Modeling of Circular Photonic Crystal Fiber Structure for High Non-linearity

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Abstract - This paper compares the PCF characteristics such as chromatic dispersion, effective area, confinement loss and nonlinearity for circular PCF having 5 rings of air holes and 4 rings of air holes. Proposed structures are simulated by using Comsol multiphysics. Method used for simulation is finite element method (FEM). For both the cases of circular structures air filling fraction i.e. d/Λ=0.5. From the numerically simulated results it’s shown that circular PCF with 5 rings of air holes provides large negative dispersion, which is of the value of -150ps/(km.nm), hence such PCF have high potential to be used as a dispersion compensating fiber in optical communication systems. Circular PCF with 5 rings of air holes offers low confinement loss of the order of 10^{-10} dB/m. Circular PCF with 5 rings of air holes offers low effective area. In the case of nonlinearity circular PCF with 5 rings of air holes has a value of 38.38 W^{-1} km^{-1} and that for circular PCF with 4 rings of air holes has 14.47 W^{-1} km^{-1} at 1550 nm. From the above optical properties for both the structures, it is seen that structure with 5 rings of air holes is suitable for majority of application such as dispersion compensation fiber and supercontinuum generation. Nonlinearity can be increased by increasing the number of rings. By increasing nonlinearity value it became suitable for supercontinuum generation.

Keywords - Confinement loss, Circular PCF Dispersion, Effective Area, Nonlinearity, Photonic crystal fibers.

I. INTRODUCTION

Nowadays photonic crystal fibers (PCF) [1,2,3] is of much attention all around the world. PCF which is also known as holey fibers are special type micro structured fibers. It consist of central defect region surrounded by multiple air-holes, which run along entire fiber length. Main difference between a PCF and the conventional one is the index profile of core/cladding. PCF can offer more flexibility than conventional fibers in design of optical properties such as birefringence, dispersion and confinement loss. PCF with low and flattened dispersion are useful for improving optical fiber communication capabilities. It has achieved increased attention because of its novel optical characteristics [4,5,6]. PCF guide optical waves through one of the two methods: effective-index guidance and photonic band gap guidance. PCF has two parameters to define its geometrical structure, they are diameter of air hole(d) and pitch length(Λ). By varying this two parameter PCF with different properties can be obtained. Advantage of using Photonic crystal fiber is that we can achieve very good properties in birefringence, dispersion, nonlinearity.

Typically, in PCF air holes are arranged on the vertex of an equilateral triangle with six air holes in the first ring around the core, which is called the HPCF. Beside the hexagonal structure other structures such as, square lattice, cob web, honeycomb, octagonal and decagonal [7,8,9,10] are proposed for the design of PCF.

In this paper various properties of PCF like chromatic dispersion, effective area, confinement loss and nonlinearity has been studied for circular PCF[11] having 5 and 4 ring of air holes. Finite element method (FEM) with perfectly matched boundary layers (PML) are used for analyzing the dispersion and leakage properties of PCF. It has been shown that circular PCF with 5 ring air holes provide large negative dispersion compared to 4 ring circular PCF structure. Based on the numerically simulated result nonlinearity value for circular PCF with 5 rings of air holes is greater than that of 4 rings of air hole structure. By increasing the number of air hole nonlinearity can be increased for a circular PCF, hence can be used for supercontinuum generation.

II. DESIGN OF PCF STRUCTURES

Proposed model for circular PCF having 5 rings of air hole and 4 rings of air holes is shown below. The structure is surrounded by a perfectly matched layer(PML). This layer acts as absorbing region.
Fig. 1: Proposed structure of circular PCF with 5 ring of air holes, pitch $\Lambda = 1.45 \mu m$ and hole diameter $d = 0.725 \mu m$.

Proposed PCF structures which is of circular shape with 5 ring of air holes and 4 ring of air holes are shown in Fig. 1 and Fig. 2. D and $\Lambda$ denotes diameter and pitch length for the structures. Background material used is silica. For both the PCF value of the diameter i.e. $d = 0.725 \mu m$ and that of pitch length i.e. $\Lambda = 1.45 \mu m$. PML region which acts as boundary for this structure is of thickness $2 \mu m$. The validation of the design is done by using FEM with PML for accurate modelling of PCF.

