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Design and Analysis of Single Mode Photonic Crystal Fibers with Zero Dispersion and Ultra Low Loss

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***Abstract*—PCFs (Photonic Crystal Fibers) with 'T' – shaped core have been proposed in this paper. 'T' –shaped core PCF structures have been analyzed using two different background materials: silica and lead silicate. A total of 360^0 rotation at an interval of 90^0 has been introduced in the design of PCF structures. PCF structures A, B, C and D with rotation of 0^0, 90^0, 180^0 and 270^0 have silica as wafer. Similarly PCF structures E, F, G and H with similar rotation have lead silicate as background material. Numerical investigations shows structures 'D', 'F', 'G' and 'H' to have anomalous dispersion. PCF structures 'F', 'G', and 'H' have reported birefringence of the order of 10^{-2}. Besides, other PCF structures report birefringence of the order of 10^{-3}. Ultra low confinement loss has been observed in all the investigated PCF structures. Moreover, splice loss observed by the structure is very low. Large mode area has been shown by all the designed PCF structures.**

***Keywords*—Photonic crystal fibers, dispersion, birefringence, splice loss, confinement loss, effective mode area**

I. Introduction

MICROSTRUCTURED fibers or Holey fibers are made of a single material silica. Finite number of air holes arranged in periodic manner forms the cladding region. Core region is made by creating a defect at the centre and PCFs have silica as background material [1-3]. PCFs offer freedom to manipulate various optical properties which is not possible in standard fibers. Photonic crystal fibers on the basis of principle of guiding mechanism are subdivided as index guided PCFs [4] and photonic bandgap fibers [5]. Index guided PCFs have solid cores and guided light based on modified total internal reflection. Due to the reflection under counteract between cores and cladding region, light gets propagated into the core region due to modified total internal reflection. PCFs fibers have hollow cores or core with lower refractive index than that of cladding region. PCFs since its discovery in 90's have always been superior to the standard fibers due to various unique features it offered. These features include dispersion [6], birefringence [7], endlessly single mode propagation [8], large nonlinear coefficient [9] and low losses [10]. PCFs are classified as Index guided [11] and PBG effects [12]. This classification is made based on light guiding mechanism. Due to its design flexibility, various new structures have been reported by the researchers. Researchers introduce new geometry of PCF structures like 'D' shaped PCF structure [13], 'S' and 'U' shaped structure [14], 'C' shaped structure [15] and 'P' shaped structure [16]. Moreover, flexibility in structures have been reported by producing variation in pitch factor, tailoring the dimension of air holes in the cladding region and introducing doping in the core-cladding materials. These variations in arrangements of holes and pitch factors lead to a new PCFs with different unique properties.

For long haul data transfer at 1.3μm, optical communication systems with PCFs have been installed. Moreover at 1.55μm wavelength or communication wavelength PCFs with higher magnitude of dispersion has been observed. Optical pulse became spreading or splitting due to a phenomenon called dispersion. Hence it must be minimized for efficient data transfer in optical communication systems. Microstructured optical fibers are considered to have potential to be exploited for realization at this wavelength for wide application. It is to be noted that control over dispersion can be easily achieved by tailoring diameter of air holes in the cladding region and also by monitoring pitch factor (Λ). Pitch factor is often defined as the distance between centers of two consecutive holes. Hence controllability of dispersion in PCFs have always been challenging for researchers [16-19]. Material dispersion and waveguide dispersion together results total dispersion in single mode PCFs [20]. Frequency dependent power distribution in the non homogeneous cross section of the fibers results waveguide dispersion. Similarly, frequency dependent variation of the intrinsic material results material dispersion. Generally, the intrinsic electromagnetic properties of dielectric materials have very thin frequency dependent relations and hence material dispersion is often taken to be zero. Controllable zero dispersion and high nonlinear coefficient makes PCFs widely applicable for nonlinear applications like soliton and supercontinnum generations.

Polarization control in fiber optic instruments and optic sensors are achieved easily by highly birefringent PCFs. Standard fibers lack in maintaining state of polarization. In PCFs, highly birefringence can be easily achieved by tailoring the radius of the air holes in the cladding region. Moreover,

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breaking the symmetry of the core or asymmetric core also results high birefringence. Holes of different dimension in the first ring of air holes region produces PCFs with high birefringence and large effective mode area. These fibers have improved sensitivity for sensing applications like temperature sensors and pressure sensors and can be easily realized by birefringent PCFs [21-24]. Large number of air holes in the cladding region allows the leakage of light from core to the exterior cladding region. Splice loss between PCFs and other optical components puts limitation in its remarkable development. It is to be noted that low splice loss between photonic crystal fibers and standard fibers leads to various technologies based applications like fiber sensors, optical communication system and lasers [25-27].

