Comparative study of hybrid Hexagonal PCF structure on Dispersion and Confinement Loss at different pitch of Air holes

Priyanka Arora, Mayank Joshi

Abstract— **Photonic crystal fibers (PCF) play most interesting and promising role in optical communication industry than conventional optical fibers. There are several unusual optical properties of PCF, which makes PCF more flexible and useful than conventional one. These properties are single mode operation, flattened dispersion, zero chromatic dispersion, large birefringence, low confinement loss. These properties are achieved by carefully design the PCF structure. This paper proposes a PCF structure of fused silica glass with an array of circular or elliptical air holes running along its length. In this paper I proposed 3 PCF designs with varying hole pitch and compared their results. The methodology I adopted to propose these designs with circular air holes is, by changing the pitch of the air hole rings. I designed the PCF structure with three different hole pitch(∧) of 2.0µm,2.03µm,2.05µm. By this investigation I selected the design with hole pitch(∧)=2.0µm as my best result, because it provide very low confinement loss less than 10-5dB/km in the wavelength from 1.1µm to 2.0µm, zero dispersion at 1.55µm wavelength, and ultra flat dispersion over a wide wavelength range 1.1µm to 2µm range.**

Index Terms— **Photonic crystal fiber (PCF), index guiding PCF, Photonic band gap fiber(PBGF), dispersion, confinement loss, finite difference time domain(FDTD), transparent boundary condition(TBC).**

I. INTRODUCTION

Photonic crystal fiber has received increasing attention because of its novel optical characteristics. Which are far improved and different from those of conventional optical fiber [1].Photonic crystal fibers (PCFs) plays a most important role in optical communication system because of their various unusual optical properties such as broadband negative chromatic dispersion, endlessly single-mode [2], high nonlinearity , and high birefringence [3] which are not found in standard optical fiber.

In conventional optical fiber when light is directed into an optical fiber, it suffers from various transmission Losses, such as absorption and scattering losses. The effectiveness of the wire depends on its ability to transmit the light ray in long distance applications with little scattering or little absorption of the light as possible. Transmission losses can be reduced when the transmitted light ray must exhibit total internal reflection (TIR) within the fiber. The refractive index of the dielectric medium needs to be accounted, when considering the propagation of light through an optical fiber . Now a days typical fibers are made out of glass or plastic since it is possible to make them thin and long. The fiber is constructed with a core with high refractive index surrounded by a layer of cladding at a lower refractive index.

Manuscript received.
Priyanka Arora, Department of ECE, Marudhar Engineering College, Rajasthan Technical University, Bikaner, India, (e-mail: pinkiarora09@gamil.com

Mayank Joshi, Department of ECE, Marudhar Engineering College, Rajasthan Technical University, Bikaner, India, (e-mail: mayankjoshi2007@gmail.com).

PCFs are also called holey fiber and microstructured fiber made of fused silica material, in which cladding consists of an array of air holes , and concentric missing ring forms solid core. The simplest (and most often used) type of PCF has a hexagonal lattice of air holes with one hole missing at center acts as core, shown in Fig.1. The refractive index of silica in 1.456 which is same as for solid core, and the refractive index of air holes is 1. So there is a big difference of refractive indices of core and cladding which makes PCF more flexible than conventional one.

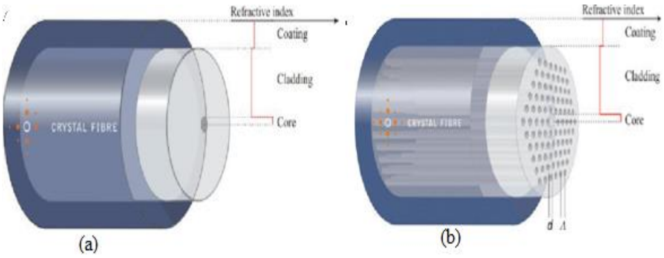

Fig.1 (a) A Standard optical fiber (b) A Photonic crystal fiber

PCFs can be divided in two basic categories. The first one is an index-guiding PCF, which is usually formed by a central solid core region surrounded by multiple air holes in cladding within a regular hexagonal lattice and confines light by total internal reflection like standard fibers [8]. The second one uses a perfect periodic structure exhibiting a photonic band-gap (PBG) effect at the operating wavelength to transmit the light in a low index core region, which is also called PBG fiber (PBGF)[8].

