LOSS CHARACTERISTICS AND MODAL DEGENERATION IN PHOTONIC CRYSTAL FIBER

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Abstract- In this paper various losses of this Photonic crystal fiber have been studied and estimated correctly through simulation. Agreement with the reference dataset supports the accuracy of this work. It has been shown that change in the bending radius modifies the modal properties of photonic crystal fiber, which is very important for a number of potential practical applications. The evolution of highly dispersive lower and higher orders cladding modes and their degeneration with respect to the fundamental core mode in a bent photonic crystal fiber has also been studied.

Keywords- Confinement Loss, Bending Loss, Splice loss, Modal Degeneration, Cladding Mode.

I. INTRODUCTION

In modern time, optically-driven data exchange medias are playing a central role in many new applications such as defence, security, sensing, transportation, computing and medicine. Today it seems that everyone wants high-speed data, dependable voice service, and high-quality video, whether these services are delivered by digital subscriber line, cable modems, or wireless architectures is insignificant as long as the service is fast and dependable. Providing all these services together requires increasing bit rate per channel or increasing the power level through the channel. Due to certain limitations of classical optical fiber [1] Photonic crystal fiber (PCF) a new class of optical fibers consisting of a central defect region surrounded by multiple air-holes that run along the fiber length has attracted great deal of attention in the optics community in recent years. PCF is being treated as potential specialized optical waveguide [2] as it is promising novel technology with several possible applications in wave guides, nonlinear optics, fiber lasers, sensory systems, ultrawide-band transmission, supercontinuum generation, high power delivery, optical amplifiers, and other functional devices [2]-[3]. PCF also has great capacity in overcoming the limits of conventional fibers and obtaining remarkable results that regular fiber cannot achieve, such as high nonlinear effects, controlled dispersion, low bending losses, low losses and high power transmittance.

During the last decade, PCF has been extensively studied for these applications utilizing their unique capabilities such as endless single mode operation, modifiable and anomalous dispersion, large mode area, non-linear effects, solitons propagation, high birefringence, and enhanced or suppressed optical nonlinearity [4]. These unique characteristics come from the fact that optical properties of the guided modes in the core can be easily manipulated by changing the structure of PCF. Transmission of signal through the fiber optic channel mainly depends upon the loss associated with the fiber. To meet the uprising demand of modern time it is very essential to estimate these losses for a given structure accurately. Losses in PCF occur due to many reasons such as fabrication, structural limitations, bending and misalignment during joining with others. Losses related to fabrication can be reduced by carefully optimizing the fabrication process. In this work, various operation related losses of PCF and their dependence on different parameters has been extensively studied. To calculate bending loss, the three-dimensional structure of the bent fiber has been transformed into a two-dimensional straight fiber by using conformal mapping of the refractive index. Comparison with a reference dataset has also been done to validate the accuracy of this work. Due to bending an important phenomenon has been noticed which is called mode degeneration occurs between core mode and cladding mode.

II. ANALYSIS TECHNIQUE

Comsol Multiphysics 4.2 has been used for this analysis. After all initial setup and geometry drawing, the refractive index of different material has been given. The refractive index of air is 1 and for silica it is wavelength dependent and determined by Sellmeier equation. Finite element method (FEM) method has been used to solve the scalar wave equation using appropriate boundary conditions. During the determination of variation of confinement loss with respect to wavelength every time for wavelength change the refractive index has also been changed. During bending the refractive index get changed due to conformal mapping and elasto-optic effect. This change has also been taken account by changing refractive index. Perfectly matched layer (PML) has been used during simulation and by a stable value of complex part of effective index founded by varying PML thickness the optimum thickness of PML has been determined. Here the thickness of PML layer has

been used is 2μm as it is stable in the region of 1 to 3μm. Analysis has been done for hexagonal PCF of Λ=1.6, 2.6 and 5μm with d/Λ ratio of 0.5 and N=3.

III. LOSS CHARACTERISTICS

The losses in PCFs occur for a number of reasons, such as intrinsic material absorption loss, structural imperfection loss, Rayleigh scattering loss, confinement loss, bending loss and splice loss. Losses related to operation of PCF are confinement loss, bending loss and splice loss.

