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Tunable Selective Liquid Infiltration: Applications to Low Loss Birefringent Photonic Crystal Fibers (PCF) and Its Single Mode Realization

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Abstract

In this article, we've theoretically investigated the application of selective liquid infiltration towards realizing birefringent Photonic Crystal Fiber (PCF) and its operation in the single mode region. Birefringence has been created in a symmetrical structure PCF by infiltrating liquid of certain refractive indices in diagonally opposite air-holes. Different air-hole fraction along with different infiltrating refractive indices has been considered towards studying the effect of the parameters towards birefringence and loss. Cut-off properties for different infiltrating liquid has been performed and it has been found that PCF infiltrated with higher Refractive Indices (RI) liquid is suitable for broader range of single mode operation. The present structure provides very low loss and that can also be minimized with higher number of air-hole rings without affecting the birefringent property. Tunability property of the infiltrating liquid for various temperatures has been studied. By varying the refractive indices of the infiltrating liquid the birefringence can be well tuned. Our research will be useful in designing a birefringent PCF from conventional symmetrical PCF by infiltrating liquids in two diagonally opposite air-holes and proper choice of PCF parameter for single mode operation at a desired wavelength of interest.

Keywords

Photonic Crystal Fiber; Birefringent Fiber; Polarization Maintaining Fiber; Liquid Infiltration

Introduction

Polarization maintaining fibers (PMFs) or birefringent fibers is extensively used in many communication systems and optical devices. Birefringence can be achieved in two major customs. The first one is to apply asymmetrical stress to the core region of the fiber by introducing some material with higher thermal co-efficient. Second method of creating asymmetry in the core is by creating an asymmetry by different index profile or spatial asymmetry in the core of the fiber. High birefringence can be achieved in those PMFs such as PANDA fibers [Tajima et al, 1989;], elliptical-clad fibers [Namihira et al, 1982;], and bow-tie fibers [Liu et al, 1994;] with the birefringence in the range of $5*10^{-4}$.

Photonic crystal fibers (PCFs) [Broeng et al, 1999; Birks et al, 2001; Knight et al, 2003], also called micro-structured optical fibers (MOFs), are special type of fibers with air-holes of certain pattern (generally triangular or hexagonal and square) running across the length of the fiber. PCF are characterized with air-hole diameter (d) and hole to hole distance (Λ) in a dielectric background like silica. By changing the geometrical parameters, several unique properties, which could not be achieved with normal optical fiber, could be achieved with PCFs. Out of numerous attractive properties exhibited by PCFs, a particularly exciting feature is that PCF can be made highly birefringent [Ortigoss-Blanch et al, 2000; Suzuki et al, 2001; Simpson et al, 1983; Kubota et al, 2004; Roychoudhuri et al, 2004; Steel et al, 2001; Hansen et al, 2001;] as the PCF core and cladding offers a large refractive index contrast. The anisotropy and thereby the birefringence in a PCF can be implemented using elliptical air-holes [Steel et al, 2001;] and with asymmetric core [Hansen et al, 2001;] or asymmetric distribution of air holes in cladding [Ortigoss-Blanch et al, 2000;]. Out of various ways of obtaining higher birefringent value from the PCF, asymmetric core PCF is one of the most studied structures.

In addition to altering the geometry, asymmetry in the core of a PCF can also be formed by infiltrating the air-holes, either completely or selectively, by various liquids such as water [Martelli et al, 2005;], ethanol [Yiou et al, 2005;], polymers [Eggleton et al, 2001; Kerbage et al, 2002; Cox et al, 2006;], and liquid crystals [Zhang et al, 2005; Alkeskjold et al, 2006;]. In this research of the application of selective liquid infiltration, we report our study of the transmission and polarization properties of the PCFs where the diagonal air-holes of the PCFs are infiltrated with selective liquid. As the symmetry of the PCF breaks, the fiber does not retain the property of endlessly single-mode for a wide wavelength range. Subsequently, we have studied the single- mode properties of the PCF by considering different values of infiltrating indices in the air-holes. We have also discussed the tunable properties of the liquid infiltrated PCF for tuning of birefringence and propagation loss.

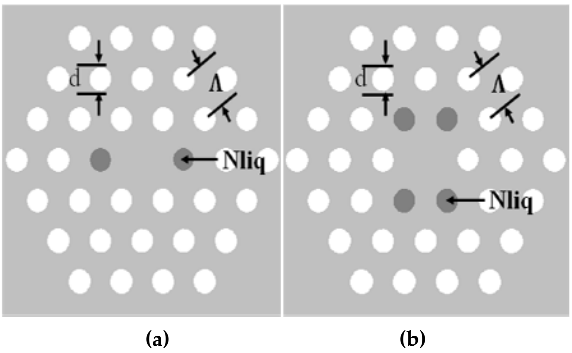


FIG. 1 SCHEMATIC DIAGRAM OF THE TWO STUDIED STRUCTURE (A) STRUCTURE-A (B) STRUCTURE-B

Geometry of the Studied Structure:

Fig. 1 shows the geometrical cross section of the proposed fibers where we have considered three air-hole layers in the cladding. The six-fold symmetry of the structure is broken by filling the air-holes along one of the axis in the first case (we call this "structure-A"); and we have considered the axes to be the x axis, where as for the second case (we call this "structure-B") we infiltrate the remaining air-holes of the first air-hole ring. Throughout our study, the wavelength dependence of the background silica has been considered with Sellmiers' equation, whereas the liquid has fixed value of refractive indices (RI). The benefit of working initially with an artificial (wavelength independent) liquid is that we needn't choose a liquid apriori from the great number of available index-matching liquids. Refractive indices differ by $5*10^{-3}$ or even smaller are available with M/s Cargille-Sacher Laboratories Inc, USA. Customized liquids with certain RI's can also be available upon requirement from the manufacturer. Infiltrating different liquids will give us the opportunity to achieve required results and accordingly the tunability of the structure can be studied for different applications. The results obtained with artificial liquids lead us to certain optimization of the parameters. These values give us approximate values of the parameters that we are going to use for practical realization. Now with those values we can select the available liquids with refractive indices nearer to the previously optimized liquid and from there we re-adjust the other parameters to have desired result.