Many PCF designs have been designed to achieve ultra-flattened chromatic dispersion. These PCFs may have hexagonal PCFs (H-PCF), square PCFs(S-PCF), circular PCFs(C-PCF), triangular PCFs. H-PCFs are the most conventional type of PCF structures and are the most widely used in telecommunication industry and various applications. [2]. In real time applications, chromatic dispersion of PCF have to be controlled. In particular, ultra flattened dispersion PCFs are indispensable for optical data transmission systems over a wide wavelength range because of the reduction of the accumulated dispersion difference in telecommunication bands without any zero-dispersion wavelength. Conversely, research is still going on to make it more enhanced by limiting dispersion and all other losses. The finite difference time domain method [4] and the TBC boundary condition is used for the simulation [2]. The schematic representation of a hexagonal PCF lattice is shown in Fig.2, in which the spacing between two consecutive holes is known as hole pitch (^), and d is the diameter of holes. Circular air holes are created using elliptical waveguide.

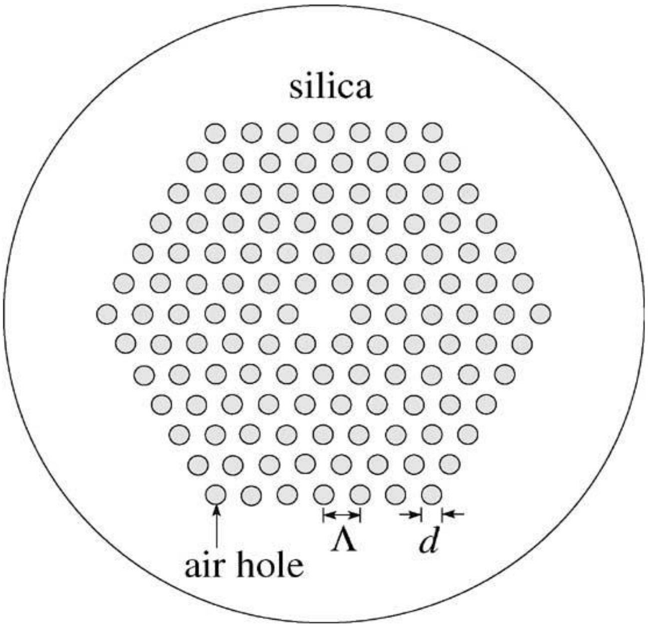

Fig.2 Photonic crystal fiber representation

PCF has number of important features, which makes it more useful in various optical applications. Its very important feature is to achieve zero dispersion, low confinement loss, and flat dispersion over a wide wavelength range. These features are achieved by varying the design parameters of PCF structure. These design parameters of PCF are hole pitch (^), hole diameter, number of rings, radius of major and minor axis of elliptical air holes. By varying these design parameters, engineers can carefully design the PCF structure, and desired PCF properties (i.e. low dispersion, zero confinement loss) can be achieved.

II. Dispersion

When light Ray travelling along the fiber, it suffers from dispersion phenomenon. Dispersion means broadening of transmitted pulses as they travel along the fiber. Pulses become indistinguishable at the receiver input due to the pulse broadening & overlape with its neighbouring pulse. This effect of overlapping between two pulses is known as inter symbol interference (ISI).