Fig. 2: Proposed structure of circular PCF with 4 ring of air holes, pitch $\Lambda = 1.45 \mu m$ and hole diameter $d = 0.725 \mu m$.

Fig. 3: Intensity profile for 5 ring air hole circular PCF structure

Fig. 3 is obtained by using Comsol 3.5a based on FEM. It shows the intensity and the shape of output light in two dimension. From consol we get the values for real and imaginary part of $n_{\text{eff}}$ for different wavelength readings.

III. EQUATIONS OF CHROMATIC DISPERSION, CONFINEMENT LOSS, EFFECTIVE AREA AND NONLINEARITY

Chromatic dispersion can be calculated easily from $n_{\text{eff}}$ versus the wavelength value as shown in the below equation

$$D(\lambda) = -\frac{\lambda}{c} \frac{d^2 \text{Re}(n_{\text{eff}})}{d\lambda^2} \text{ps/(nm km)} \quad (1)$$

Where Re $(n_{\text{eff}})$ is the real part of effective mode index, $\lambda$ is the wavelength and $c$ is the velocity of light in vacuum.

Confinement loss depends on number of air holes rings, air hole diameter and hole to hole spacing. Confinement loss, which is a fraction of leaky modes is calculated from the imaginary part of $n_{\text{eff}}$ by using equation below

$$L_c = 8.686k_0 \text{Im}(n_{\text{eff}}) \text{ dB/km} \quad (2)$$

where Im is the imaginary part of effective mode index, and $k_0$ is the free space wave number, which is equal to $2\pi/\lambda$.

Effective measure of the area over which the fundamental mode is confined during its propagation can be calculated from effective area. The effective area equation is given as
\[ A_{\text{eff}} = \frac{\iint |E|^2 \, dx \, dy}{\iint |\mu| \, dx \, dy} \, \mu m^2 \quad (3) \]

Where \( E \) is the electric field in the medium which is obtained by solving an Eigen value problem from Maxwell equations.

Nonlinear (6) optical effects always appear when the power density of light is large enough, regardless of the material. From equation 5 its clear that nonlinearity and effective area are inversely related and is given as

\[ \gamma = \frac{2n}{\lambda} - \frac{n_2}{A_{\text{eff}}} \, W^{-1} \text{km}^{-1} \quad (5) \]

\( \lambda \) is the wavelength, and \( n_2 \) is the nonlinear refractive index of the core region. \( n_2 \) for silica is \( 2.8 \times 10^{-20} \, m^2 \, W^{-1} \).

IV. SIMULATED RESULTS

By using Comsol multiphysics effective refractive index of the fiber can be found out, which are useful for studying the characteristics of PCF.

Fig. 5 shows the relation between \( n_{\text{eff}} \) vs. wavelength for circular PCF having 4 and 5 rings of air holes. From figure it is seen that \( n_{\text{eff}} \) value is greater for circular PCF having 4 ring air holes than circular PCF with 5 ring air holes every wavelength. Maximum \( n_{\text{eff}} \) value for circular PCF with 5 ring of air hole is 1.42 and that for 4 ring of air hole is 1.44.

\[ \text{Fig. 5 } n_{\text{eff}} \text{ vs. wavelength for circular PCF with five rings and 4 rings of air holes (D/\Lambda=0.5)} \]

Fig 6 shows the wavelength dependence for chromatic dispersion of circular PCF having 5 and 4 rings of air holes and having air filling fraction i.e \( D/\Lambda=0.5 \). From fig it is clear that dispersion curve in circular PCF with 5 rings of air holes shows large negative dispersion. Circular PCF with 5 ring air hole offers large negative dispersion, which is of the value of \(-150 \, \text{ps/(km.nm)}\). Dispersion curve crosses zero at 1500nm for circular PCF with 5 rings of air holes and for circular PCF with 4 ring of air hole curve crosses zero at 1400nm.