The effect of selective infiltration to the air-holes can be visualized as follows; due to the infiltration of the liquid into the selective air-holes, the local effective indices of the air-holes are raised and thereby an asymmetry is created at the core. The manufacturing of these PCFs can be performed in a couple of steps. One must first selectively block specified air-holes and then infuse the liquid into the unblocked holes using an applied pressure through vacuum pump. One possible way can be the fusion splicing technique with tailored electric arc energies and fusion times to selectively fuse [Martelli et al, 2005; Yiou et al, 2005; and 20 Alkeskjold et al, 2006;] the outer rings of the PCF. The inner ring of the air-holes can be infiltrated with liquid, first by fusing the outer rings of air-holes with tailored electric arc energies and fusion times [Xiao et al, 2005;] and then by immersing one end of the fiber in a liquid reservoir and applying vacuum to the other end of the fiber[Yiou et al, 2005;]. A better control can be achieved by selectively blocking the unwanted air holes with photolithographic masking technique [Sasaki et al, 2002;] or with epoxy [Cox et al, 2006;]. With the advance of technology these techniques are expected to be improved enormously in future, thereby opening new possibilities for different specialty optical fiber design in PCF. In our designed structure, exposing the air-holes in the x axis and blocking the remaining air-holes by the above mentioned techniques will generate the birefringent structure.

The guided modes along with the transmission properties of the present fiber are investigated with CUDOS MOF Utilities that simulate PCFs using the multipole method [White et al, 2002; Kuhlmey et al, 2002;]. The efficiency and validity of the methods has been covered in detail in the above articles [White et al, 2002; Kuhlmey et al, 2002;].

Numerical Results:

A particularly exciting feature, out of numerous interesting applications exhibited by PCFs, is that PCF can be made highly birefringent [Steel et al, 2001; Hansen et al, 2001; Martelli et al, 2005; Yiou et al, 2005; Eggleton et al, 2001; Kerbage et al, 2002; Cox et al, 2006;] due to the availability of large refractive index contrast available between core and cladding compared to the conventional fibers and the fabrication process allows us the formation of the required asymmetric structure near the fiber core. Highly birefringent PCFs can be used as polarization maintaining fibers, which can stabilize the polarization sates of the launching light. Besides changing the geometry to create asymmetry in the core, another way to create asymmetry will be by means of liquid infiltration to the air-holes along one of the axes.

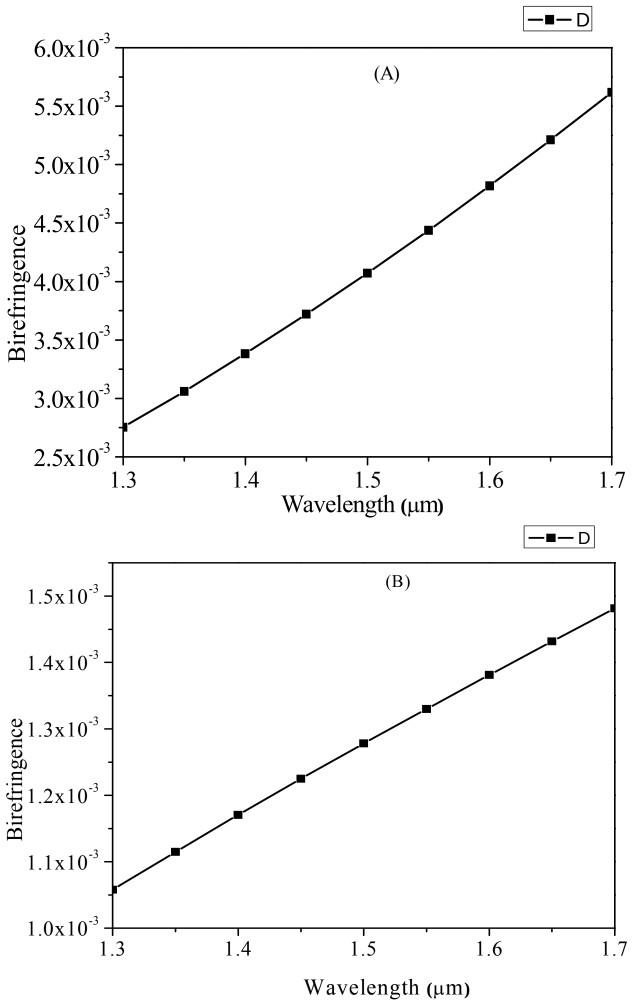


FIG. 2 BIREFRINGENCE FOR (A) STRUCTURE-A AND (B) STRUCTURE-B FOR Λ=2.3µm and d/Λ=0.95.

Dispersion and Confinement Loss Properties of the Structure:

In our work, the birefringence has been created by filling the air-holes as demonstrated by Fig. 1(a) and Fig. 1(b) respectively. For our study, we have considered the Λ value to be 2.3 µm for different values of d/Λ. Firstly, we have considered a liquid with n_L=1.43 and the corresponding birefringence of the structures with d/Λ =0.95 has been shown in Fig. 2. Figure 2 reveals that for both the structures the birefringence increases with increasing wavelength. Birefringence of the order of $5*10^{-3}$ can be achieved with "structure-A" while a value around $1.5*10^{-3}$ can be obtained with "structure-B" around the wavelength of 1550 nm. A comparison study shown in Fig. 2 (A) and Fig. 2(B) clearly shows that better birefringence can be obtained from structure-A structure *i.e.* if the liquid can be infiltrated along the *x* axis only.

