Design of 2 µm Wavelength Operation in Large Mode Photonic crystal fiber

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Abstract—**The Polarizing Maintaining (PM) photonic crystal fiber (PCF) is made to work in the wavelength of 2µm operation. It is then checked numerically in Finite Element Method. Where, we can decide its different actions and response by varying its bending radius. A new model of fiber has been made in such a way by omitting the problems that are produced by previous designs. The core region of the fiber is thulium doped with diameter of about 80µm. Two boron doped Stress Applying Parts [SAP] has been used in the inner cladding to produce the continuous Birefringence. Thus, a single mode and single polarization operation has been maintained endlessly throughout the entire fiber efficiently. This is done by varying the bending radius ranging from 33cm to 60cm and some of its Fundamental Mode and Higher Order Modes got suppressed. So far, the highest effective area obtained is around 250µm^2 and 2576µm^2.**

Keywords— **PM-PCF, 2µm wavelength, Single polarization, Core region and Overlap integral.**

I. INTRODUCTION

Fiber Laser Technology is seeking more interest than the Solid state laser. Due to its heavy rise in output power, energy efficiency, high beam quality, low cost, less maintenance and compactness, it is widely used in many applications [1]. These advantages can be well applied both in continuous wave (CW) as well as pulsed fiber laser system [2]. The fiber is constructed in such a way so as to maintain the Gaussian output beam and single mode operation throughout the entire fiber length. To fulfill these conditions the effective mode area of the photonic crystal fiber has been enlarged. Generally when we use multimode it may end up with poor beam quality so, we are using Dual Cladding [DC]. This may increase the output power drastically. Due to the changes done in the modes of the PCF fiber, some of the non-linearity effects also decreased. Using the rod-type photonic crystal fiber we can able to produce the highest values of mode area.

Too many works has been done for the development of 1µm operation in past years. Currently laser around 2µm wavelength is getting more applications on various places. It can be well used in soft-tissue surgery, free space communication, military, lidar, defense, and remote sensing places [3]. It also provides an "eye safe" property and thus, it will not damage our retina part of the eye.

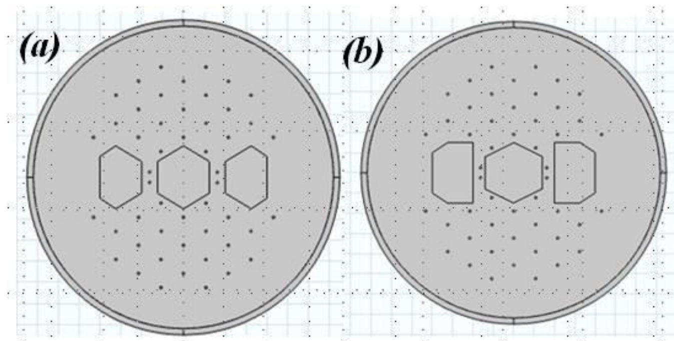

Fig. 1(a) and (b) Transectional view of the PM-PCF for 2µm wavelength operation.

Emission of 2µm wavelength can be done by doping the thulium material into the fiber. 2µm lasers are mainly used in medicinal field for surgical applications to produce exact and accurate results in both soft and hard tissue. This is because, it as a high capacity of absorption in water. It also has an ability to stop the bleeding during surgery. While doing soft tissue surgery rapid vaporization and sufficient coagulation for hemostasis can be made easily using its high-power thulium-fiber laser. We are using the rod-type fibers to avoid bending with thick silica outer layer for about 1-2mm. This types of fiber are usually tested with ytterbium doped fiber design [4]—[5]. We can also use this in thulium doped fiber design. When the light passes into the fiber, PM fiber will maintain its state of polarization for its entire length.

Thulium doped PM fiber with 80µm core diameter has been checked mathematically using the software named COMSOL MULTIPHYSICS [6]. For this diameter, the PM-PCF is made to work with the wavelength of 2µm. Bending radius can be varied from 60cm to 33cm. A new large mode PM-PCF fiber is also designed and verified numerically with the same core diameter. Birefringence can be obtained by applying the boron doped stress material into the fiber [8]. The output shows that the new design made, is capable of achieving the single mode and single polarization operation with low propagation losses and higher overlap integrals between the modes. It also exhibit higher values of effective mode area of around of 2250µm^2 and 2576µm^2.

