified expression of V parameter [4] that has already been used earlier and is given by

$$V = \frac{2\pi}{\lambda} R \sqrt{(n_{gl} + \Delta n_d)^2 - (n_{gl} - \Delta n_{gc})^2} \tag{2a}$$

Another additional fitting parameter that has been added to V [9] is given below

$$V\left(\frac{\lambda}{\Lambda}, \frac{d}{\Lambda}\right) = A_1 + \frac{A_2}{1 + A_3 exp(A_4 \frac{\lambda}{\Lambda})} \tag{2b}$$

where constants A_1, A_2, A_3 and A_4 respectively are different fitting parameters and d is the diameter, Λ is the pitch and λ is the wavelength respectively.

Here, n_{gl} is refractive index of the cladding glass, which is related to refractive index of core and difference parameter Δn_d and Δn_{gc} respectively, given by $\Delta n_d = n_{co} - n_{gl}$ and $\Delta n_{gc} = n_{gl} - n_{cl}$ (which is a function of d/Λ, λ/Λ) [4]. After computing V parameter of photonic crystal fiber from Eqs. (2a) and (2b), we determine spot size adopting Marcuse formula [1] as given below

$$w_{eff} = R \times \left(0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6}\right) \tag{3}$$

where, R is radius of the air hole. From Eq. (3) we can easily attain effective area A_{eff} [10–12] for photonic crystal fiber, using the following relation:

$$A_{eff} = k_n \pi w_{eff}^2 \tag{4}$$

where k_n [11] is a constant term.

Beam divergence for photonic crystal fiber can be measured using modal spot size w_{eff}. We can evaluate beam divergence θ [13] of photonic crystal fiber, using following equation

$$\theta = \tan^{-1}\left(\frac{\lambda}{\pi w_{eff}}\right) \tag{5}$$

Afterwards, chromatic dispersion D (λ) [14, 15] of photonic crystal fiber is evaluated for specified wavelength range of 1.5–1.6 µm, using the following relation:

$$D(\lambda) = -\frac{\lambda}{c} \frac{d^2 n_{eff}}{d\lambda^2} \tag{6}$$

3. Results and discussion

In this study, we have incorporated L and C communication band for a constant Λ to compute V parameter using Eqs. (2a) and (2b) with addition of fitting parameter Δn_d. We have compared both the photonic crystal fibers materials, as illustrated in Fig. 2. Figure 2 reveals that V parameter increases more linearly for crown glass relative to phosphate glass. The computed values of V are smaller in case of crown glass. The highest value of V has

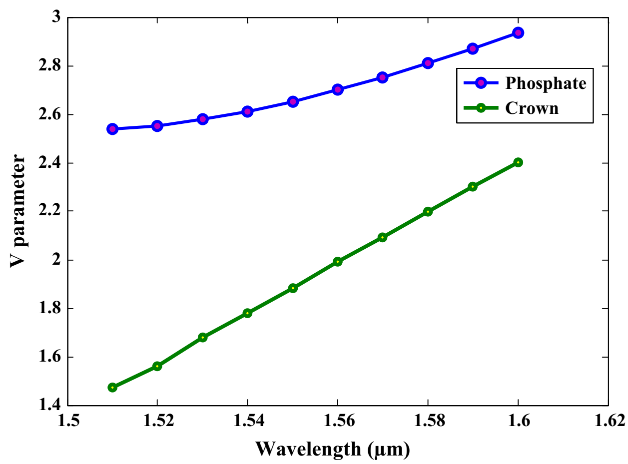

Fig. 2 Variation of V parameter with wavelength λ for $\Delta n_d = -7 \times 10^{-4}$ for crown and phosphate glass PCF

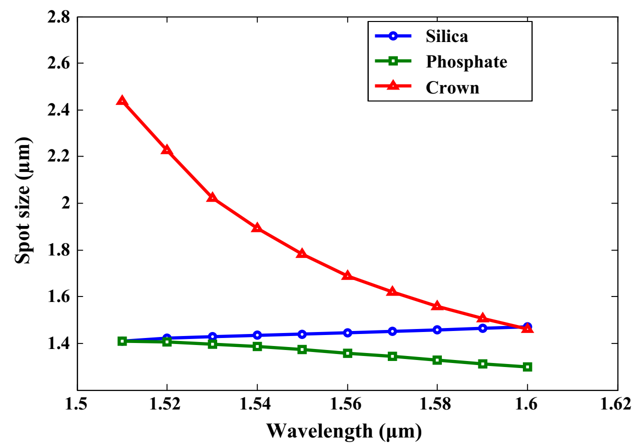

Fig. 3 Experimental plot of spot size versus λ for crown and phosphate PCFs. The data for silica PCF are also included fro comparison

been computed to be ~2.406, which tallies exceptionally with preset value of single mode fiber. In the smaller wavelength region, V starts growing slowly in case of phosphate photonic crystal fiber relative to crown photonic crystal fiber, although estimates of V with respect to phosphate possess higher magnitude compared to the latter. The overall incremental variation within the specified wavelength range comes out to be ~0.5–1.1, as evident in Fig. 2. Alternatively, the already studied phosphate photonic crystal fiber exhibits slower growth in V in the entire L and C communication band. All these results implicate that crown photonic crystal fiber shifts more towards single mode region than phosphate photonic crystal fiber.