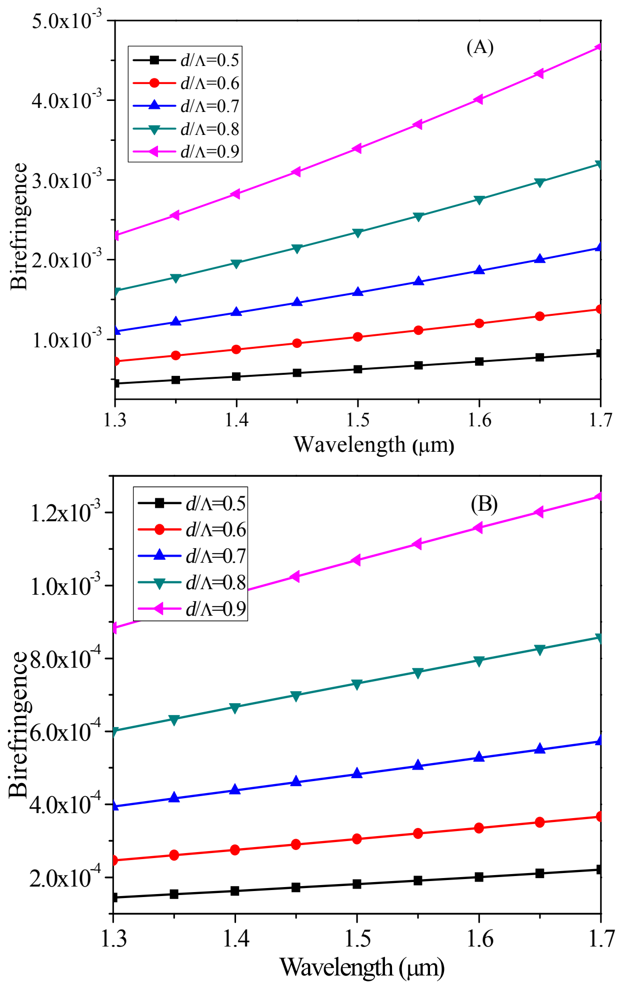


FIG. 3 BIREFRINGENCE FOR DIFFERENT VALUES OF D/Λ FOR BOTH TYPES OF STRUCTURES (A) "STRUCTURE-A" (B) "STRUCTURE-B".

Birefringence of the liquid infiltrated PCFs are shown in Fig. 3(A) and Fig. 3(B) for structure-A and structure-

B respectively for different air-filling fraction (d/Λ). As the air-hole diameter increase, the birefringence increases for both types of structures. This can be attributed to the fact that as the air-hole diameter increases, the amount of liquid-infiltrate also increases, which in turn increases the asymmetry of the structure giving higher values of birefringence. Again it has been observed that for all the cases structure-A has always higher values of birefringence than structure-B. The corresponding confinement losses for the structures are presented in Fig. 4(a) and Fig 4(b) respectively.

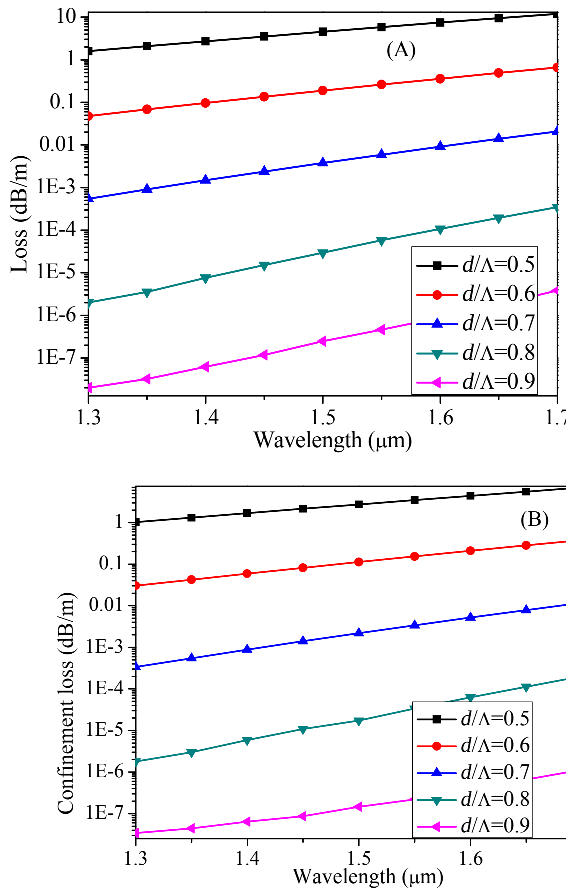


FIG. 4 CONFINEMENT LOSSES FOR DIFFERENT VALUES OF D/Λ FOR BOTH TYPES OF STRUCTURES (A) “STRUCTURE-A” (B) “STRUCTURE-B”.

For smaller values of air-hole diameter, we have higher values of effective indices, which in turn gives lower values of step potential and there by higher amount of confinement losses. For all values of d/Λ, “structure-B” is always having lower values of losses than structure-A. So, we can see that for higher values of d/Λ, the birefringence increases and confinement losses also reduces and for customized application we can have two different possible structures; in one the birefringence is better (structure-A) and in another one loss is lower(structure-B). But, the loss advantage (shown by structure-B) is not that great compared to the birefringence advantage shown by structure-A because of the fact that loss can be reduced significantly by increasing the number of air-hole rings. So, from now onwards we’ll confine our discussion only on the first type of structures (“Structure-A”) only.

Tunability of the birefringent PCF is established in Fig.5(a) for different values of refractive indices of the infiltrating liquids. A detailed study of the tunability has been performed in a different section (section-4). The refractive indices of the liquid can be changed by changing the temperature of the liquid with the temperature co-efficient of the liquid is of the order of $-4*10^{-4}/^{0}C$ or infiltrating the air-holes with different liquids available with M/s Cargile-Sacher Laboratories Inc. To demonstrate the tunability, we infiltrate liquid of different indices varying from 1.32 to 1.42 for the PCF with d/Λ=0.75 along the x axis; then our studies are compared at two wavelengths of 1.31 μm and 1.55 μm, which are two most important wavelengths for optical communication. So birefringence can be raised by infiltrating liquid with higher index as higher value of refractive indices increases the asymmetry.

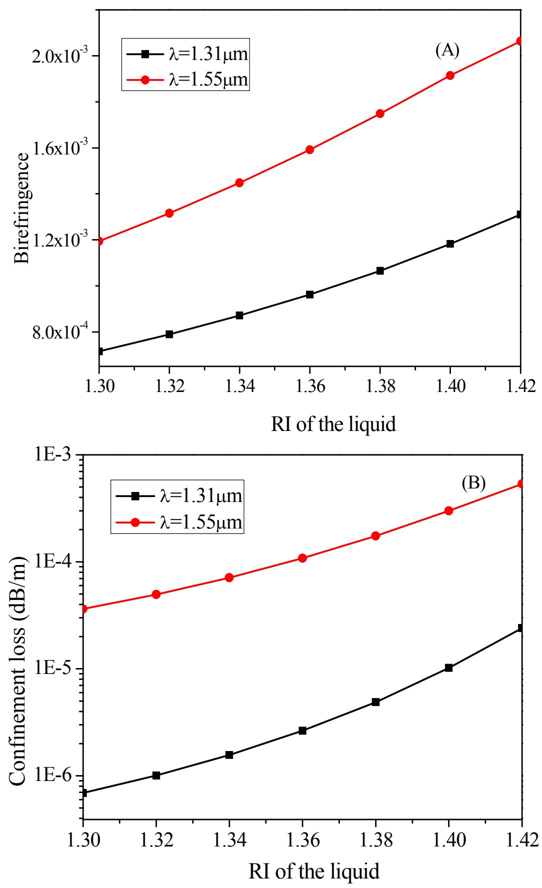


FIG. 5 BIREFRINGENCE AND CONFINEMENT LOSS FOR DIFFERENT VALUE OF RI FOR λ=1.31μm AND λ=1.55μm.