II. FIBER DESIGN

The transactional view of the photonic crystal fiber under inspection is shown in Fig. 1(a) and (b). A normal commercial fiber is modified to work in 2µm wavelength have been represented by Fig. 1(a). The geometry of the PCF fiber is formed by grouping the number of hexagonal cells. The center core of the fiber is doped with the thulium silica material. The shortest distance between the two cells is known as pitch Λ_1 whose value is given as 13.4µm. Diameter of the core is around 80µm. One side of the hexagon shape in thulium doped region is measured as 33.5µm. Four cell rings is used to form the inner cladding portion of the fiber. The value for d/Λ_1 is 0.18. The thickness of the outer air cladding is about 6µm and its diameter of 150µm. The refractive index for the pure silica material nSi = 1.4381. The refractive index for the thulium doped material in the core is about nC = 1.44. The refractive index of the boron doped cladding material is about nCl = 1.43.

The newly made fiber is shown in Fig. 1(b). The Thulium and boron material is doped in the center core and cladding part of the fiber with same refractive indices. The only difference is that shape of the stress applying parts gets changed. This is because, more number of stress is applied in this model. And also the size of central core region of thulium material gets increased.

III. SIMULATION OUTPUTS

There are totally two steps exists in the mathematical part. These are calculation of Birefringence and Bend loss with overlap integrals. It can be mathematically observed using the software COMSOL MULTIPHYSICS 5.1 version. For the Boundary condition, perfectly matched layer can be used for the analysis [6].

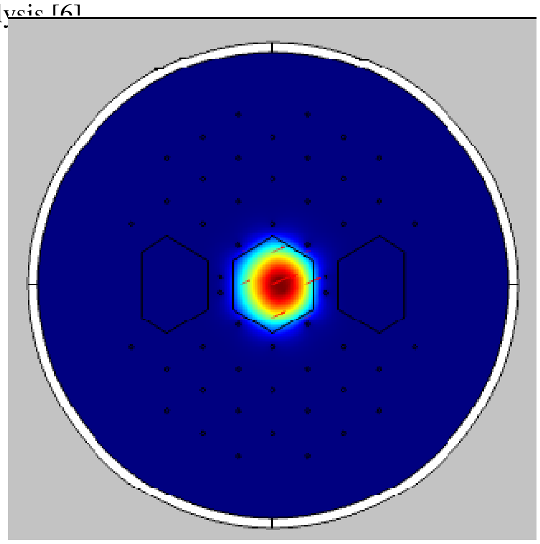

Fig. 2. Light confinement of the fiber design in COMSOL

During thermal cooling, the different materials of thulium and boron materials expands some permanent stress in the core. From this we can produce Birefringence 'B' value. Due to this high stress induced by B, FM is confined towards center of core which is shown in the Fig. 2. The difference between the x and y component of anisotropic refractive index is said to be birefringence B. This can be verified using the software COMSOL MULTIPHYSICS 5.1v. It can be calculated using the formulae,

$$B = C_x - C_y \quad (1)$$

Where C_x and C_y is the refractive indices of x and y direction. The B value ranges from 1 x ⁻ to 4 x ⁻ . It is well spreaded in the core region of the PCF with single polarization that is shown in the Fig. 3(a) and (b). Thus single polarization has been maintained effectively throughout the fiber length.

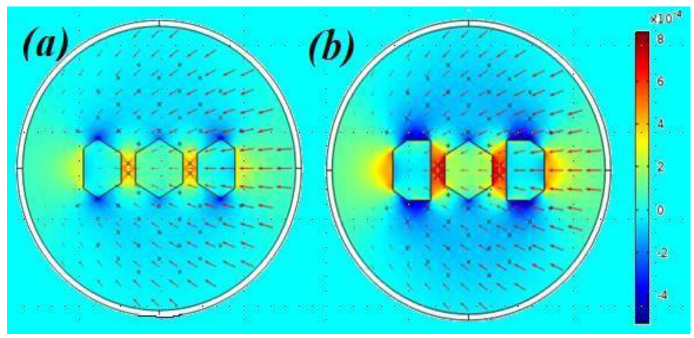

Fig. 3(a) and (b) Birefringence light confinement of the both the fiber models with single polarization.

The properties of the modes can be analyzed in the final part of the calculation. The numerical examination of the mode overlap integrals and the propagation losses while bending the fiber has been verified in this section. The difference between each mode decides the desired mode properties. Generally, FM should be greater than 0.85 and the difference between FM and HOM should be more than 0.25. Then it is said to be single mode operation. The results are observed in Fig. 4(a) and (b). The mathematical representation of the losses with respect to the bending radius of the modified fiber of 2µm wavelength is shown in Fig. 4(a). These propagation losses can be found using the formulae,

$$L = \frac{\quad}{\quad} * - * Img(neff) \quad (2)$$

Where L is the propagation losses, $neff$ is effective mode index of the fiber, λ is wavelength of PM-PCF. There should be more intensity difference between each modes.