The value of refractive index of silica glass is calculated by sellemier formula-

$$\varepsilon = n^2(\lambda) = 1 + \frac{A_1\ \lambda^2}{\lambda^2 - \lambda_1{}^2} + \frac{A_2\ \lambda^2}{\lambda^2 - \lambda_2{}^2} + \frac{A_3\ \lambda^2}{\lambda^2 - \lambda_3{}^2} \quad \text{.........................} \quad (1)$$

Where λ is the wavelength in µm.

For fused silica (fluorine-doped silica 1 mole %) sellmeier constants are

A_1=0.69616630 λ_1= 0.068404300µm

A_2=0.40794260 λ_2=0.11624140µm

A_3=0.89747940 λ_3=9.8961610 µm

Refractive index of the air hole is one. Material dispersion remains unchanged for different lattice structure of designed PCFs from Same material.

Refractive index of the Fused Silica Glass is 1.456. Refractive index of the air holes is 1.0 in vacuum.

The dispersion (D) is proportional to the second order derivative of the effective refractive index (ηeff) with respect to the wavelength (λ) obtained as[3][4]:

$$D = -\left(\frac{\lambda}{c}\right)\frac{d^2}{d\lambda^2}\left[\mathrm{Re}(\eta_{eff})\right] \quad \text{......} \ (2)$$

Where D is Dispersion (ps/km/nm), $\mathrm{Re}[\eta_{eff}]$ is the real part of the effective refractive index, λ is wavelength, and c is the velocity of light in vacuum. The total dispersion is calculated as the sum of the waveguide dispersion and the material dispersion obtained as [17]:

$$D(\lambda) \approx D_g(\lambda) + \Gamma(\lambda)\, D_m(\lambda) \quad \text{.........}(3)$$

Where

D= Total/Chromatic Dispersion

D_W = Waveguide Dispersion

D_M = Material Dispersion

The material dispersion Dm also can be obtained by (2) which depend on the value of effective refractive index of the material. The effective refractive index is directly calculated from the three-term Sellmeier formula that used in equation (1).

Table 1 shows the material dispersion $D_m(\lambda)$ of fused silica glass its corresponding waveform is as shown in Fig.

TABLE 1

MATERIAL DISPERSION FOR FUSED SILICA GLASS

wavelength	Material dispersion
0.2	-3590.70
0.3	-3627.38
0.4	-2278.64
0.5	-768.57
0.6	-368.10
0.7	-204.07
0.8	-121.48
0.9	-74.15
1	-44.45
1.1	-24.22
1.2	-9.61
1.3	1.52
1.4	10.39
1.5	18.01
1.6	24.68
1.7	30.76
1.8	36.63
1.9	41.51
2	45.70

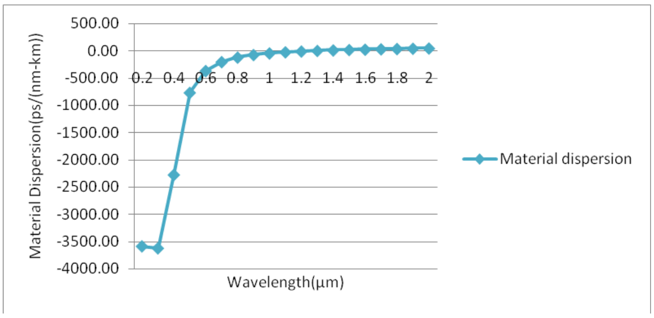

Fig. 3 Material Dispersion of Fused Silica Glass

III. CONFINEMENT LOSS

Number of losses occurs in PCFs, such as intrinsic material absorption loss, Rayleigh scattering loss, confinement loss, and so on. Confinement loss arises due to finite width of the cladding structure. Confinement loss is especially dominating in the wavelength region interesting for telecommunication applications, as usually significant negative waveguide dispersion is realized due to dispersion engineering. Low confinement loss can be achieved for small core PCFs by designing the fibers with at least 6 rings of air holes for a closely packed structure. Fabrication-related losses can be reduced by carefully handled during the fabrication process. Confinement loss occurs in single-material fibers. As the SiO_2 materials are non absorbing, they don't have any imaginary component . The guided modes are inherently leaky for PCFs that are made from pure silica because the core index is the same as the index of the outer cladding without air-holes [20].