From Fig. 5 it can be seen that the confinement losses increase with higher value of indices. The improvement of the losses can be addressed by reducing the number of air-holes infiltrated by liquid along the x axis as shown in Fig. 7 without much change in birefringent values as shown in Fig. 6.

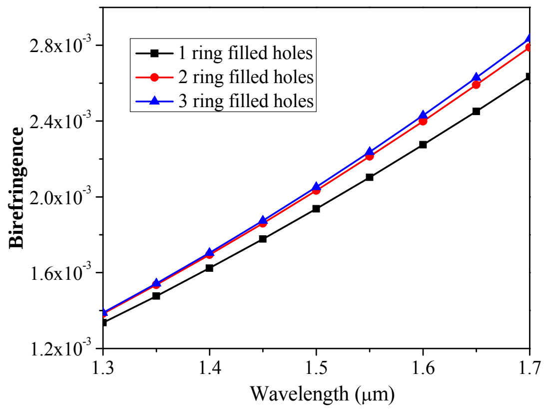


FIG. 6 CHANGE OF BIREFRINGENCE WHEN THE RI IS INFILTRATED IN THE FIRST (BLACK), FIRST TWO (RED) AND FIRST THREE (BLUE) RINGS.

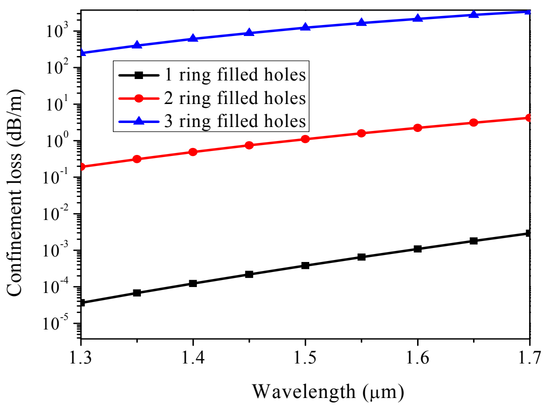


FIG. 7 CONFINEMENT LOSS VARIATION WHEN THE RI VARIES IN THE FIRST, FIRST TWO AND FIRST THREE RINGS.

Single Mode Region of the Selectively Liquid Filled Birefringent PCFs:

Triangular lattice PCFs with a symmetric core consisting are endlessly single mode for normalized hole sizes up to a value as large as d/Λ=0.406 [Kuhlmey et al, 2002 (2); Kuhlmey et al, 2002(3);], where as the symmetric core PCF with square-lattice is endlessly single mode for normalized hole sizes up to a value as large as d/Λ=0.442[Poli et al, 2005;]. This cannot be the case for the present fibers as the core region for the concerned structure is different from a normal one. We performed the cut-off analysis according to Kuhlmey *et al* [Kuhlmey et al, 2002 (1);]. The multipole method [White et al, 2002; Kuhlmey et al, 2002;] that has been used for the development of CUDOS MOF utilities has the unique ability to calculate both the modes and their losses accurately. Cut-off can be visualized by plotting Im(n_{eff}) as a function of normalized frequency [Kuhlmey et al, 2002 (2);]as loss $\mathcal{L}$ (*dB*/*km*) is directly related to Im(n_{eff}) through Eqn. (1)

$$L = \frac{2\pi}{\lambda}\frac{20}{\ln(10)}10^9\,\mathrm{Im}(n_{eff}) \tag{1}$$

We have plotted the Im(n_{eff}) value with normalized frequency as shown in Fig. 8 for d/Λ=0.1. The figure gives a transition corresponding to the transition of single-mode to multimode transition. The transition can be better viewed if we plot the second derivative of the logarithm of the imaginary part of the effective index with respect to the wavelength, the Q parameter (Eqn. (2)) as shown in Fig. 9 [**27** Kuhlmey et al, 2002 (2);].

$$Q = \frac{d^2 \log[\mathrm{Im}(n_{eff})]}{d\lambda^2} \tag{2}$$

This is a little different from the approach that has been followed in their work. Here we have changed the wavelength in place of Λ for our study. The Q parameter shows a distinct negative minimum. The dip in the graph indicates the transition region from single-mode to the multimode region. Figure 9 clearly shows a dip for d/Λ values of 0.10 for infiltrating RI =1.43 with normalized cut-off frequency (Λ/λ) to be 2.439. Above this value, the fiber will not remain single-mode. So we need to choose the available values of the parameters wisely, such that operation remains in single mode region.

The transition of the Im(neff) variation can be better visualized for higher values of d/Λ as demonstrated in Fig. 10 (a), Fig 10(b) and Fig. 10(c) for d/Λ=0.2, 0.3 and 0.4 respectively. The corresponding Q parameter variations are demonstrated in Fig. 11 (a), Fig. 11(b) and Fig. 11(c) respectively. Figure 11 clearly demonstrated the transition regions for different values. The corresponding cut-off normalized frequency for different values of d/Λ for the infiltrating liquid RI of 1.43 is demonstrated in Fig. 12. Similar calculations are performed with infiltrating RI with n_L=1.40 and n_L =1.35 and the corresponding cut-off nature/variations for different normalized frequency are presented in Fig. 13(a) and Fig. 13(b) respectively. Considering a constant air-filling fraction (d/Λ)=0.40, cut-off frequency for different values of infiltrating liquid has been presented in Fig. 14. The normalized cut-off frequency increases for higher values of n_L as can be observed from the figures; which in turn restricts the single-mode operation for higher wavelength only for a particular hole-to-hole distance (Λ). To achieve a required birefringence, we need to cleverly choose the

PCF parameters such that we could achieve high birefringence and at the same time restricting the operation within single-mode region.