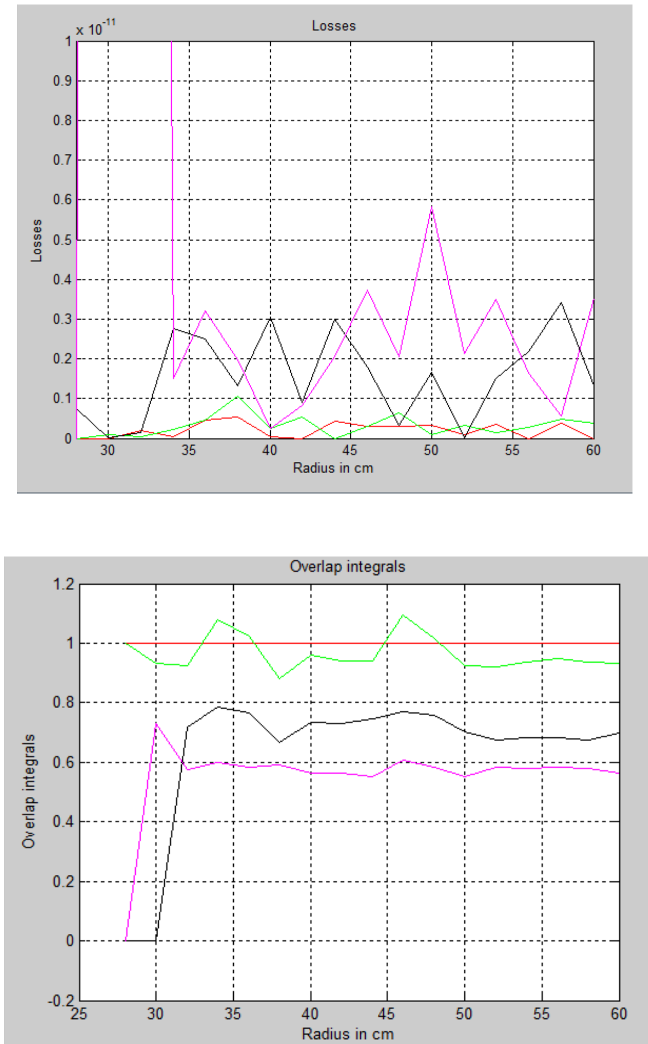

Fig. 4. Numerical results for scaled fiber. (a) Losses of the FM and HOM components. (b) Overlap integrals of the modes in the fiber on varying the bending radius in cm.

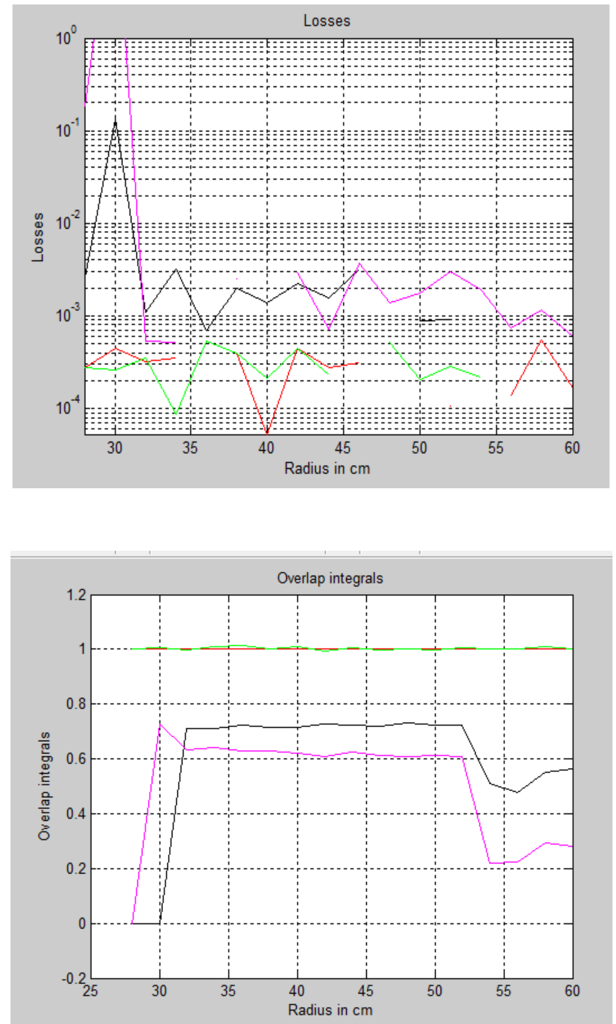

Fig. 5. Numerical results for the newly proposed fiber. (a) Losses of the FM and HOM components. (b) Overlap integrals of the modes in the fiber on varying the bending radius in cm.

