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Ultrahigh Birefringent Photonic Crystal Fiber: An Improved Design

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***Abstract*- An improved design of Photonic Crystal Fiber with extremely high birefringence and ultralow confinement loss is proposed and analyzed by full- vector finite-element method with uniaxial perfectly matched layers. Numerical results confirm that the proposed structure provides extremely high birefringence (~0.022) and ultralow confinement loss (<0.001dB/km).**

***Index Terms*- Birefringence, Confinement Loss, Finite Element Method, Photonic Crystal Fiber (PCF).**

I. INTRODUCTION

In the recent years photonic crystal fibers (PCFs) have attracted significant attention of researchers because of their extraordinary feature of flexible design parameter compared to conventional optical fibers. This has led to wide application of PCF. Based on design flexibility and large index contrast, various designs [1]-[4] for achieving high birefringence are reported in case of PCF. High birefringence in PCFs is achieved by different designs e.g. incorporating elliptical core with circular air hole in the cladding [5], elliptical air holes in the fiber cladding [6], by introducing two different sizes of air holes in the cladding adjacent to the fiber core [7], and by using complex unit cell i.e. two different sizes of elliptical air holes to replace the single unit cell (one size of elliptical air hole) in cladding region of PCF [8]. However, high birefringence leads to high confinement loss as well. This leads to adoption of a selective design of PCF which provides the optimized value of the birefringence and confinement loss. To the best of our knowledge, the design of PCF providing highest birefringence along with the lowest confinement loss in case of index guided PCF are respectively ~0.015 and <0.001dB/km as recently reported by Chen and Shen [9]. In Ref [9] birefringence is introduced by employing elliptical air holes in the fiber core and circular air holes in the fiber cladding.

In this letter, an improved structure of high birefringent PCF is proposed in which both core and cladding consist of elliptical holes whereas two outmost rings are of circular holes which provide extremely high birefringence with ultra low confinement loss. Core of the proposed PCF has the elliptical micro-air holes regularly arranged in the hexagonal lattice such that the major axis of air holes is orthogonal to the major axis of the elliptical air holes hexagonally arranged in the cladding. Extremely high birefringent PCF (~0.022) with the advantage of ultra low confinement loss (<0.001dB/km) has been obtained by incorporating circular air holes in two outermost rings in the cladding with increasing diameter. The proposed structure is a solution for the requirement of high birefringence and the low confinement loss simultaneously in the design and fabrication of PCF. The proposed PCF has a similar core (with small elliptical holes) as the PCF studied in Ref. [9]. The main differences between two PCFs i.e. the reported PCF [9] and the proposed design of PCF are (i) the air holes surrounding the core in the proposed design of PCF are also elliptical (ii) the major axis of elliptical holes in the cladding is orthogonal to the major axis of the elliptical holes in the core (iii) use of additional circular air holes in two outermost rings in the cladding to reduce the confinement loss**.** Consequently, the proposed design of PCF has a higher birefringence than the previous one with ultralow confinement loss.

II. DESIGN OF BIREFRINGENT FIBER

An improved design of PCF has been proposed which provides very high birefringence with an additional advantage of ultra low confinement loss. The core and the cladding both consists elliptical holes arranged in hexagonal lattice such that the major axis of the elliptical air holes of the cladding is orthogonal to the major axis of the elliptical air holes of the core. Though, the inter-hole spacing of the core is much smaller than the inter-hole spacing of the cladding. The design of the proposed High birefringent Photonic Crystal fiber (HB-PCF) is shown in figure 1. The core has four rings of elliptical μ-holes and is surrounded by six rings of air hole in the cladding in which four rings are of elliptical air holes whereas the last two rings are of circular air holes with increasing diameter. In our study, we consider the inter hole spacing $\Lambda = 2.2\mu\text{m}$ in the cladding and frequency dependent refractive index of the host material i.e. fused silica [10].
The length of the major axis of the elliptical air holes in the cladding is $d_1 = \Lambda$ where Λ is the inter hole spacing and minor axis $d_2 = 0.8\Lambda$. The length of the major axis and minor axis of the elliptical air μ-holes in the core of PCF is $d_3 = 0.06\Lambda$ and $d_4 = 0.02\Lambda$, respectively.