In this paper we have investigated PCF structure with ‘T’ shaped core. Four PCF structures have silica as background material and four structures have lead silicate as wafer. Some of the PCF structures simulated have reported zero dispersion. Other structures, however reports anomalous dispersion behavior. PCF structures have reported very high birefringence. These fibers are found to be excellent couplers as they have shown very low splice loss. However, confinement loss observed for these structures are ultra low.

II. MODELING PCF STRUCTURE

PCF structure with ‘T’ shaped core has been investigated. Two different material silica and lead silicate (non silica) have been used as background material. A total four rotations has been introduced in the structure of 90°. Hence in total eight PCF structure have been investigated in the paper. Four PCF structures have silica as background material and four PCF structures have lead silicate as wafer. Schematic diagram of the designed PCFs is shown in Fig1. (a), Fig 1.(b), Fig 1.(c) and Fig 1.(d). Structure E, F, G & H are same as that of structure A, B, C & D respectively except they have lead silicate as background material.

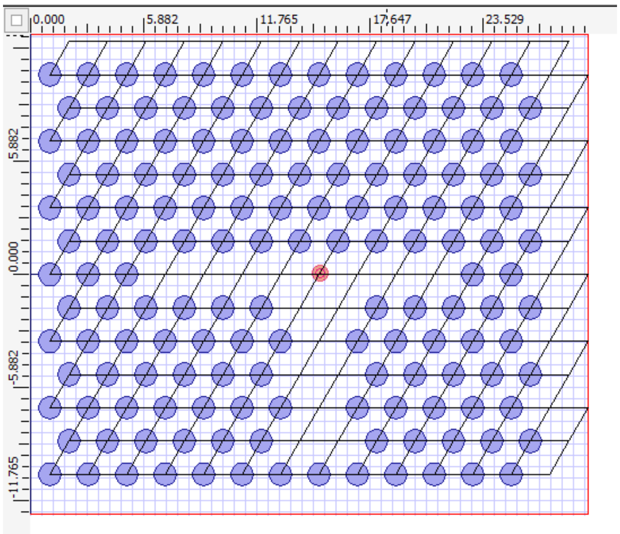

Fig. 1 (a). PCF structure A

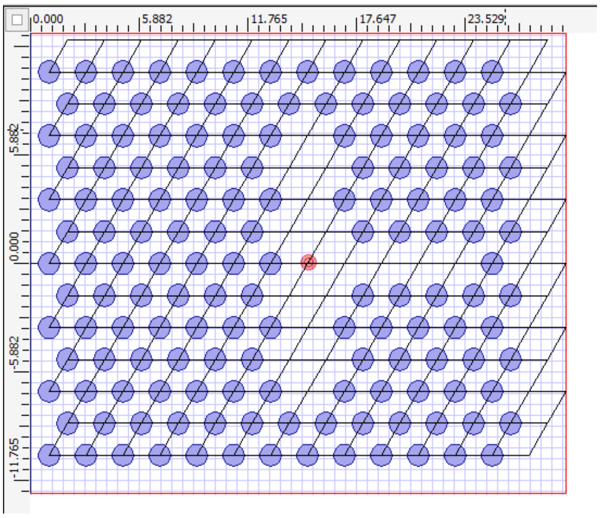

Fig. 1 (b). PCF structure B

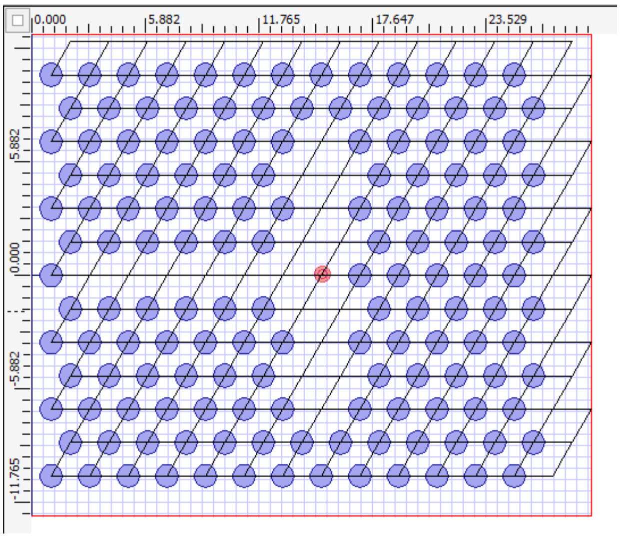

Fig. 1 (c). PCF structure C

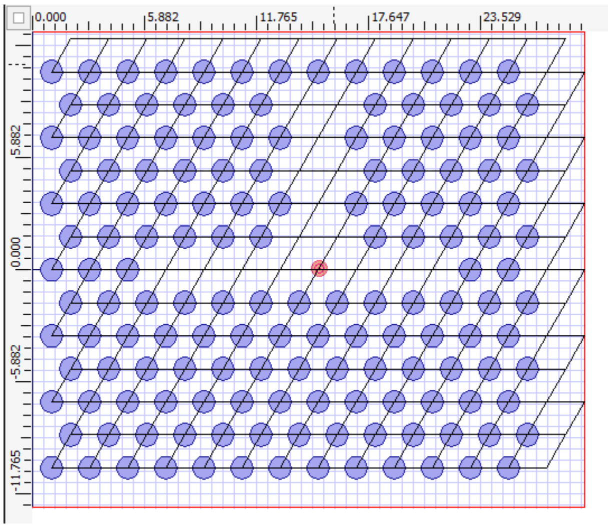

Fig. 1 (d). PCF structure D

TABLE I
PCF STRUCTURE DESCRIPTIONS

PCF Structure	Wafer	Description
A	Silica	'T' shaped core with 0° rotation
B	Silica	'T' shaped core with 90° rotation
C	Silica	' T' shaped core with 180° rotation
D	Silica	'T' shaped core with 270° rotation
E	Lead silicate	'T' shaped core with 0° rotation
F	Lead silicate	' T' shaped core with 90° rotation
G	Lead silicate	'T' shaped core with 180° rotation
H	Lead silicate	' T' shaped core with 270° rotation

III. THEORETICAL ANALYSIS

To calculate the wavelength dependent effective index number of the propagating modes of fibers, a full vector mode of finite difference time domain (FDTD) method has been used. Designed fiber is analyzed by full vectorial finite difference time domain method (FDTD). FDTD is a commonly used way to show electromagnetic equations. Introducing PML boundary condition, Maxwell's equations both for electric and magnetic field are given as [28]