The confinement loss can be calculated by using imaginary part of η_{eff} i.e, the effective modal index [20] as given below [9], [14]:

$$L_c = 8.686 * \text{Im}[k_o \eta_{eff}] * 10^3 \text{ dB/km}$$

Where $k_0 = \frac{2\pi}{\lambda}$ is the free space wave number and $\text{Im}[\eta_{eff}]$ denotes the imaginary part of the effective modal index and .

While talking about the PCFs with finite no. of rings in PCF and confinement loss becomes an important issue. The confinement loss reduces exponentially as the number of air holes rings gets increased. Also, on increasing the air-holes diameter results in the increasing of the air filling fraction which in turn reduces the confinement loss.

IV. DESIGN & SIMULATION

I designed 3 different structures of PCF at different hole pitch. Dimension of hole pitch for design1, design2, and design 3, is taken as 2.0μm, 2.03μm, 2.05μm respectively. All pcf structures have same number of rings which is equal to 6. In all designs 1st & 2nd rings are circular with radius of 0.3μm each; 3rd ring is elliptical with major radius of 0.5μm & minor radius of 0.3μm; 4th ring is elliptical with major radius of 0.6μm and minor radius of 0.4μm; 5th & 6th rings are circular with radius of 0.5μm each.

Cross section of design-1, design-2, design-3 at different pitch is shown in fig.4, fig 5, fig6 respectively.