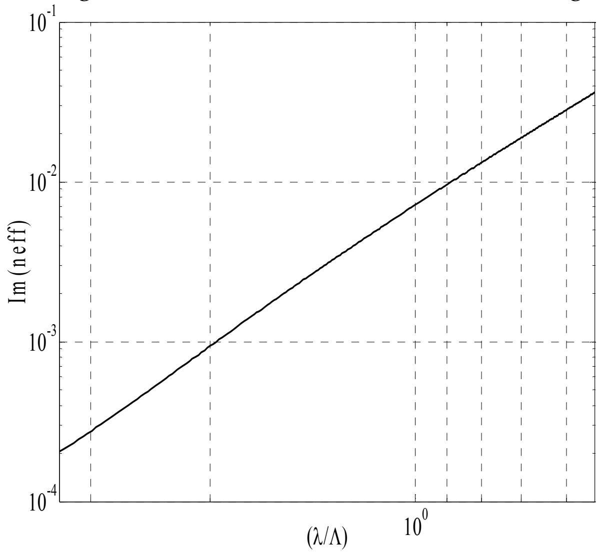


FIG. 8 IM(N*EFF*) AS A FUNCTION OF *λ*/Λ FOR THE PCF STRUCTURE WITH TRIANGULAR-LATTICE FOR *d*/Λ=0.1

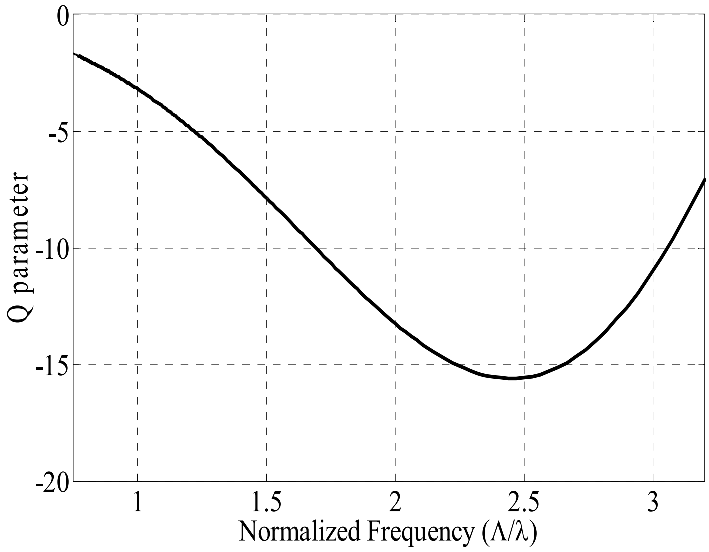


FIG. 9 Q PARAMETER VARIATION WITH Λ/*λ* FOR n_L=1.43 FOR *d*/Λ=0.1

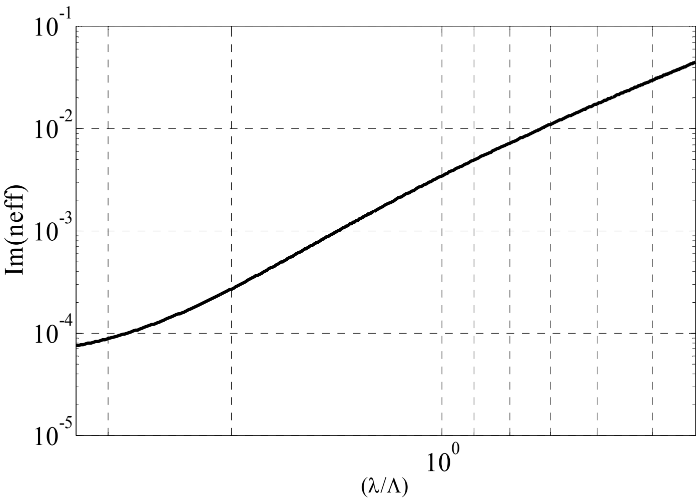


FIG. 10(a) IM(N*EFF*) AS A FUNCTION OF *λ*/Λ FOR THE PCF STRUCTURE WITH TRIANGULAR-LATTICE FOR *d*/Λ=0.20.

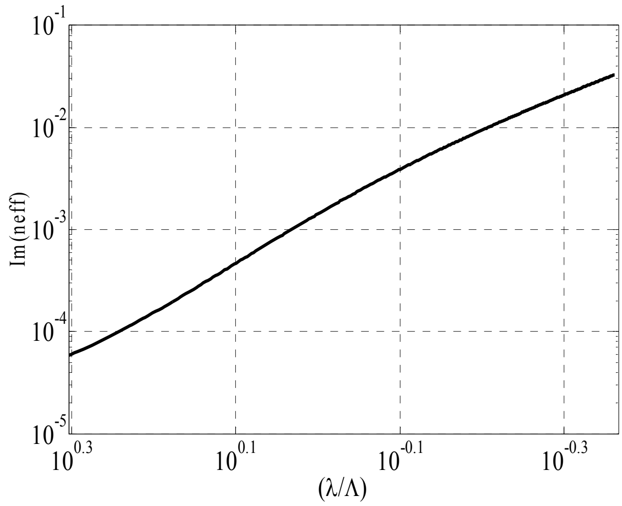


FIG. 10(b) IM(N*EFF*) AS A FUNCTION OF *λ*/Λ FOR THE PCF STRUCTURE WITH TRIANGULAR-LATTICE for *d*/Λ=0.30.

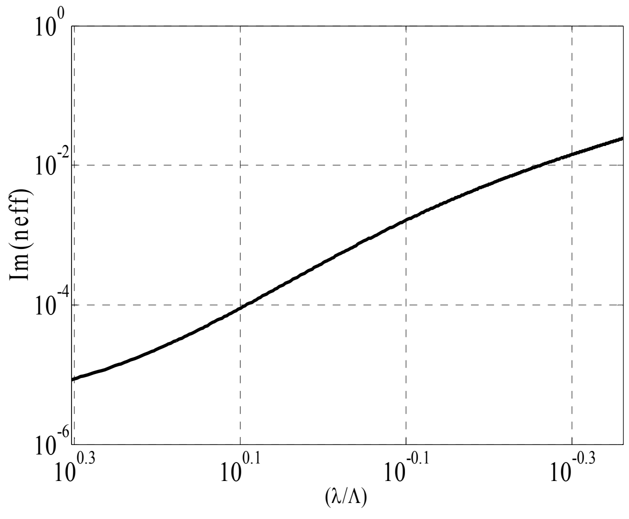


FIG. 10(c) IM(N*EFF*) AS A FUNCTION OF *λ*/Λ FOR THE PCF STRUCTURE WITH TRIANGULAR-LATTICE FOR *d*/Λ=0.40.