Center to center distance between the elliptical air μ-holes in the core of PCF is $\Lambda' = 0.1\Lambda$. Diameters of air holes of fifth and sixth rings in the cladding are $d_5 = 0.6\Lambda$ and $d_6 = 0.8\Lambda$, respectively. Two outmost rings of cladding are meant to reduce the confinement loss as these two rings introduce the refractive index step variation due to which it will act as a jacket for the given PCF structure.

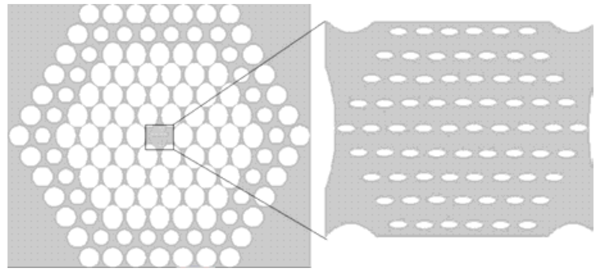

Fig. 1. Schematic diagram of the proposed PCF with four rings of elliptical air holes and the two outermost rings of circular air holes in the fiber cladding and the elliptical air μ-holes in the fiber core.

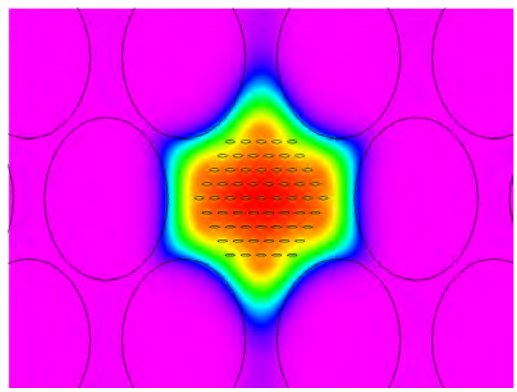

Fig.2. The profile of the major electric field component of the y-polarized fundamental mode at a normalized frequency 1.

We apply the full-vector finite-element method using Rsoft-FEMSIM software and uniaxial perfectly matched layers to study the birefringence i.e.

$$\text{Modal birefringence} = |n_x - n_y| \tag{1}$$

The difference between the effective indices of the *x*-polarized and *y*-polarized fundamental modes of this PCF. The confinement loss can be computed from the imaginary part of the effective modal index [11] as

$$\text{Confinment loss} = 8.686\,\text{Im}[k_0 n_{eff}] \tag{2}$$

in decibels per meter, where Im stands for the imaginary part, n_{eff} is the effective index of the *x*-polarized or y-polarized fundamental mode.

Figure 2 illustrates the profile of the major electric field component of the y-polarized fundamental mode at a normalized frequency of 1. Figure 3 shows the comparison of the modal birefringence using equation 1 for the proposed PCF with the reported one and the study of birefringent behavior for different d_2 / d_1.

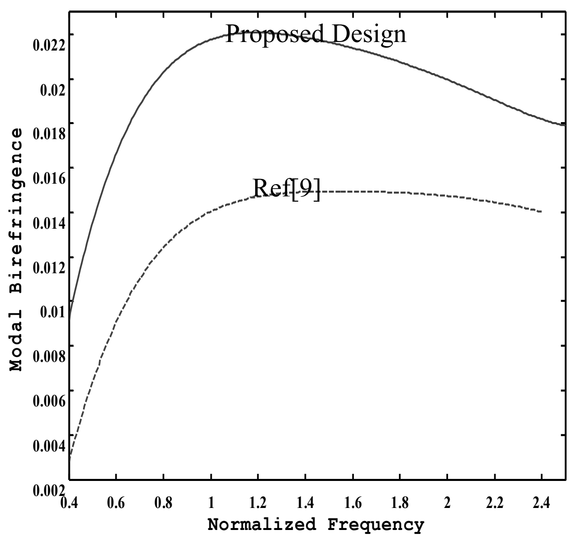

Fig.3. Comparison of the modal birefringence obtained for the proposed PCF with the reported one.

Figure 4 shows the confinement losses for the x-polarized (filled circles with dashed line) and y-polarized (filled squares with solid line) fundamental mode which has been computed by equation 2.

III. RESULTS AND ANALYSIS

Figure 3 shows the comparison of modal birefringence of our proposed PCF with the recently reported high birefringent PCF [9] and it is clear from the figure that the proposed PCF yields higher birefringence than the reported one due to the fact that the birefringence not only introduced by elliptical holes in the core but also supported by the orthogonal elliptical air holes in the cladding.

