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Analysis of Optical Characteristics for Photonic Crystal Fiber at Small Core Diameters

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Abstract— ***In the present study photonic crystal of eight ring with modified inner most ring has been considered. The important optical properties like chromatic dispersion, effective area, nonlinear coefficient and confinement loss has been studied. Each characteristic has been investigated under different core diameter of the photonic crystal fiber. Each iteration has been done within range of wavelength 1000nm -1600nm .Using software like COMSOL MULTIPHYSICS and MATLAB, each parameter were realized. This design has made the propagation of electromagnetic waves of higher wavelength through the core under tight confinement. The novel design has made the light of higher wavelength to be trapped inside the core of very small diameters (1µm-3µm).A good confinement loss has been achieved due to increase of the number of rings.***

Index Terms— ***Photonic crystal fiber (PCF), Finite Element Method, Chromatic Dispersion, Confinement Loss, and Nonlinear Coefficient.***

I. INTRODUCTION

One of the most interesting recent developments in the field of fiber optics is considered to be Photonic Crystal Fiber (PCF).Due to its excellent flexibility for the cross section has achieved unique properties like dispersion control, less confinement loss, controlled effective area and high nonlinearity by varying the air hole size and pitch distance [1]. The PCF has given solution to the development of communication systems and increase of date rate transfer, were considered as the major concerns in the communication field. Photonic crystals are made from special periodic structures including two media with different dielectric constants [3]. In the simplest PCF type, called index-guiding PCFs, light is confined to a solid core with higher refractive index surrounded by a closed pack of air holes in regular pattern, while in photonic band gap (PBG-PCFs), at a low-index hollow core light is guided by photonic band gap effect. Each structure will guide light in limited spectral region with a finite bandwidth. Highly Nonlinear Fibers (HNLFs) with low chromatic dispersion are of extreme interest for many photonic applications, like Supercontinuum generation, Raman amplification, Four wave mixing etc [5].
Currently, it attracts more attention because of the high potential for numerous applications in such diverse fields as spectroscopy, pulse compression, biomedical applications and the spectral slicing of broadband Supercontinuum spectra has to create multi-wavelength optical sources for sources wavelength division multiplexing (WDM) optical communication systems[7]. In this paper the discussion has been made about photonic crystal fiber with very small core diameter of 1µm-3µm for the study of optical characteristics like confinement loss, nonlinear coefficient, effective area and dispersion coefficient which plays major roles in generation of supercontinuum and dense wavelength division multiplexing (DWDM) applications. With the help of software like COMSOL MULTIPHYSICS and MATLAB made these studies possible.

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II. OPTICAL CHARACTERISTICS FOR PCF

1. Chromatic Dispersion.

Chromatic dispersion plays an important role in the performance of a highly nonlinear fiber, as it directly affects pulse broadening, phase-matching conditions, in order to determine the bandwidth and power requirement of the device in which the fiber will be used. Dispersion can be varied by changing air hole diameter and pitch sizes of the PCF. For most telecommunications applications a zero-dispersion wavelength around 1550 nm is desirable, with a small dispersion magnitude and slope designed is possible. The total dispersion is the sum of material dispersion and waveguide dispersion. Control of the chromatic dispersion in PCFs is one of the most critical problems in optical communication systems. The chromatic dispersion, D in [ps/(nm.km)], of a PCFs is easily calculated using the formula given below[4],

$$D(\lambda) = \frac{-\lambda}{c} \frac{\partial^2 Re(n_{eff})}{\partial \lambda^2} \qquad (1)$$

Where c is the velocity of light and $Re(n_{eff})$ is the real part of nonlinear refractive index. The material dispersion given by Sellmeier's formula is directly included in the calculation.