A. Confinement Loss

PCF provide confinement and guidance of light in a defect region around the centre. For the light confinement mechanism, index-guiding PCF relies on total internal reflection to confine light in the region of a missing air hole forming a central core.

The SiO! materials do not have an imaginary component because this material is not absorbing. PCF is usually made from pure silica, and so the guided modes are inherently leaky because the core index is the same as the index of the outer cladding without air-holes [5].

Due to the fixed number of layers of air holes, leaking of the light from the core to the exterior matrix material takes place through the bridges between air holes, resulting in confinement loss. Because of the finite transverse extent of the confining structure, the effective index is a complex value; its imaginary part is related to confinement loss through Eq. 1 [5], where L is in decibels per meter.

$$L = \frac{40\pi \,\mathrm{Im}(n_{eff})}{\lambda \ln(10)} \times 10^6 \qquad (1)$$

The variation of confinement loss with respect to wavelength for different pitch has been presented in Fig. 1. Confinement loss is related to pitch. For fixed d/Λ, if pitch is increased, the air hole diameter also increased so the fraction of air is also increased. As fraction of air has been increased the light gets more confinement in core so confinement loss is decreased. This loss also depends on number of air-holes rings that surround the solid core. By increasing the number of air-holes rings this loss can be reduced exponentially.

The optimum number of air hole rings considering Rayleigh scattering limit for practical fabrication process is determined from the geometry of the structure. Confinement loss is also closely related to wavelength. As wavelength is increased the field penetration in cladding region have also been increased so the confinement loss also increased. The phenomenon of field penetration has been depicted in Fig. 2.

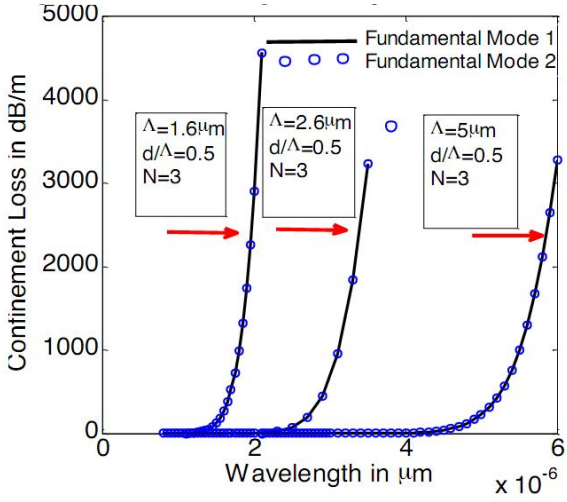
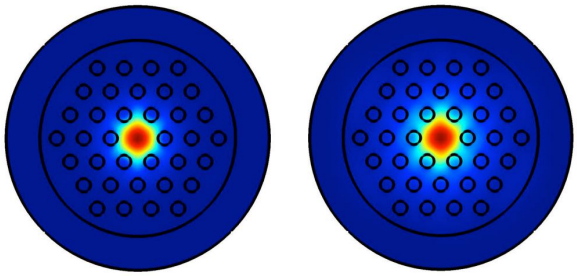


Fig 1: Confinement loss versus wavelength.



(a) Norm E at λ=1.5**μm** for Λ=1.6**μm**

(b) Norm E at λ=2.1**μm** for Λ=1.6**μm**

Fig 2. Cladding penetration for higher wavelength.

B. Bending Loss

Like conventional telecom grade optical fibers PCFs are needed to be bent, twisted, and stressed for being cabled or placed in forms of coils for using as transmission medium. Many sophisticated applications such as ring resonators, arrayed waveguide filters, optical delay lines, and s-band attenuators also require bending of PCF. When the fiber is bent the different part of the mode has to travel different distances for curvature shape of the fiber. But this is not possible as the speed of light is the same unless the mode partly moves into the cladding with lower refractive index and higher speed of light. So the mode moves out from the core and into the cladding. As a result the field distribution of the fundamental mode in a straight fiber is different from field distribution in a bent waveguide. So the incident beam is converted into higher order mode. As the incident mode is converted into higher order mode so power loss in a bent fiber is more than in the straight fiber. This loss is called bending loss.