\[ \text{Fig. 6: Dispersion variation with the wavelength for circular PCF with 5 rings and 4 ring of air holes (D/\Lambda=0.5)} \]

Fig. 7 shows the confinement loss for circular PCF with five rings and 4 ring of air holes (D/\Lambda=0.5).

\[ \text{Fig. 7: Comparison of confinement loss for circular PCF with five rings and 4 ring of air holes (D/\Lambda=0.5)} \]
Fig. 8: Effective area vs wavelength for circular PCF with five rings and 4 ring of air holes (D/Λ=0.5)

Fig 7 shows the comparison of confinement loss for circular PCF with 5 and 4 rings of air holes. With infinite number of air holes PCF may have zero confinement loss. But; practically confinement loss is finite since numbers of air holes are finite, which in this case is 5 and 4. From Fig 7 its evident that confinement loss is lower for Circular PCF with 5 ring of air holes. At wavelength 1550nm circular PCF structure with 5 rings of air holes has confinement loss of 2.357*10^-10 dB/m and that of 4 rings of air holes is 1.4*10^-5 dB/m.

Fig. 8 shows the wavelength dependence of effective area for circular PCF having 5 and 4 rings of air holes. It is evident from figure that effective area for circular PCF having 5 rings of air holes is lower than that having 4 rings of air holes.

Fig. 9: Nonlinearity vs wavelength for circular PCF with five rings and 4 ring of air holes (D/Λ=0.5)

Fig 9 shows the nonlinearity curve for circular PCF having 5 and 4 rings of air holes. From equation 5 it is clear that as effective area increases nonlinearity decreases. It can be seen from figure 9 that nonlinearity value is greater for circular PCF with 5 rings of air holes. At 1550nm nonlinearity value for circular PCF with 5 rings of air holes is 38.38W^-1km^-1 and that for circular PCF having 4 rings of air holes is 14.47W^-1km^-1. Maximum nonlinearity value obtained for circular PCF with 5 rings of air hole is 90W^-1km^-1.

Table 1 shows different optical properties for 5 rings of air holes at 1550nm.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Optical properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Dispersion</td>
<td>-150(ps/(km.nm))</td>
</tr>
<tr>
<td>Lc</td>
<td>Confinement loss</td>
<td>2.357*10^-10 dB/m</td>
</tr>
<tr>
<td>Aeff</td>
<td>Effective area</td>
<td>2.8500µm</td>
</tr>
<tr>
<td>γ</td>
<td>Nonlinearity</td>
<td>38.38W^-1km^-1</td>
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</tbody>
</table>

V. CONCLUSION

Comparison for the Circular PCF’s with 5 and 4 rings of air holes and with d/Λ=0.5 are made by taking into account optical properties such as chromatic dispersion, confinement losses, effective area and nonlinearity. From the numerical simulated results it has been shown that with the same geometrical parameters CPCFs with 5 ring of air holes have lower chromatic dispersion, effective area. Negative dispersion offered by circular PCF with 5 rings of air holes is -150ps/(km.nm) and that with 4 rings of air holes are -13.26 ps/(km.nm). Circular PCF’s with 5 rings of air holes offers low effective area and confinement loss. Confinement loss values for circular PCF with 5 and 4 rings of air holes at 1550nm are 2.357*10^-10 dB/m and 1.4*10^-5 dB/m . Nonlinearity for circular PCF with 5 rings of air holes is greater than that of circular PCF with 4 ring of air hole. Value of nonlinearity at 1550nm for circular PCF with 5 rings of air hole is 38.38W^-1km^-1 and that for 4 rings of air hole circular PCF is 14.47W^-1km^-1. From the simulated result we can conclude that if we increase the number of air hole rings we get large nonlinearity. Further investigations in constructing highly nonlinear fiber with the Circular PCF are underway. So that circular PCF can be used for supercontinuum generation.

VI. REFERENCES


12) S.S. Mishra.; Vinod Kumar Singh.;"Study of non-linear properties of hollow core photonic crystal fiber", Optik, vol. 122, no. 8, pp. 687-690