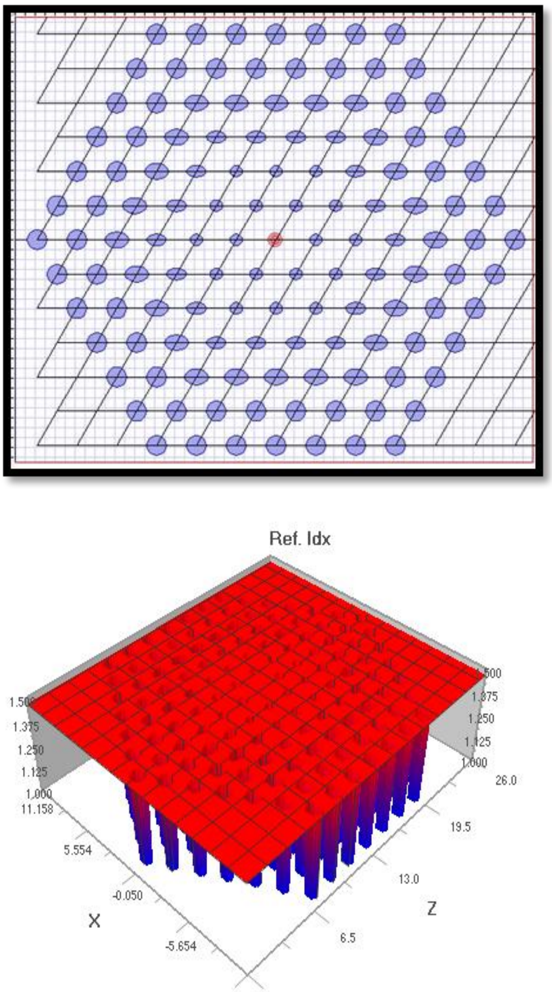

Fig. 4 Cross section of proposed PCF at pitch=2.0μm

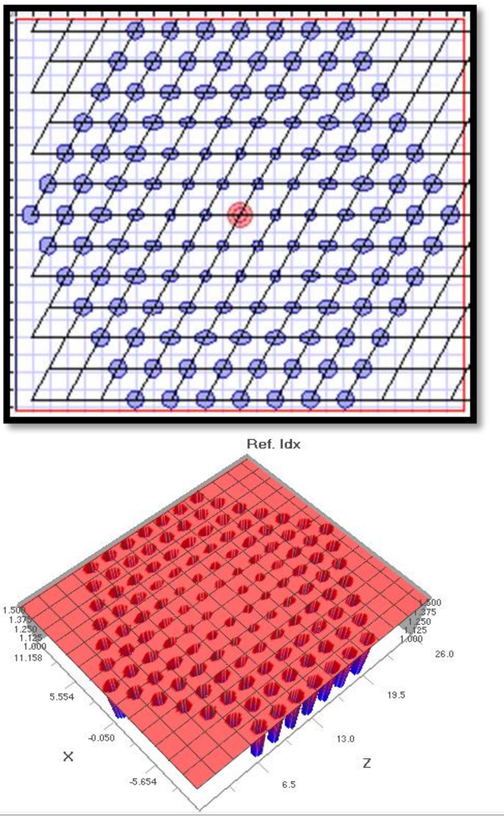

Fig. 5 Cross section of proposed PCF at pitch=2.03μm

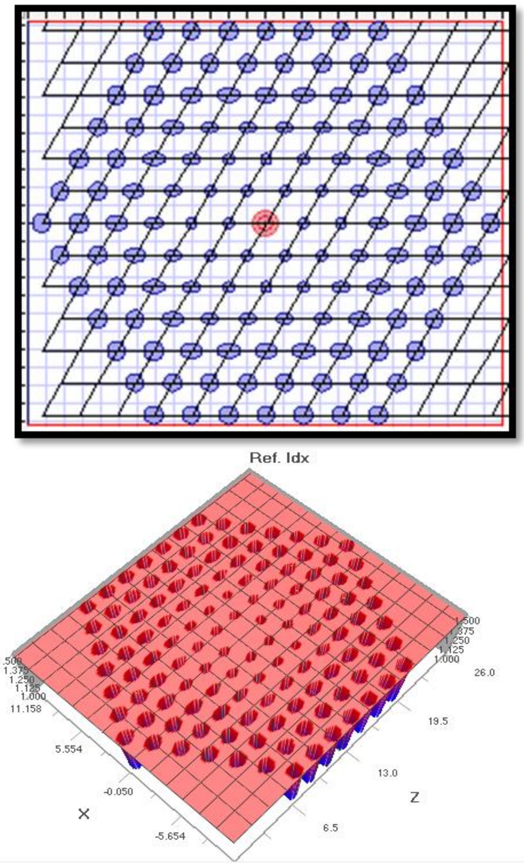

Fig. 6 Cross section of proposed PCF at pitch=2.05µm

V. SIMULATION RESULT

I have already designed 3 PCF structures with different pitch. Comparison among all the designs is based on effective refractive index, waveguide dispersion, and chromatic dispersion are represented in table 2, table 3, table 4, and corresponding waveform also shown in fig 8, fig 9, fig10.

TABLE 2
REFRACTIVE INDEX OF PROPOSED PCF AT DIFFERENT PITCH

Refractive Index of proposed PCF at different pitch			
Wavelength(µm)	Pitch=2.0 µm	Pitch=2.03 µm	Pitch=2.05 µm
0.2	1.45716066	1.45714724	1.45719024
0.3	1.45626434	1.45624480	1.45632989
0.4	1.45527935	1.45534353	1.45538736
0.5	1.45447019	1.45465768	1.45461842
0.6	1.45377963	1.45390680	1.45397414
0.7	1.45271593	1.45285822	1.45296728
0.8	1.45158272	1.45174235	1.45189558
0.9	1.45025829	1.45042368	1.45063607
1	1.44887954	1.44905592	1.44930667
1.1	1.44745371	1.44762576	1.44793262
1.2	1.44600061	1.44616825	1.44652431
1.3	1.44457295	1.44472557	1.44513142
1.4	1.44316185	1.44329263	1.44375130
1.5	1.44178407	1.44188770	1.44239510
1.6	1.44044542	1.44052211	1.44107697
1.7	1.43914856	1.43919749	1.43979776
1.8	1.43790090	1.43791940	1.43856264
1.9	1.43670031	1.43668863	1.43737090
2	1.43554316	1.43550468	1.43622422