2. Nonlinear Coefficient & Effective Area

When intense pulse like laser propagates through photonic crystal fiber (the medium), the response of the medium becomes both linear and nonlinear. Nonlinear effects includes four wave mixing (FWM), Four Wave Mixing (FWM), Soliton affects, Self Steepening (SS), self and cross phase modulation (SPM and XPM), Stimulated Raman Scattering (SRS), etc. Most of the nonlinear effects in optical fibers therefore originate from nonlinear refraction, a phenomenon that refers to the intensity dependence of the refractive index resulting from the contribution of third order susceptibility $\chi^{(3)}$. Supercontinuum generation (SC) is one of the complex nonlinear phenomenon leads to spectral broadening of intense light pulses passing through a nonlinear material, attracts very much in the field of research. The nonlinear coefficient, γ in $W^{-1} Km^{-1}$ is calculated with the following equation (2),

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$$\gamma = \frac{2\pi n_2}{\lambda * A_{eff}} \quad (2)$$

Where n_2 is the nonlinear refractive index of silica(2.66x10-20 m2/W) and A_{eff} is the area covered by the light during propagation through PCF. It depends on the shape, wavelength (λ) and effective refractive index .It is calculated by,

$$A_{eff} = \frac{\left[\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|E(x,y)|^2\,dxdy\right]^2}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|E(x,y)|^4\,dxdy} \quad (3)$$

3. Confinement Loss

Whenever an electromagnetic wave propagates through a photonic crystal fiber there will be small portions of energy will definitely escapes. As the number of air holes is finite, the power leakage is inevitable. By proper selection of air hole diameter (d) and pitch (Λ) the loss could be minimized as possible. The number of layers also plays an important role where selection of small pitch is impossible. The number of air hole will change the effective refractive index and the relation with the confinement loss is given by,

$$L = \frac{8.686 * 2\pi * Im(n_{eff})}{\lambda} \quad (4)$$

It is expressed in dB/m. Where Im (n_{eff}) is the imaginary part of complex effective refractive index and λ is the wavelength of the light.

III. DESIGN OF PROPOSED STRUCTURE

The Full vector Finite element method (FEM) is an attractive mathematical tool for analysis complex geometries of hollow core as well as solid core photonic crystal fiber. Figure 1 shows the eight layered hexagonal air hole rings with solid core. As the number of rings increases it is difficult to confine the higher wavelength of electromagnetic wave through the core .So only the inner layer hole is modified with smaller air hole radius which is the half diameter of the actual diameter (d).

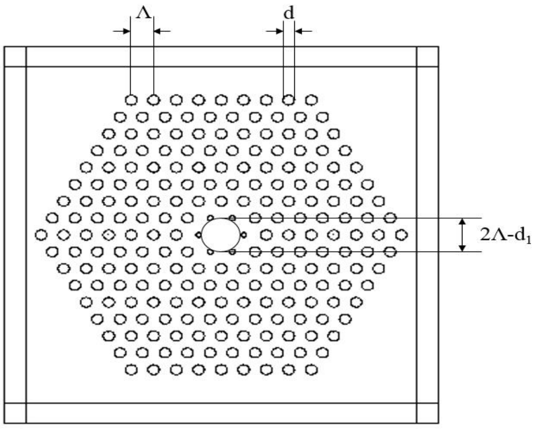

Figure 1: The cross sectional view of the eight layer PCF

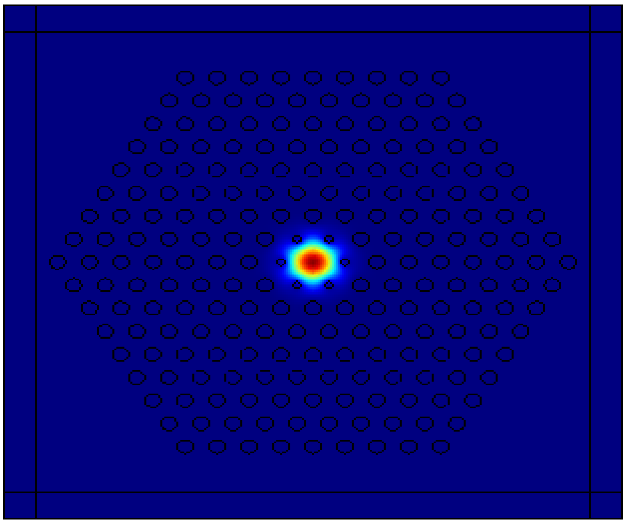

Figure 2 : Dimensional view of single mode Gaussian output of the proposed design .