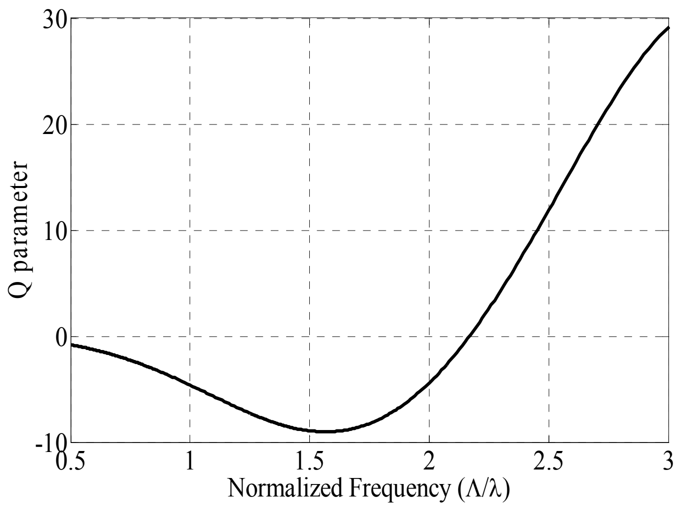


FIG. 11(a) Q PARAMETER VARIATION WITH Λ/*λ* FOR n_L=1.43 FOR *d*/Λ=0.20.

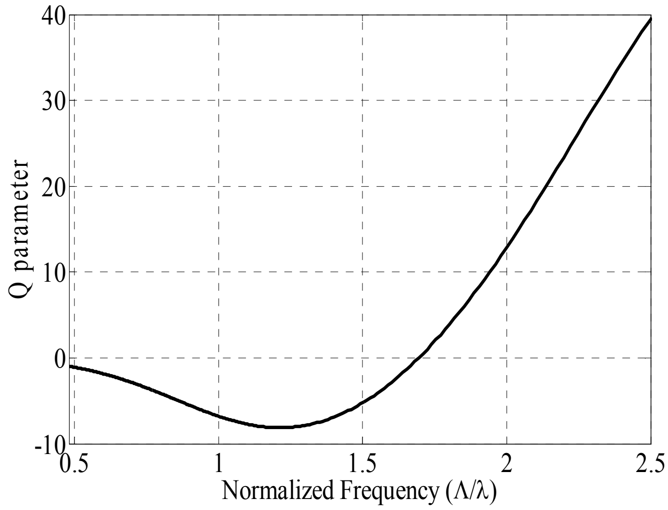


FIG. 11(B) Q PARAMETER VARIATION WITH Λ/λ FOR n_L=1.43 FOR d/Λ=0.30.

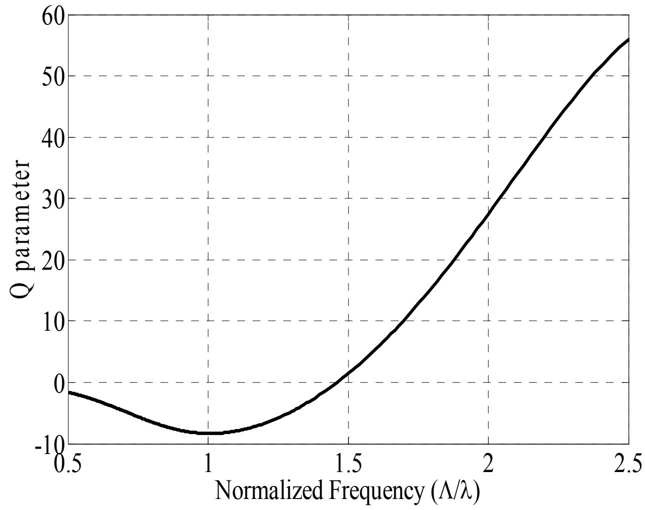


FIG. 11(c) Q PARAMETER VARIATION WITH Λ/λ FOR n_L=1.43 FOR d/Λ=0.40.

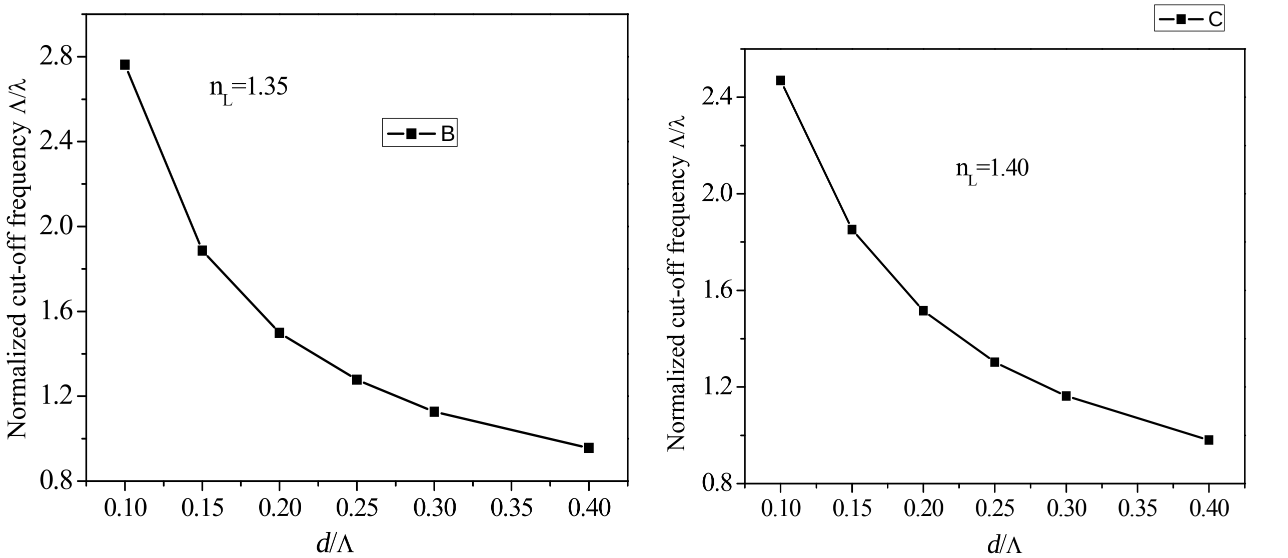
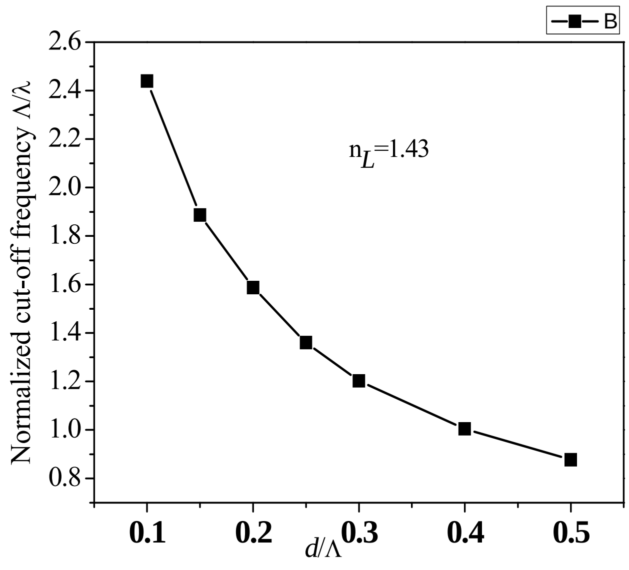