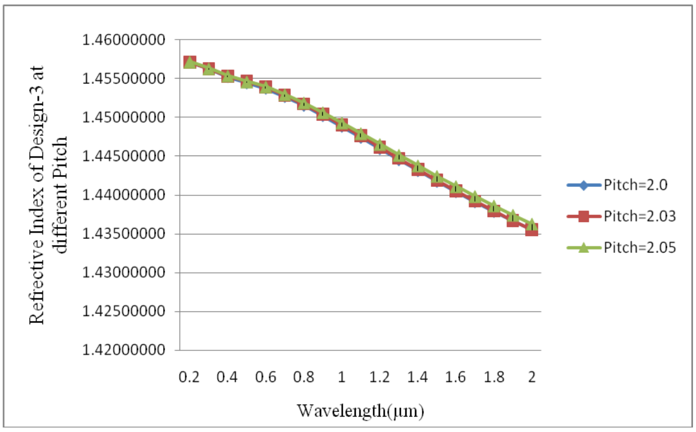

Fig. 7 Effective Refractive index of proposed PCF

Fig. 7 shows that the value of effective refractive index increases when pitch of the ring is increases in the structure in the available wavelength.

TABLE-3
WAVEGUIDE DISPERSION OF PROPOSED PCF AT DIFFERENT PITCH

Waveguide Dispersion of proposed PCF at different Pitch			
Wavelength(µm)	Pitch=2.0 µm	Pitch=2.03 µm	Pitch=2.05 µm
0.2	10.32681000	3.49525100	9.74824400
0.3	2.25606100	-5.47703900	1.82501300
0.4	-12.72847000	-12.24114000	-12.99766000
0.5	-1.66323400	8.85362500	-2.51549000
0.6	34.88363000	36.41119000	33.29003000
0.7	41.05890000	37.07198000	39.69821000
0.8	33.77470000	34.82276000	34.04689000
0.9	26.03851000	27.27237000	27.93733000
1	14.65597000	16.78161000	16.13199000
1.1	6.98800100	9.38124000	8.96662000
1.2	-4.01978100	-1.20583400	-0.93564730
1.3	-9.96055700	-6.75600700	-7.03353300
1.4	-14.28171000	-12.27016000	-11.52064000
1.5	-19.18452000	-18.47028000	-17.38453000
1.6	-22.93720000	-22.39016000	-21.34810000
1.7	-26.54687000	-25.70904000	-24.16805000
1.8	-28.03640000	-28.21802000	-26.40477000
1.9	-28.10619000	-29.75242000	-28.29157000
2	-28.37463000	-31.15155000	-30.34099000

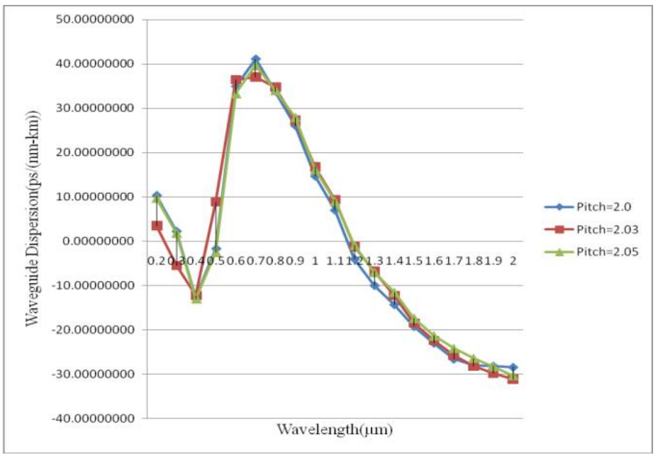

Fig. 8 Waveguide dispersion with wavelength

Fig 8 shows the variation of waveguide dispersion with different pitch in different wavelength.