$$jk_0 S\varepsilon_r E = \nabla \times H \quad (1)$$

Here S is the sparse matrix.

$$s = \begin{bmatrix} s_y / s_x & 0 & 0 \\ 0 & s_x / s_y & 0 \\ 0 & 0 & s_x . s_y \end{bmatrix}$$

Where, $S_x = \frac{1-\sigma_s}{j\omega\varepsilon_0}$ and $S_y = \frac{1-\sigma_s}{j\omega\varepsilon_0}$

Proper meshing size is chosen and applied with the help of equation (1) transformed into a matrix. By employing spatial matrix 'S' optical field distribution of fundamental mode and modal index number is obtained.

Dispersion, an important aspect in data communications has been a challenge for the researchers. Dispersion directly affects walk off parameter, broadening of optical pulses and phase matching conditions. Dispersion also determines bandwidth and power requirement of optical devices. For a smooth functioning of optical communication systems, zero dispersion magnitude fibers are required. Total dispersion (D_{Total}) is the sum of waveguide dispersion and material dispersion [29-30].

$$D_{Total} = D_{waveguide} + D_{material} \quad (2)$$

$$D_{waveguide} = \frac{-\lambda}{c} \frac{d^2 \mathrm{Re}[n_{eff}]}{d\lambda^2} \quad (3)$$

c is the velocity of light in vacuum. $\mathrm{Re}[n_{eff}]$ is the real part of the modal index number.

Material dispersion can be obtained using sellemeir's equation

$$\eta^2_{silica}(\lambda) = 1 + \frac{\sum_{k=1}^{3} b_k \lambda^2}{\lambda^2 - \lambda_k^2} \quad (4)$$

b_1=0.6961663, b_2=0.4079426, b_3=0.8974794

λ_1= 0.0684043μm, λ_2= 0.1162414μm, λ_3= 9.896161μm

$$D_{material} = \frac{-\lambda}{c} \left(\frac{d^2 n_m}{d\lambda^2}\right) \quad (5)$$

Birefringence in fibers is determined by the difference between the real part of effective index of two orthogonally polarized modes. Hence birefringence is calculated using [31]:

$$B = \left| n^x_{eff} - n^y_{eff} \right| \quad (6)$$

Splice loss in PCFs play a vital role in determining its coupling with other optical componenets. Splice loss in PCFs can be calculated using:[31]

$$L_s(dB) = 20\log\left[\frac{1}{2}\left(\frac{MFD_1}{MFD_2} + \frac{MFD_2}{MFD_1}\right)\right] \quad (7)$$

Where MFD1 is the mode field diameter of designed PCFs. MFD2 is the diameter of single mode fiber to be coupled with deigned PCFs. MFD2 considered in this paper is 10μm.