This intensity distribution over x and y component can be calculated using the formulae,

(3)

From the Fig. 4. It is clearly visible that the propagation loss of the FM of the fiber is too low when compared with the other modes. It varies from 30cm to 60cm. While the loss of the higher order mode has the highest loss of about 1 x $^{-}$. But the loss should be minimum only then we can able to obtain the single mode and single polarization operation. Similarly the overlap integral difference should be more than 0.25. In the Fig. 4(b) it is very clear that the difference in overlap of the modes is 0.3. This again proves that the designed PM-PCF works with single mode operation. Similarly the newly proposed fiber also checks the losses and overlap modes. This loss is also minimum of about $^{-}$. It is too low when checked with previous models. Here you can see the FM overlap larger than 0.25 for bending radius varying from 30cm to 53cm. Higher order modes produces more losses and hence only FM can be preserved while suppressing all the other HOM. When the bend loss is low, then the bending radius gets high. Above 60cm, it acts as a straight step index fiber.

The effective mode area of both the fiber designs were shown in the Fig. 6(a) and (b). Through which we can see how effectively mode area gets utilized. It not only checks for the core area but also to the whole region. Thus, it is found that an effective area is around 2250µm² and 2576µm².

$$Aeff = \qquad (4)$$

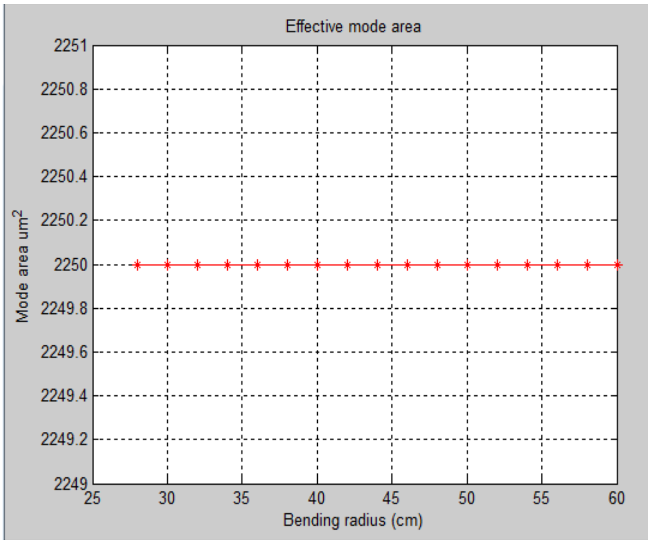

Fig. 6.(a) Effective mode area of the scaled fiber for 2µm region.

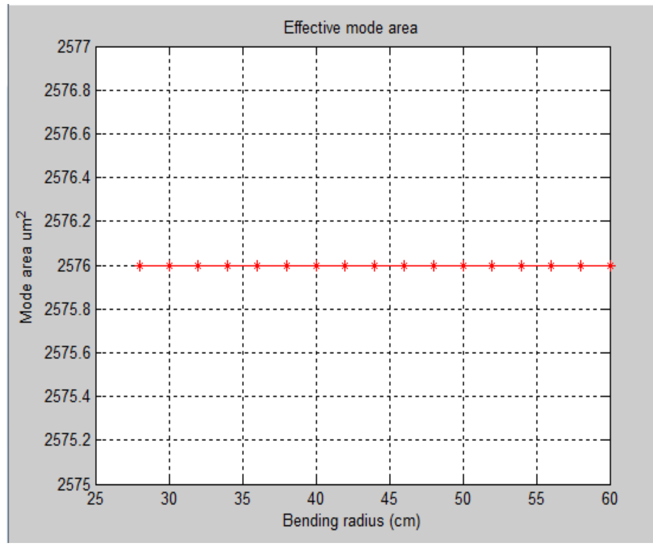

Fig. 6.(b) Effective mode area of the new fiber design for 2µm region.

Where *Aeff* is effective mode area of the PM-PCF, *E* is Electric field distribution inside the core region. This can be mathematically proved by pointing vector [7]. Thus the remarkable value of effective mode area is obtained in the PM-PCF with the large mode area of 2µm wavelength.

IV. CONCLUSION

The polarizing maintaining PCF with large mode area have been efficiently designed for 2µm wavelength operation. The thulium doped fiber has a diameter of about 80µm. From the result it is very clear that single mode operation and single polarization for this PM-PCF is achieved effectively for the entire length of the fiber. It is observed that the propagation losses of the FM is too low than the higher order modes. For both the designs, single polarization is maintained endlessly with FM mode overlap greater than 0.85.

Bending radius is set in a range between 30cm to 60cm. The Birefringence value ranges from 1 x $^{-}$ to 4 x $^{-}$. Some of the Fundamental Mode and Higher Order Modes have been suppressed. Hence the effective area of 2250µm² and 2576µm² is achieved. These values are too high and cannot be noticed in the previous models.

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