FIG. 13 CUT-OFF Λ/λ VALUES FOR DIFFERENT d/Λ vALUES FOR N_L VALUES OF (A) 1.35 AND (B) 1.40



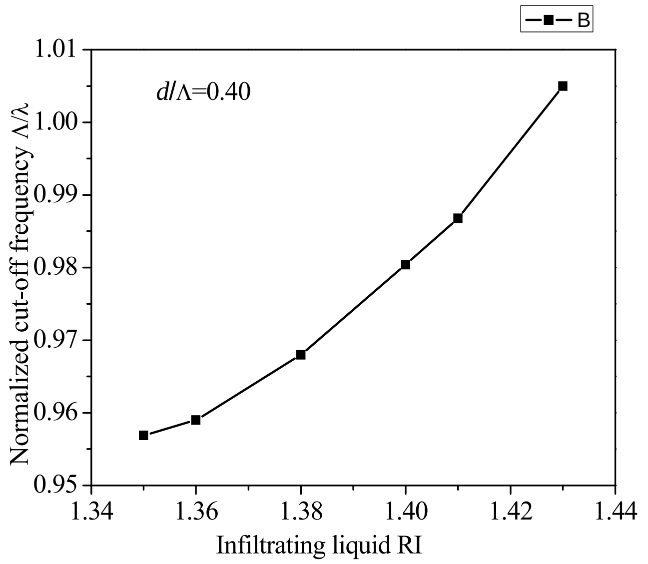


FIG. 12 CUT-OFF Λ/λ VALUES FOR DIFFERENT d/Λ VALUES FOR n_L =1.43.

FIG. 14 CUT-OFF Λ/λ VALUES FOR DIFFERENT N_L VALUES FOR d/Λ=0.40.

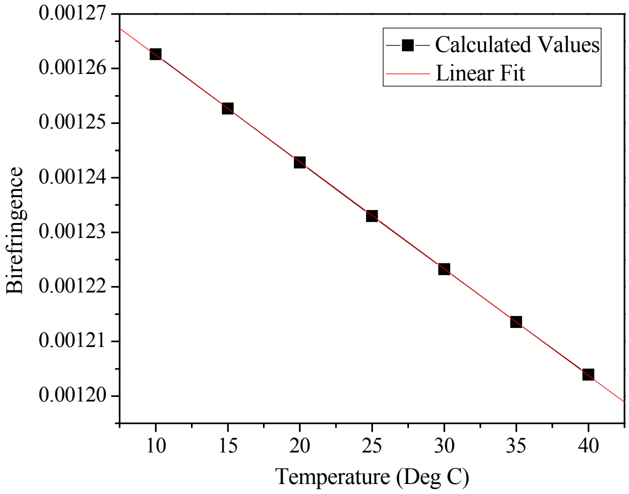


FIG. 15 VARIATION OF BIREFRINGENCE AS FUNCTION OF OPERATING TEMPERATURE FOR OIL#1

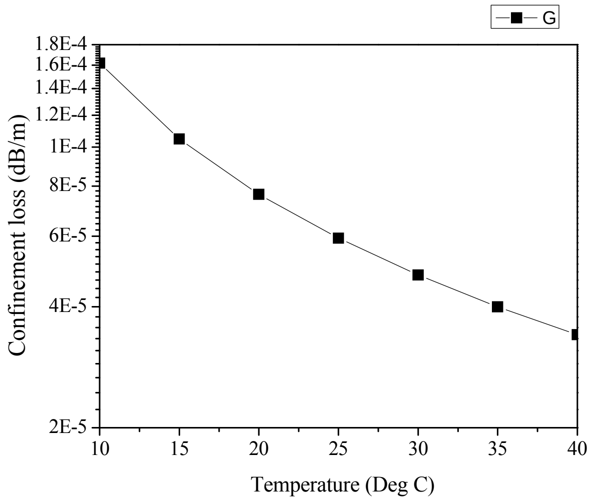


FIG. 16 LOSS VARIATION CORRESPONDING TO FIG. 15.

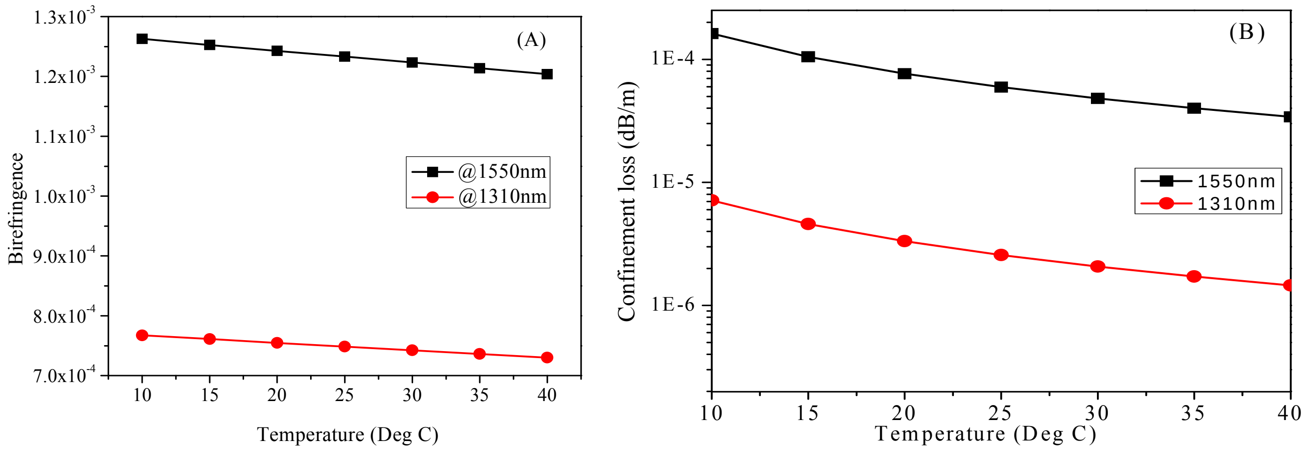


FIG. 17 (A) BIREFRINGENCE AND (B) CORRESPONDING CONFINEMENT LOSSES VARIATION AT TWO DIFFERENT WAVELENGTHS OF 1310NM AND 1550NM WITH LIQUID#1