The total dispersion or chromatic dispersion is the sum of material dispersion and waveguide dispersion. Table 4 and Fig.9 show the value of chromatic dispersion for the above proposed designs at different pitch and their dependence on the wavelength respectfully.

TABLE 4
CHROMATIC DISPERSION OF PROPOSED PCF AT DIFFERENT PITCH)

Chromatic Dispersion(ps/(nm-km)) at different Pitch			
Wavelength(µm)	Pitch=2.0 µm	Pitch=2.03 µm	Pitch=2.05 µm
0.2	-3580.37	-3587.21	-3580.95
0.3	-3625.13	-3632.86	-3625.56
0.4	-2291.37	-2290.88	-2291.64
0.5	-770.24	-759.72	-771.09
0.6	-333.22	-331.69	-334.81
0.7	-163.02	-167.00	-164.38
0.8	-87.71	-86.66	-87.44
0.9	-48.11	-46.88	-46.21
1	-29.79	-27.67	-28.32
1.1	-17.23	-14.84	-15.25
1.2	-13.63	-10.81	-10.54
1.3	-8.44	-5.24	-5.52
1.4	-3.89	-1.88	-1.13
1.5	-1.17	-0.46	0.63
1.6	1.75	2.29	3.34
1.7	4.22	5.05	6.59
1.8	8.59	8.41	10.22
1.9	13.41	11.76	13.22
2	17.32	14.55	15.36

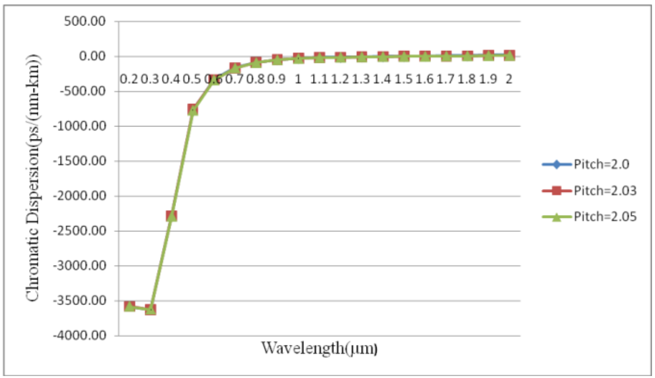

Fig. 9 Chromatic dispersion of PCF Design at different pitch

The above results shows that the value of chromatic dispersion at different pitch. At pitch 2.0 shows almost flat dispersion which mentioned in the above table where its value is zero at 1.55 µm.

Table 6.9 and Fig. 6.12 show the value of confinement loss and its variation with wavelength for above proposed design.

TABLE 5
CONFINEMENT LOSS (DESIGN-3 AT DIFFERENT PITCH)

Confinement Loss (dB/km) of Design-3 at different Pitch			
Wavelength (µm)	Pitch=2.0 µm	Pitch=2.03 µm	Pitch=2.05 µm
1.1	-0.0000004959	0.0000000000	0.0000000000
1.2	-0.0000004546	-0.0000004500	0.0000000000
1.3	-0.0000016784	-0.0000012600	-0.0000004200
1.4	-0.0000050652	-0.0000027300	-0.0000015600
1.5	-0.0000116369	-0.0000058200	-0.0000029100
1.6	-0.0000190918	-0.0000105700	-0.0000051100
1.7	-0.0000218192	-0.0000138000	-0.0000067400
1.8	-0.0000272740	-0.0000175800	-0.0000084900
1.9	-0.0000330159	-0.0000212500	-0.0000097600
2	-0.0000362745	-0.0000253600	-0.0000117300