We look into another relevant modal parameter, i.e., spot size, which connects chiefly the radius where intensity just drops to $1/e^2$ of the intensity on beam axis [16]. We determine spot size for the two glass materials having dissimilar indices and are shown Fig. 3. In addition to computed values, we include experimental data for silica photonic crystal fiber, which reveals variation as observed in Fig. 3. On increasing λ, spot size decreases for crown photonic crystal fiber. This matches with values enlisted in Table 1. In a similar manner, phosphate photonic crystal fiber shows a deviation as the wavelength is augmented. While for smaller λ, the phosphate photonic crystal fiber shows good convergence towards experimental data as compared to the crown photonic crystal fiber. However, the good convergence of the crown photonic crystal fiber and rapid decay of spot size with increasing λ suggests better controlling over single mode operation [3]. As we use effective index method to evaluate the modal parameters; it yields deviation from experimental findings in accordance with the change in refractive index of glass materials. Because of the considerable differences in refractive indices of material composites from that of silica glass; we

Table 1 Values of the parameters and experimental data

Modal parameter	Compositional element	A	B	C
w_{eff} (μm) (spot size)	Silica (exp)	1.458	1.464	1.47
	Phosphate	1.329	1.313	1.298
	Crown	1.558	1.507	1.462
MFD (μm)	Silica	2.916	2.928	2.940
	Phosphate	2.657	2.626	2.596
	Crown	3.116	3.103	2.924
θ (rad) (beam divergence)	Silica (exp)	0.326	0.325	0.323
	Phosphate	0.356	0.359	0.363
	Crown	0.307	0.317	0.326

Wavelength ranges from 1.55 to 1.6 (μm) i.e., $A = 1.58$, $B = 1.59$, $C = 1.6$

observe this variation of enumerated results from experimental data. Since spot size varies directly with refractive index, the characteristic behavior of crown and phosphate photonic crystal fiber is quite expected, as illustrated in Fig. 3. As reported earlier [17, 18], photonic band gap structure shows anomalous behavior with respect to effective refractive index. This justifies our findings towards material aspects. Further, the relation between wavelength and refractive index for propagation of light also establishes our outcome.

It is observed in Fig. 4 that effective area decreases with increasing λ corresponding to crown glass. Since effective area varies proportionately with square of spot size, it also follows the same trend that we have observed in Fig. 3. Due to this squared dependence large scatter is noticeable compared to silica fiber. We also observe that phosphate and crown material based photonic crystal fibers shows lower values of effective area in comparison to experimental data. As it links non-linearity [11], declining value of A_{eff} for crown glass implicates that non-linearity, is diminished relative to phosphate glass. Since it deals with non-linearity so drop off A_{eff} with λ for crown glass shows less effective towards non-linearity, relative to phosphate photonic crystal fiber.

Additionally, beam divergence of crown and phosphate photonic crystal fibers shows large deviation in our study as illustrated in Fig. 5. Beam divergence is found to increase with rise in wavelength in both the photonic crystal fiber, quite commensurate with experimental value. In this figure, we can observe that at lower wavelength side phosphate photonic crystal fiber shows better counterpart with the experimental data; whereas at higher wavelength region crown photonic crystal fiber shows better control over the results. Thus, we can make use of these two glass based photonic crystal fibers for relative variation in wavelengths. Though the values are increasing with respect to wavelength, yet we can see results of crown photonic crystal fiber are very low compared to experimental one. Consequently, we can predict that it can be used for better tuning, as it is known that beam divergence has an immense effect on beam quality control. In case of beam divergence for silica photonic crystal fiber, experimental value shows little dependence on wavelength; whereas in our material based observation shows direct dependence on wavelengths. Since we basically exploit refractive index variation, it brings in noticeable differences in results. However, crown photonic crystal fiber exhibits rapid rise in the L and C bands where as relatively slow growth can be observed with respect to phosphate glass photonic crystal fiber. It is worthwhile to note that computed values corroborate experimental data and also with the fact of quality control than that of phosphate glass photonic crystal fiber.

The numerically computed values suggest that crown photonic crystal fiber has less dispersion than phosphate photonic crystal fiber. Figure 6 gives the variation of dispersion with respect to wavelength. As shown in Fig. 6, the crown photonic crystal fiber is characterized by negative dispersion throughout L and C bands, whereas phosphate photonic crystal fiber registers zero dispersion in the same band of λ. The appearance of negative values in dispersion for the crown photonic crystal fiber, places it in long distance haul. Apart from this, zero dispersion as found in phosphate glass lessens its applicability in the same domain as it necessitates to be compensated for showing dispersion.