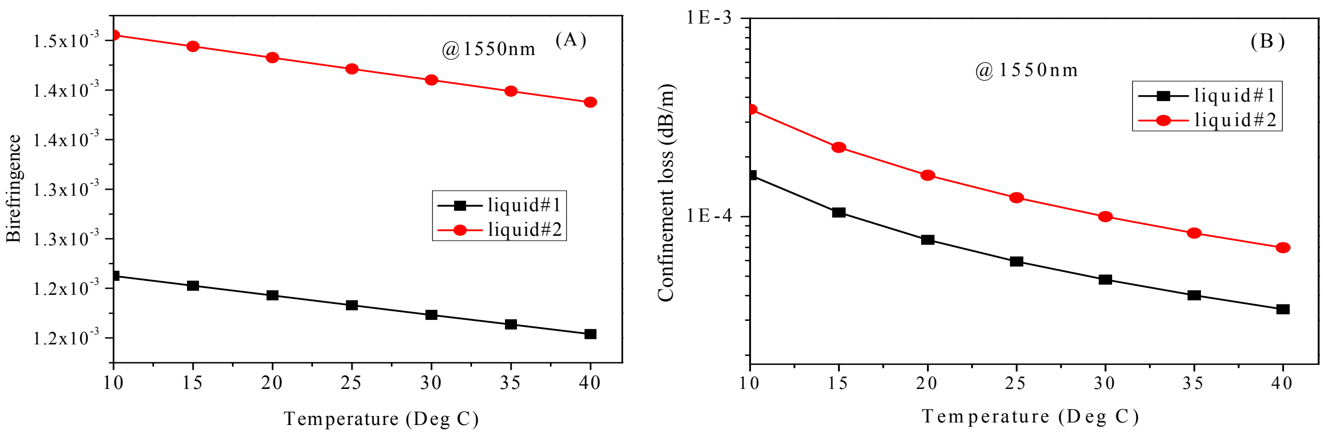


FIG. 18 (A) BIREFRINGENCE AND (B) LOSSES FOR LIQUID#1 AND LIQUID#2 FOR DIFFERENT OPERATING TEMPERATURES AT THE OPERATING WAVELENGTH OF 1550NM

Tunability of the Liquid-infiltrated Birefringent PCF

It is well known that once a design is fixed and fabricated the corresponding property can't be changed further. So to have a different or optimized design, we need another fiber to be fabricated. Now here comes the advantage of liquid filled PCF. Here in this type of selective liquid infiltrated PCF, we can change the RI of the infiltrating liquid by changing the temperature of the infiltrating liquid or re-infiltrate another liquid in the same design and thereby tuning the required properties according to the requirement. Here we discuss the birefringent property that can be achieved by infiltrating the liquid with a particular RI. Here we discuss the infiltration with two different liquids (as liquid#1 and liquid#2 respectively) having RI of 1.344 and 1.383 at a wavelength of 1550 nm at 25 ^{0}C as given by Eqn.(3) and Eqn. (4) respectively. The temperature co-efficient of the liquids (available with M/s Cargile lab) are -3.39 *10^{-4}/^{0}C and -3.44*10^{-4}/^{0}C respectively. These temperature coefficients are much larger than that of fused silica, so a change of temperature will affect the RI of the liquid only. Figure 15 demonstrates birefringence of the structure (with Λ=2.3μm and d/Λ=0.7). With the increase of the temperature the birefringence is getting reduced which is a direct consequence of Fig. 5. With the increase of temperature, the RI of the liquid gets reduced and the structure become less asymmetric and consequently low birefringence. The nature shows a linear relation with a slope of -1.95*10^{-6} /^{0}C. The corresponding loss of the structure has been presented in Fig. 16. With the increase of the temperature, the loss of the structure improves. A comparison of the birefringence and loss of the structures for two different wavelengths of 1310nm and 1550nm are shown in Fig. 17. The figure shows that with the increase of wavelength birefringence increases (Fig. 17(a)) at the cost extra losses (Fig. 17 (b)). We have compared the birefringence and propagation loss property for two different liquids as demonstrated in Fig. 18. The figure clearly presents that with a liquid with high RI, high birefringence can be obtained as can be seen from Fig. 18(a). The corresponding loss can be observed from Fig. 18(b) which illustrates that the loss is higher with higher RI liquid as expected from Fig. 5(b).

Cauchy equation for Oil#1 is known to be [M/s cargile Ltd.]:

$$Liquid1\#n1(\lambda)=1.3432154+237036/\lambda^2-4.943692\times10^{10}/\lambda^4 \quad (3)$$

$$Liquid2\#n2(\lambda)=1.3813595+307592/\lambda^2-2.614332\times10^{11}/\lambda^4 \quad (4)$$

where λ are in Angstrom.

Conclusion and Discussion:

We have studied the application of selective liquid infiltration where birefringence has been created in a symmetrical PCF by infiltrating liquid in the diagonally opposite sir-holes. Different air-hole fraction along with different infiltrating liquid has been considered towards studying the influences of different parameters towards birefringence and losses. It has been observed that with the increases of air-hole fraction, both the birefringence and losses are improved. With increase of infiltrating liquid, the birefringence improves while the structure becomes lossy. Our numerical analysis establishes that better birefringence can be attainable if we infiltrate liquid along x axis of the normal triangular PCF. We have obtained a high birefringence value of the order of 5*10^{-3}, which is quite higher than the available polarization maintaining fiber. We have also investigated the single mode property of regular PCF when the structure is infiltrated with liquid of certain refractive indices along the x axis to achieve asymmetry in the core. A wise adjustment of the available parameters is required so that single mode operation is possible for present day metro in-line applications especially from the visible range to the near IR wavelength covering C-band. Tunable property of the liquid infiltrated PCF has been investigated for different temperature in detail. Our study will unleash a new dimension towards realizing birefringence fiber based devices from a conventional non-birefringent PCF.

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