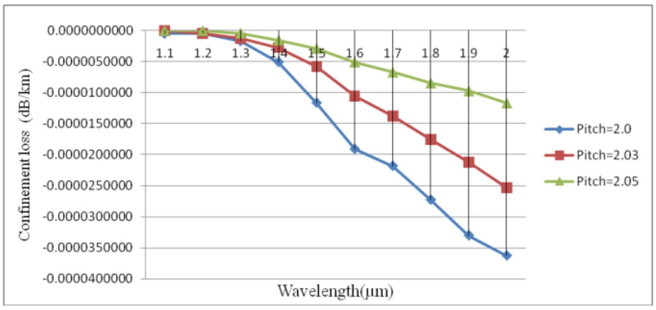

Fig. 10 Confinement loss with wavelength (Design-3 at different Pitch)

From the above results, In order to achieve flattened dispersion and minimum confinement loss PCFs is proposed and is optimized by introducing different arrays of small holes into the cladding as shown in the designed structure. In the optimized PCFs, the parameter of the small air holes is varied. From Figs. 6.4 and 6.7, it can be found that the dispersion of the optimized PCFs becomes zero at wavelength 1.55 µm when the pitch of the circular air holes is 2.0 µm and also optimize minimum confinement loss(less than 10^{-5} dB/km). The proposed PCF in Fig. 6.4, air holes in the cladding are a positive influence on flat dispersion and minimum confinement loss. This can be explained by the fact that when the small holes are introduced into the cladding area which contains circular air holes, the asymmetry in the cladding will be decreased. It can be observed from Fig. 6.4 that for the optimized PCFs the ultra flattened chromatic dispersion in a wide wavelength band is obtained. The diameter and pitch of the small air holes in the cladding is discussed in our simulation work.

VI. Conclusion

In this work I designed a novel PCF structure of silica glass of hexagonal lattice, with circular air holes and discuss the effect of varying pitch dimension on dispersion and confinement loss. I obtained the results from a PCF design at three different pitch dimensions such as 2.0µm, 2.03µm, 2.04µm and concluded that dispersion and confinement loss decreases with decreasing pitch dimension. Therefore it is investigated that a PCF structure with hole pitch (Λ) = 2.0µm provide the best result than other two designs with pitch as 2.03µm, 2.05µm.

In my work, I observed the value of dispersion is -1.17 ps/(nm-km) at 1.5µm, 1.75 ps/(nm-km) at 1.6µm and is zero in 1.55µm wavelength when the pitch is 2.0 µm of the circular and elliptical air holes. This design also gives the minimum confinement loss less than 10^{-5}dB/km in the wavelength from 1.1µm to 2.0µm. With this flat dispersion and low confinement loss, pcf design with hole pitch (Λ) can be properly utilized in wideband transmission applications and could suppress undesirable transmission impairments.

VII. Future Scope

Innovations to further improve the usefulness of photonic crystal fiber continue in both academic research centers and companies, in order to obtain a further reduction of the losses, which can have an important role for future telecommunications, to investigate alternative materials, and to expand the range of possible PCF designs and applications. The most interesting possibilities for PCFs are related to fiber-based signal processing devices including tunable properties, fibers for dispersion management. PCF based solutions have been used by many sensor classes which are temperature sensors, strain sensor, pressure sensor. PCF can also be used for terahertz radiation guidance and has been employed in many applications in imaging, spectroscopy, biology, medical science and communication technology. At the University of Sydney in Australia, researchers have manufactured photonic-crystal fibers based on a polymer optical fiber. They say it is easier to fabricate polymer optical fiber than glass photonic-crystal fibers because only one polymer is involved and there is not any requirement of dopants. The company plans to manufacture prototype fiber components and short haul transmission fibers.

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Priyanka Arora is persuing M.Tech from Marudhar Engineering college, Rajasthan Technical University, Kota, Rajasthan. She received the B.Tech from Govt. Engineering College, Bikaner.

Mayank Joshi working as Assistant Professor in Marudhar Engineering College, Bikaner.