Bending loss has been determined through the beam propagation method (BPM), in conjunction with the conformal mapping technique. The first step in the process is to transform the circularly curved fiber to an

equivalent, straight fiber by the process of conformal mapping [6]. The modified refractive index for bent is given in Eq. 2 [6], where, n!"#$%&'" is refractive index of the fiber material and R is bending radius and x is coordinate system. The exponential term accounts for the increase in optical path length along the fiber with distance from the centre of curvature. Relatively slow bends (x<<R) is essential to apply this first-order approximation. An additional to this change another change occurs to refractive index due to stress-optic effects or elasto-optic effect [7]. This phenomenon has been depicted in Eq. 3, where ν is Poisson Ratio, P !!andP !" are the component of elasto-optical tensor and R is Bending radius. Combining above equations we get effective bending radius, which is depicted in Eq. 4. In equation 4 the denominator subtracted from 1 is known as linear coefficient χ. By combining all equations final Eq. 5 has been found [7]. The value of □ for silicon is −0.22 [7]. The resulting index distribution was tilted with respect to the straight fiber, increasing away from the centre of the bend.

$$n' = n_{material}\exp(\frac{x}{R}) \approx n_{material}(1+\frac{x}{R}) \quad (2)$$

$$n_{material} = n\left[1-\frac{n^2 x}{2R}[P_{12}-\upsilon(P_{11}-P_{12})]\right] \quad (3)$$

$$R_{eff} = \frac{R}{1-\frac{n^2 x}{2R}[P_{12}-\upsilon(P_{11}-P_{12})]} \quad (4)$$

$$n' = n_{material}(1+(1-\chi)\frac{x}{R}) \quad (5)$$

$$L_B = 8.686 * \mathrm{Im}(\beta) \quad (6)$$

Refractive index profile of bent and straight profile has been presented in Fig.3 we can easily determine the value of bending loss by using the effective index through Eq. 6. From this equation bending loss has been determined. This result has been compared with a reference result [7]. The result has been depicted in the Fig. 4.

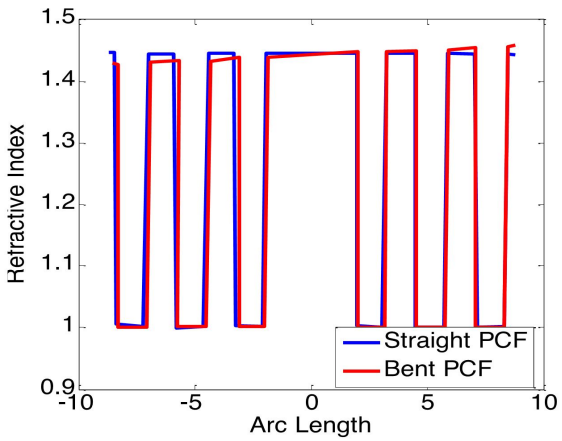


Fig 3. Refractive index of straight and bent fiber.

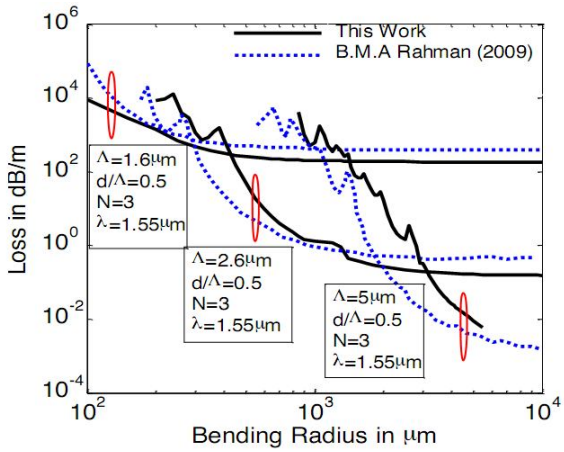


Fig 4. Variation of total loss with bending radius.