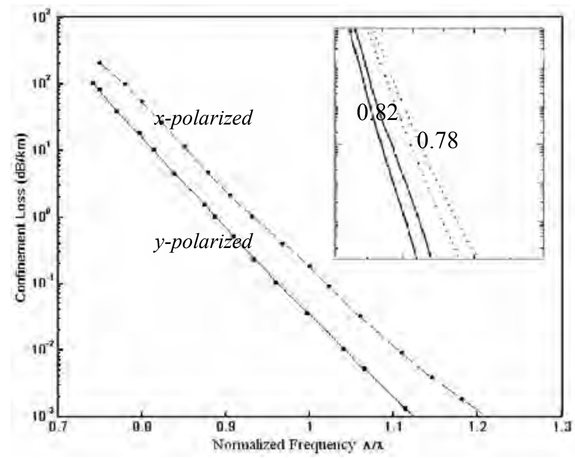

Fig.4. Confinement losses of the x-polarized (filled circles with dashed line) and the y-polarized (filled square with solid line) of the fundamentals modes for the proposed PCF as a function of normalized frequency. Inset shows the confinement losses for e=0.78 (dotted line) and e=0.82 (solid line)

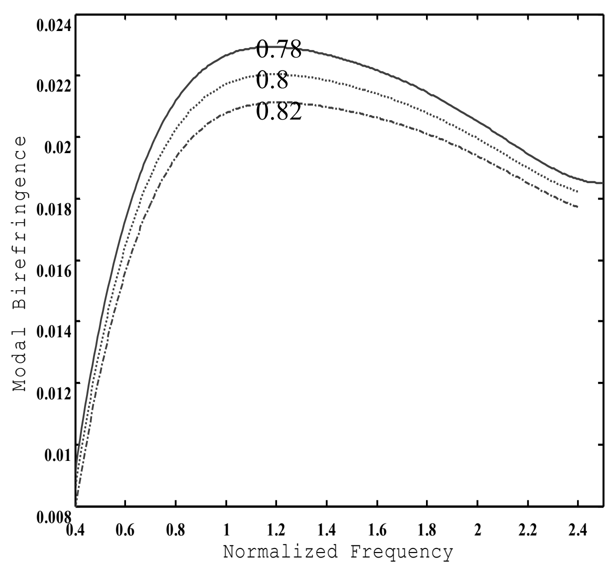

Fig.5. Illustrate the modal birefringence of the PCF as a function of normalized frequency with varying ellipticity 'e' from 0.78 to 0.82 by an interval of 0.02.

This is because of the fact that the proposed design of PCF consists of the orthogonal elliptical air holes in the core and cladding. Figure 4 shows the confinement loss for the x-polarized fundamental mode and y-polarized fundamental mode, respectively. The confinement loss is very low, less than 10^{-3} dB/km for higher normalized frequencies. This is due to the fact that the confinement of optical signal enhances because of the incorporation of two additional circular air holes in the last two rings in the cladding of the proposed PCF. It is mentioned here that the birefringence can be further increased by decreasing 'e' values i.e. the ratio of the minor axis to the major axis. Higher modal birefringence i.e. $|n_x-n_y|$, is expected as the 'e' value decreases, which is confirmed by the numerical results as shown in figure 5. Figure 5 shows the birefringence of the PCF as a function of normalized frequency with varying ellipticity, 'e' from 0.78 to 0.82 by an interval of 0.02 at the cost of confinement loss, as shown in the inset of figure 4.

IV. CONCLUSIONS

In comparison with the reported ultra high birefringent PCF [9], the proposed PCF yields higher birefringence. It has been found that the proposed design of PCF provides an ultrahigh birefringence (~0.022) with ultra low confinement loss (< 0.001 dB/km). Thus, ultrahigh birefringence and ultralow confinement loss can be achieved simultaneously using proposed design of PCF. In the recent past, it has been observed that PCF with smaller size of air holes and thereby smaller pitch are being fabricated to obtain desired application specific transmission characteristics. PCF with a single elliptical air micro-hole in the fiber core [12] has already been manufactured successfully, therefore it is expected that the fabrication of PCF similar to the proposed design could be routinely fabricated in the near future.

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