A new circular photonic crystal fiber for effective dispersion compensation over E to L wavelength bands

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Abstract—**This paper presents a new circular photonic crystal fiber (C-PCF) for effective dispersion compensation covering E to L wavelength bands ranging from 1360-1625 nm. To investigate its guiding properties, finite element method (FEM) with a perfectly matched layer absorbing boundary condition is used. From our numerical simulation, it is found that the designed C-PCF simultaneously shows a large negative dispersion of about -248.65 to -1069 ps/(nm.km) over E to L wavelength bands and a relative dispersion slope (RDS) exactly equal to that of a single mode fiber (SMF) at 1.55 μm wavelength. It is also found that residual dispersion after compesating 40 km long SMF is within ±62 ps/nm which ensures application of C-PCF in high speed WDM system. Besides, dispersion slope, slope compensation ratio, effective area and confinement loss of the proposed C-PCF are also evaluated and discussed.**

Index Terms—Chromatic dispersion, Dispersion compensating fiber, Finite element method, Photonic crystal fiber.

I. INTRODUCTION

In fiber optic communication systems, dispersion limits the maximum transmission distance and the bit rate [1]. The dispersion causes the broadening of optical pulses when transmitted through the fiber. Thus, the dispersion must be compensated in the long distance optical data transmission system to nullify the pulse broadening. Presently, dispersion compensating fibers (DCFs) are widely used and commercially available for dispersion compensation which is designed to have large negative dispersion [2-7]. However, DCF using conventional fibers give a high negative dispersion only at a particular wavelength but not over wide band [8]. In order to reduce the length of DCF and hence to reduce the cost significantly, we need high negative dispersion [7, 9]. However, it is difficult to achieve high negative dispersion using the conventional DCFs. In addition, high negative dispersion of DCFs is needed to be achieved over a wide range of wavelength so that it can be used in broadband communication system. Hence, compensation of dispersion and dispersion slope are simultaneously required. Recently, photonic crystal fibers (PCFs) or holey fibers or microstructured optical fibers consists of a microscopic array of air channels running down their length that make a low index cladding around the undoped silica core [10] have gained attentions in the field of dispersion

management of transmission fiber, sensing and telecom applications [10-11]. Now-a-days, it has become a promising candidate especially as a dispersion compensator as it allows us to tune dispersion properties in a way which is not possible for the conventional fibers.

To compensate dispersion of SMF, different types of PCF structures have already been proposed in [12-22]. PCF with hexagonal structure employing nine air-hole rings is proposed in [12] to compensate dispersion over S+C+L band but the negative dispersion is not sufficiently large, number of rings are relatively high and relative dispersion slope (RDS) is not perfectly matched with RDS of SMFs. Modified Octagonal-PCF using six air-hole rings has been studied in [13] which achieves negative dispersion of only -239.5 ps/(nm.km) at 1.55 μm with 90% slope matching. Although, good dispersion compensating characteristics are obtained by [14, 20] but available bandwidth for dispersion compensation is narrow and no effort was made to match RDS with the RDS of SMF. PCF with dual concentric core without Ge doping have been proposed in [17-19] but insufficient bandwidth for dispersion compensation is further noticed. Dual concentric core fibers have been proposed in [21-22] for broadband dispersion compensation of SMF, but the problem owing to Ge doping still remains. Recently, PCF for broadband dispersion compensation of SMF have been proposed [15, 23] using five air-hole rings. PCF with square-lattice [15] reports a negative dispersion of -204.4 ps/(nm.km) and an RDS of $0.003543\,nm^{-1}$ at 1.55 μm wavelength which is not exactly equal with SMF's RDS. Moreover, PCF with hexagonal structure in [23] shows perfect RDS matching with SMF but exhibits insufficient negative dispersion of -130 to -360 ps/(nm.km) in a 1.30-1.60 μm wavelength range which will ultimately increase the length of designed DCF. As a solution, there is a still need for large negative dispersion over a broad range of wavelength and at the same time RDS of $0.0036\,nm^{-1}$ at λ=1.55 μm.