Light confinement ability of PCFs within the core region is determined by confinement loss. In PCFs leaky mode are complex and major. Hence these require special attention of the researchers. Leakage of modes or light from core region to the exterior cladding region occurs through bridges formed between air holes. This results in confinement loss. It can be calculated in dB/km by using the formula [31].

$$L_c = 8.686\, k_0 I_m \left[n_{eff} \right] \quad (8)$$

$I_m n_{eff}$ is the imaginary part of modal index number. K_0 is termed as wave number and is equal to 2π/λ.

High density of power is required for nonlinear effects. Nonlinearity in fibers is observed at high light intensities. Smaller effective mode area offers highly dense power. Moreover, effective mode area is related to the spot size having a Gaussian width 'w'. For such cases [32]:

$$A_{eff} = \pi \omega^2 \quad (9)$$

Also A_{eff} is calculated using [32]:

$$A_{eff} = \frac{\left(\int |E|^2 dxdy\right)^2}{\int |E|^4 dxdy} \quad (10)$$

E is the electric field distribution. A non linear coefficient decides the degree of non linear effects. This non linearity is observed in fibers at high propagating powers. However, nonlinearity (ɣ) in PCFs can be obtained [33]:-

$$\gamma = \frac{2\pi}{\lambda} \cdot \frac{\eta_2}{A_{eff}} \quad (11)$$

η_2 is the non linear refractive index of material used. Number of modes propagating inside the fibers is determined by normalized frequency. It is also termed as V-effective parameter (V_{eff}). PCFs having value $V_{eff} \leq 4.1$, ensures endless single mode propagation. V_{eff} of any PCFs can be determined using mathematical expression given below [33]:

$$V_{eff} = \frac{2\pi \wedge}{\lambda} \sqrt{n_{core} - n_{eff}} \qquad (12)$$

IV. Simulation And Results

We have investigated eight PCF structure with 'T' shaped core. Some air holes have been removed to form 'T' shaped core PCF structure. All circular holes are of the equal area. Diameter of air hole taken is 1.2µm. A full vector module of FDTD method has been used.

Dispersion as a function of wavelength has been plotted in Fig 2. Structure 'D', 'F', 'G' and 'H' have reported zero magnitude dispersion. However, other structures also have shown anomalous dispersion behavior. Thus structure 'F' , 'G' and 'H' allow high data rate transfer at 'S', 'C' and 'L' communication length.

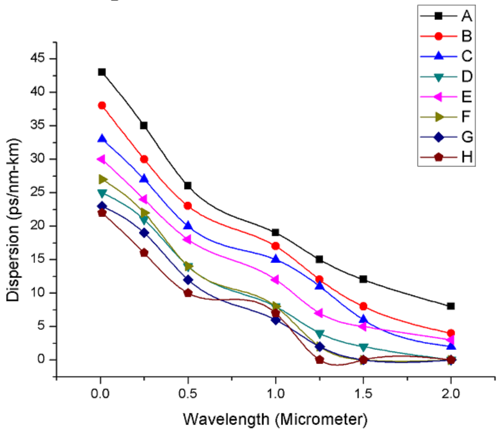

Fig. 2. Dispersion behavior

Birefringence reported by the PCF structure 'F', 'G' and 'H' is of the order of 10^{-2}. Moreover, other structures have reported birefringence of the order of 10^{-3}. Thus, these structures can be used for medical applications and fiber optical sensors. Birefringence at different wavelength has been plotted in Fig 3.

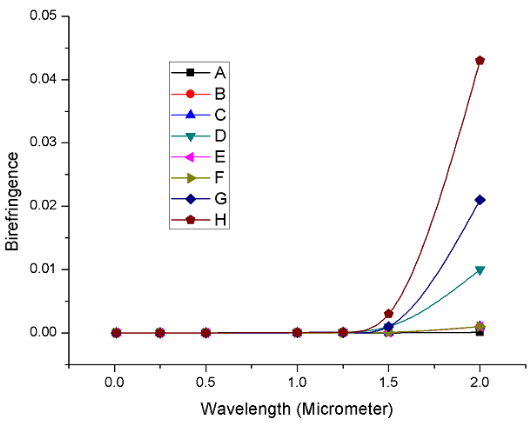

Fig. 3. Birefringence

All the structures simulated in the paper have been reported ultra low confinement loss. However, the confinement loss reported by structures 'G' and 'H' are of the order of 10^{-7}. Confinement loss at different wavelength is plotted Fig 4.