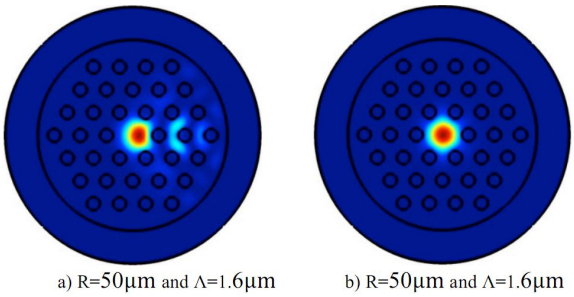
In Fig.4 it is obvious to us that, for a lower pitch length of 1.6 μm, the bending loss increases monotonically as the bending radius is reduced. It can tolerate high bending. But in this case bending loss is higher. For low pitch leakage loss which is also called confinement loss is also high as the PCF is operating close to its modal cut-off. In large bending radius the loss gets saturated. This loss is confinement loss or leakage loss. So using a PCF with such a smaller pitch length is often not preferred due to its higher leakage losses. As the pitch length is increased, for 2.6 μm the leakage loss is reduced by 3 orders of magnitude as expected. The bending loss is also lower after a certain radius. Beyond this radius, as the bending radius is reduced, the bending loss increases progressively and as a result the total loss also increases. It can be noted that increases in the bending loss with the bending radius are more rapid as the bending radius is reduced, compared to the case with a lower pitch length of 1.6μm. At a lower bending radius, the nonmonotonic nature is also seen with oscillations in the total loss values. When the pitch length is increased further, for pitch length of 5μm the leakage loss is significantly reduced to 10!!dB/m and a PCF with a larger dimension is often then preferred. But, in this case the PCF is more susceptible to bending, and the total loss value increases rapidly as the bending radius is reduced. It also cannot tolerate too much bending. For some fixed radius, this value can be higher than that of a PCF with a lower pitch value. The moving of core mode into the cladding region and phenomenon of higher tolerance of bending for lower value of pitch has been shown in Fig. 5.

IV. MODAL DEGENERATION

Mode degeneration occurs in PCF during bending. Two cladding mode can be degenerated and one core and cladding mode can be degenerated. First incident is called cladding - cladding mode degeneration and 2nd one is called core cladding mode degeneration. To study this mode degeneration more closely, the smaller bending radius range is considered in some

further detail using an expanded range and creating many additional simulated results. The real part of effective index decreased with the bending radius for core mode. Cladding mode has higher refractive index. But it falls sharply. So there is a transition between these two modes. This phenomenon is presented in Fig.7 [7]. In this figure the horizontal sections of these two lines represent the core mode while the slanted line represents a highly dispersive cladding mode. Cladding mode has smaller core area then core mode. As bending radius is decreased the effective index of cladding mode is being increased. For Λ=5μm when bending radius is close to 1445μm [7] the effective index of this cladding mode becomes equal to that of the core mode, and they become degenerated. In a similar way for the transition in the effective indices and loss values, the spot sizes of these modes also go through a transition.

This mode degeneration causes a mixing of these modes, the formation of the supermodes and the transformation from one mode to another. These cause rapid changes in their modal properties and the effective index, the spot size, and the bending loss values. A higher pitch value or larger d/Λ ratio increases the silica bridging regions, and such mode degeneration can appear at a higher bending radius, which may often be encountered in practical applications. In these cases, the mode degeneration appears more frequently and shows as noisy loss values in experimental measurements. In core mode all field are confined in core while in cladding mode all field are confined in cladding region between the 2nd or 3rd air hole rings. The field profile has been presented in Fig. 8 to understand the core mode and cladding mode. Fig.8 clearly depicts that the origin of localized cladding modes lies in the region between the air holes. These areas are smaller than the PCF core. For a straight PCF these modes are with the lower effective indices so they do not interact with



a) R=50μm and Λ=1.6μm b) R=50μm and Λ=1.6μm

Fig 5. Electric field distribution for bent fiber.

C. Splice Loss

For various practical applications it is essential to join a fiber with another fiber. During this procedure two fibers are needed to be stripped and cleaved to high quality. The cleaved facets should be flat and the cleave angles should be low. Due to the misalignment of fibers during joining a special types of loss occur in PCF, which is called splice loss. The splice loss also depends upon the effective area of two fibers and the transverse offset of two fibers joined. The formula to determine splice loss from spot size or effective area is given in Eq. 3.9 [8], here □ is Splice loss in dB; u is transverse offset between two fibers, □!"# is spot size of PCF.

$$\alpha = 4.343\left[\frac{u}{W_{PCF}}\right]^2 \qquad (7)$$

The Fig. 6 presents the splice loss versus wavelength graph for different pitch. It depicts that the splice loss is higher for smaller pitch and smaller for higher pitch and the splice loss decrease with the increase in wavelength as spot size increase with wavelength and decrease with pitch. The rate of decrement is higher for smaller pitch and vice versa.