In this structure the core diameter (2Λ-d_1) is varied from 1µm-3µm, where d_1 is air hole diameter of inner most ring, d is the diameter of rest of the rings which is twice the radius of inner ring and Λ is pitch length. The simulation is carried out with the help of software COMSOL MULTIPHYSCIS under wavelength of 1000nm-1600nm.By varying the air filling ratio (d/Λ) and with anisotropic perfectly matched boundary layers (PML) is used to calculate the nonlinear refractive index. The PML conditions are good enough to analyze the leaky mode of the PCF .Usually four layer hexagonal rings are used and here in order to reduce the leakage eight layers has been used. Figure 2 shows the output after simulation and the light is passing through the center of the PCF.

IV. SIMULATION RESULT

Figures 3, 4, 5 and 6 show the graph of variation of confinement loss, Dispersion coefficient, Nonlinear Coefficient and Effective area versus wavelength ranging from 1000nm-1600nm respectively. In the new design the air hole diameter (d_1) of inner most layer is reduced to half of the outer air hole diameter (d). Therefore, for core diameter 1µm, the two air filling ratio d/Λ = 0.28 and d_1/Λ = 0.14, for core diameter 2µm the air filling ratio is d/Λ =0.4 and d_1/Λ = 0.2 and finally for core diameter 3µm it is d/Λ = 0.25 and d_1/Λ=0.12.

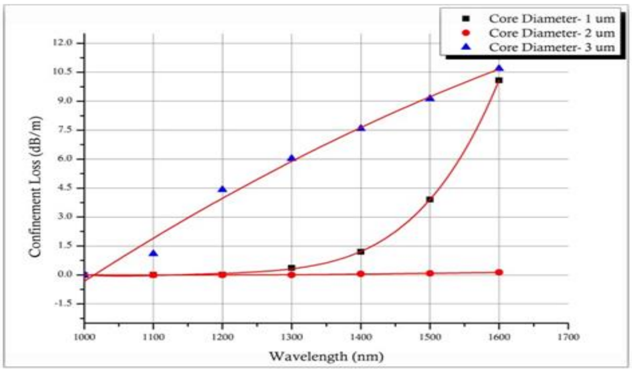

Figure 3: shows the variation of Confinement loss versus Wavelength at different core diameters.

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From figure 3 it is clear that core diameter has no role in the confinement loss but the major parameter on which it is depending is the air filling ratio. In our design air filling ratio d/Λ of core diameter (2μm>1μm>3μm) has inverse effect on confinement loss. So the graph has clearly shows that as the air filling ratio increases the confinement loss decreases.

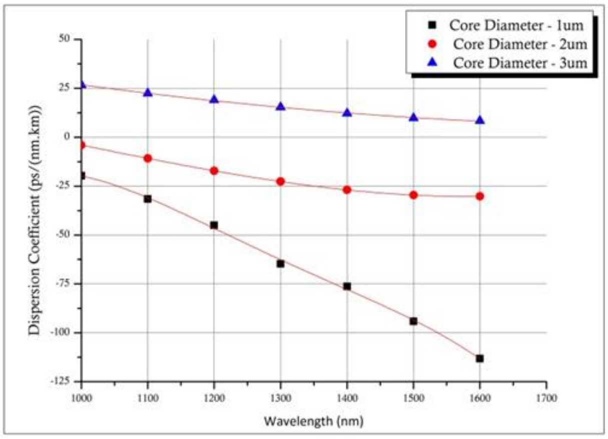

Figure 4: shows the variation of Dispersion Coefficient versus Wavelength at different core diameters.