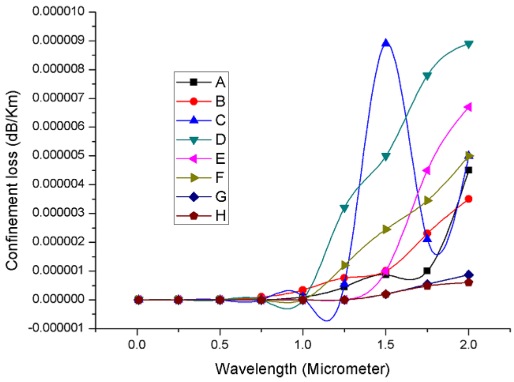

Fig. 4. Confinement loss

Splice loss decide the coupling efficiency of fibers with other optical components. To make optical communication system efficient, splice loss should be much lesser. At different wavelength calculated splice loss is plotted in Fig 5.

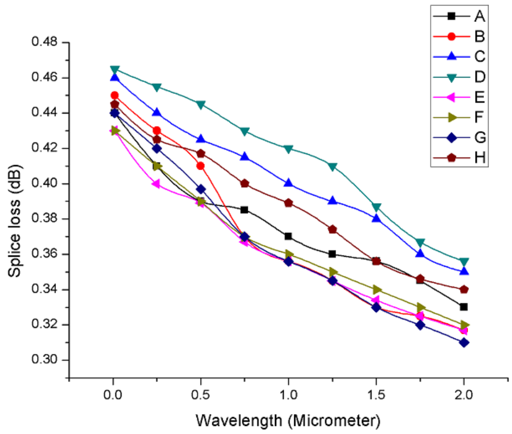

Fig. 5. Splice loss

Effective mode area as a function of wavelength has been plotted in Fig 6. It has been found from the curve, that designed PCFs have large mode.

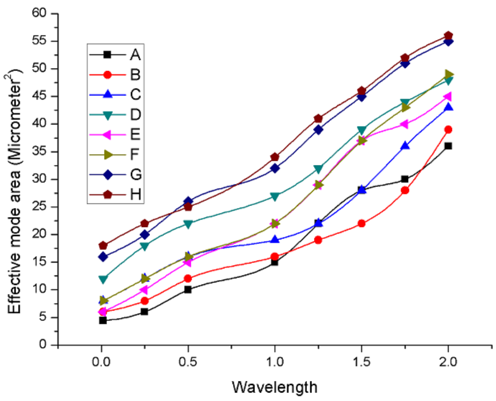

Fig. 6. Effective mode area

Fig. 7 shows normalized frequency of all the designed fibres as a function of wavelength. Obtained values of V_{eff}, ensures that all the designed PCF structures support endless single mode propagation.

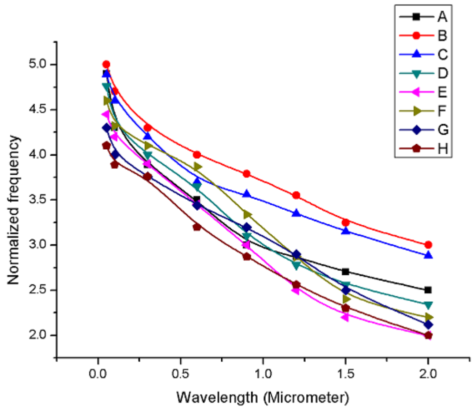

Fig. 7. Normalized frequency

TABLE II
COMPARISON WITH PREVIOUS REPORTED PCF STRUCTURES

PCFs	**Dispersion (ps/nm-km)**	**Birefringence**	**Confinement Loss (dB/km)**
Ref-[28]	65	10^{-4}	10^{-2}
Ref-[29]	55	10^{-3}	--
Ref-[34]	60	10^{-3}	--
Ref-[35]	55	10^{-3}	10^{1}
Structure G	Zero	10^{-2}	10^{-7}
Structure H	Zero	10^{-2}	10^{-6}

CONCLUSION

Large mode area PCFs with 'T' shaped core has been investigated in this paper. Among all the eight investigated structures, three PCFs structures 'F', 'G' and 'H' have reported zero dispersion over 'S', 'C' and 'L' communication bands. Other PCF structures also have shown anomalous dispersion behavior. Birefringence reported by structures 'F', 'G' and 'H' are 1×10^{-2}, 2×10^{-2} and 5×10^{-2} respectively. Thus, three PCF structures have shown zero dispersion behavior along with very high birefringence. Hence, these PCFs structures can widely be used for optical sensors, optical communication systems and medical applications.

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