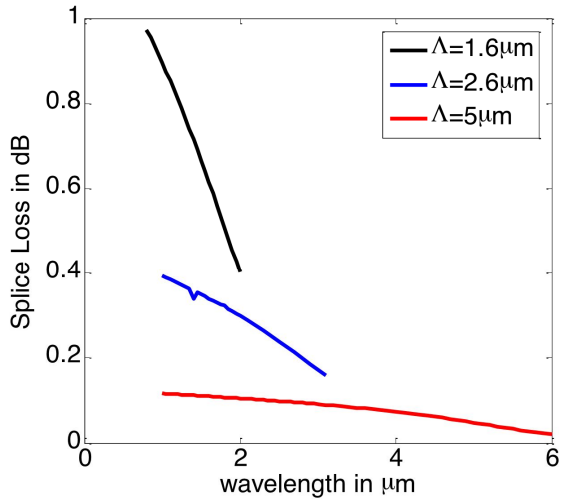


Fig 6. Variation of splice loss with respect to wavelength.

the PCF core mode. However, for a bent PCF, as the local equivalent index is increased, the dispersion slopes of these modes are higher, and for smaller bending radius they can be phase matched to the core mode to form coupled supermodes. It has also been shown that these cladding modes can also cover several bridging regions simultaneously and also support the higher order modes.

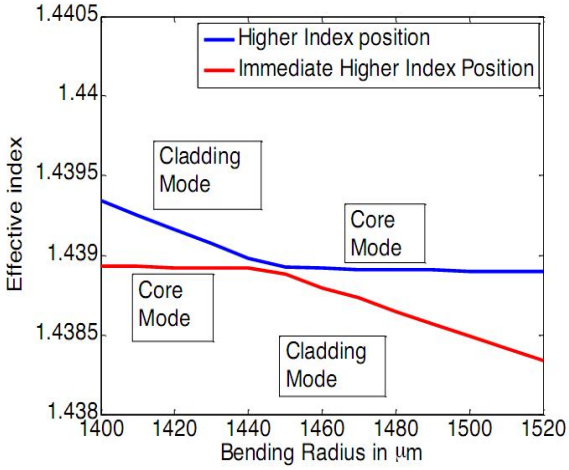
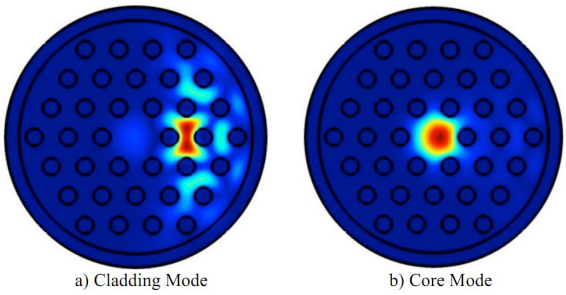


Fig 7. Variation of Effective Index with R.



a) Cladding Mode b) Core Mode

Fig 8. Field of Core mode and cladding mode.

CONCLUSION

Losses related to PCFs are hampering their application for using as communication channel. Deep study on this particular topic has been done to know the nature of losses and to find out way to avoid the problem caused by these losses. The dependence of losses on designing parameters has also been analyzed. Advanced application of bending effect in ring resonators, arrayed waveguide filters, optical delay lines, and s-band attenuators has extensively been studied. Mode degeneration occurs during bending, due to core-cladding mode degeneration losses of each mode varies.

The degeneration point depends upon bending radius. The origin of these fundamental and higher order cladding modes, the coupling between them, and ultimately the coupling of these cladding supermodes with the fundamental core mode can affect the design of various PCF based applications. The study of this mode degeneration gives insight to the practical application of PCFs and the optimum handing conditions during many “real world” applications. This understanding is also useful in the study of PCF-based devices.

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