In figure 4 shows the variation of Dispersion coefficient (ps/(nm.km)) with wavelength. It can be observed that as the core diameter increases the dispersion coefficient is also increases. Also the zero dispersion is expected to be in below 1000nm for core diameter 1μm and 2μm which is the emission wavelength of ultrafast lasers like Ti : Sapphire laser. This gives the idea that at large core diameter it is able to reduce the nonlinearity at higher wavelengths which is common issue in the communication field.

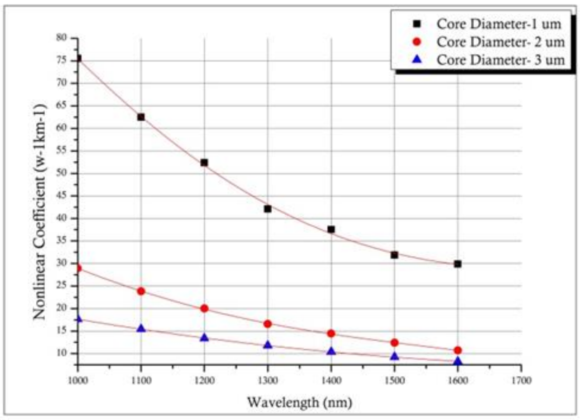

Figure 5: shows the variation of Nonlinear Coefficient versus Wavelength at different core diameters.

From the figure 5 it is observed that maximum nonlinear coefficient achieved for core diameter 1μm is 75 $W^{-1} km^{-1}$, while for core diameter 2μm and 3μm is found to be 29 $W^{-1}km^{-1}$ and 17 $W^{-1} km^{-1}$ respectively. The effective area graph(figure 6) is found to be inversely proportional to nonlinear coefficient. This is because as the core diameter decreases which definitely reduces the effective area leads to high nonlinearity as per equation (2) and (3).In telecommunication window ie 1300nm and 1550nm the maximum nonlinearity achieved is 42 $W^{-1} km^{-1}$ and 31 $W^{-1} km^{-1}$ at core diameter 1μm.

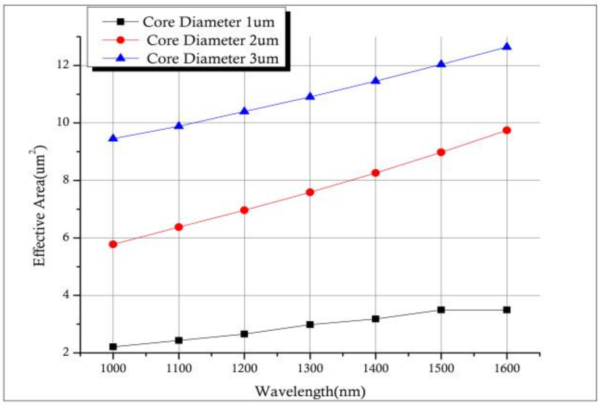

Figure 6: shows the variation of Effective Area versus Wavelength at different core diameters.

V. CONCLUSION

In this paper, the PCF properties like confinement loss, dispersion coefficient, effective area and nonlinear coefficient has been studied under different core diameters. Here, a new design is proposed for the confinement of higher wavelength through the core with tight air hole distribution. In this design nonlinear coefficient of approximate of 75 $W^{-1}km^{-1}$ has been achieved which is sufficient to generate nonlinear optical process like supercontinuum using moderate power lasers. In Future, another parameter, birefringence can also be analyzed Highly birefringent PCFs are widely used to manufacture new high-performance polarization maintaining fibers in the fields of optical frequency metrology, sensor technology and optical telecommunication [9].Also at telecommunication windows like 1300nm and 1550nm we have obtained good nonlinear coefficient which is made possible to obtain highly nonlinear fibers at these bands. Also by proper selection of large core area it is made possible to reduce nonlinearity on these communication bands since this parameter affects the proper transmissions of information in dense wavelength division multiplexing (DWDM) systems.

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