The systematic adoption of Effective index method leads to the fact that the crown photonic crystal fiber has low loss than that of phosphate photonic crystal fiber. We have arrived in a situation, where we have got a focused beam on the use of the crown photonic crystal fiber rather than using phosphate photonic crystal fiber, as we have

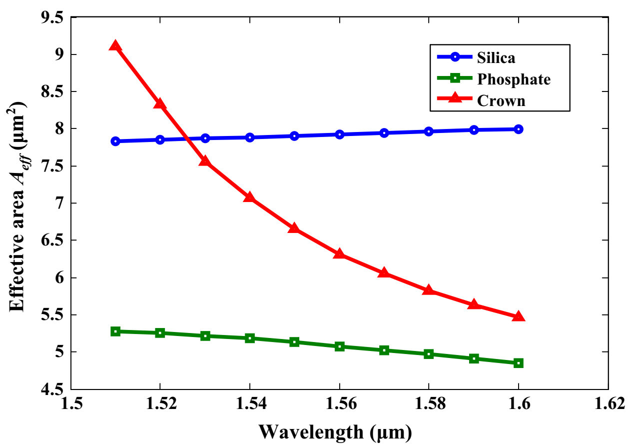

Fig. 4 Variation of effective area (L and C band) versus wavelength along with experimental data for crown, phosphate and silica PCFs

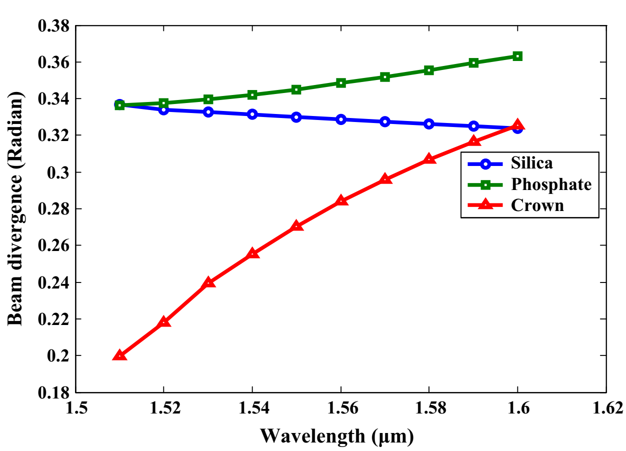

Fig. 5 Beam divergence for two PCF's versus λ along with experimental values for crown glass, phosphate glass and silica PCFs

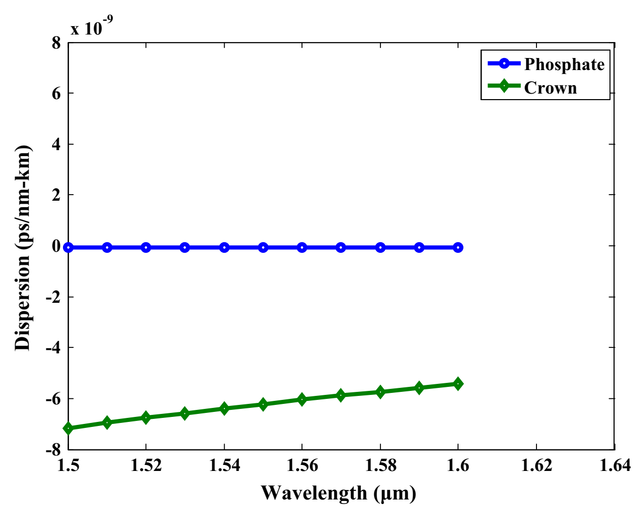

Fig. 6 Dispersion versus λ for crown and phosphate PCFs

taken up the refractive index range beyond the range of normal photonic crystal fiber that has been used. The theoretical analysis shows that the spot-size, effective area and the beam divergence of crown photonic crystal fiber has more beam quality control than the phosphate photonic crystal fiber as for more focused beam they have to decrease with the increase of wavelength. [19, 20]. Further the crown glass photonic crystal fiber can be used as many types of communication applications. Also it can be asserted that its low loss with λ value enables crown photonic crystal fiber in effective long-haul communication [21] and as an efficient waveguide [22] keeping with reduced intrinsic loss.

4. Conclusions

In summary, we execute numerical modeling of photonic crystal fiber. We present a comparative analysis of modal properties of photonic crystal fibers with guiding cores composed of seven missing air holes in the context of two varying compositional elements for cladding, via, phosphate and crown glass. Based on the analogies between step index fibers and photonic crystal fibers, we comprehensively study the effective refractive index of photonic crystal cladding and effective core radius, followed by reformulation. With the new effective index and core radius, the modal properties for phosphate and crown glass photonic crystal fibers are numerically evaluated and compared. The estimated parameters are found to be in good agreement with that of experimental investigations in the wavelength of interest. Simultaneously, the comparative analysis reveals that crown glass photonic crystal fiber is preferable to phosphate glass in the *L* and *C* bands of communication so far low beam divergence, higher spot size and low loss are concerned. We have discussed how we can use crown glass photonic crystal fiber for low loss communication system in the range of single mode using crown glass photonic crystal fiber. A low beam divergence can be important for applications such as pointing or free-space optical communications. Effective index method leads to the fact that crown glass photonic crystal fiber can be used for long distance communication purpose, which is considered to be effective for carrying proper information to profitable distances than phosphate photonic crystal fiber.

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