In this study, we report a new circular photonic crystal fiber using five air-hole rings which simultaneously gives high negative dispersion over a wide range of wavelength as well as perfectly matched RDS with that of SMF using FEM. Simulation results show that it is possible to achieve large negative dispersion of about -248.65 to -1069 ps/(nm.km) over E to L telecommunication band as well as RDS of $0.0036\,nm^{-1}$ at λ=1.55 μm, better dispersion slope and slope compensation ratio respectively. It is expected that the proposed C-PCF would be the viable alternative for dispersion compensator to compensate the positive dispersion and dispersion slope of SMF.

II. STRUCTURE OF THE PROPOSED C-PCF

Fig. 1 represents air-hole distribution of the proposed dispersion compensating C-PCF. The proposed C-PCF contains only five air-hole rings and the material of studied is taken to be silica. The air-holes on the 1st ring are rotated at an angle 60^0 while air-holes on the 2nd to 5th rings are rotated at an angle 45^0, 30^0, 15^0, and 7.5^0 respectively. The number of air-holes of the proposed structure for rings 1, 2, 3, 4 and 5 are respectively 6, 8, 12, 24 and 48. The air-hole diameter of 1st and 4th ring is d_1 while air-hole diameter of the 2nd, 3rd and 5th ring is selected as d_2, d_3 and d_4.
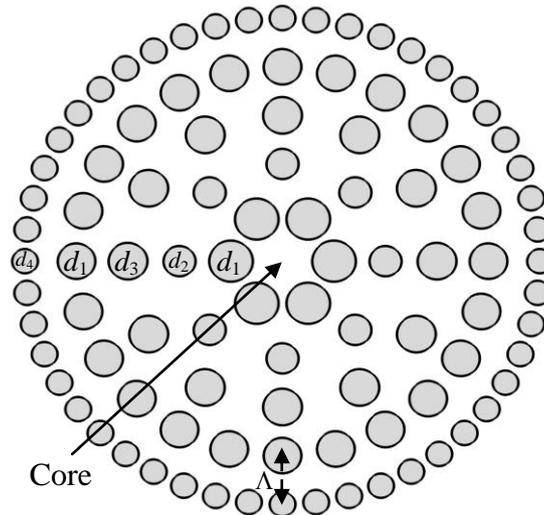
Fig. 1. Air-hole arrangement of the proposed C-PCF.

III. NUMERICAL ANALYSIS

The numerical simulation of the proposed C-PCF is carried out by FEM [24] with perfectly matched layer absorbing boundary condition. The modal effective indices n_{eff} are found by solving an eigen value problem drawn from the Maxwell's equation using FEM. Hence, chromatic dispersion, $D(\lambda)$ confinement loss, L_c and effective area, A_{eff} of the proposed C-PCF can be calculated with the following equations [12, 23]. The chromatic dispersion $D(\lambda)$ in ps/(nm.km) is easily calculated from the following equation

$$D(\lambda) = -\frac{\lambda}{c} \frac{d^2 \operatorname{Re}[n_{eff}]}{d\lambda^2} \tag{1}$$

where, $\operatorname{Re}[n_{eff}]$ is the real part of effective refractive index n_{eff}, λ is the wavelength, c is the velocity of light in vacuum. It should be pointed out that chromatic dispersion, $D(\lambda)$ is algebraic sum of material dispersion and waveguide dispersion upon which material dispersion is calculated from Sellmeier equation and is directly included in the FEM calculation process. However, the waveguide dispersion strongly depends on the silica-air structure itself and can be altered significantly by modulating some parameters like geometry of the air-holes, pitch, and air-hole diameters. Hence, the chromatic dispersion, $D(\lambda)$ of PCF is related to those additional design parameters and by optimizing these parameters, suitable dispersion properties can be achieved for dispersion compensation of SMF.

Confinement loss is a parameter used in optical fiber to represent its light confinement ability within core region. In PCF, confinement of light within its core region increases appreciably with the increase of number of air-hole rings and then confinement loss is reduced. Fortunately, there is a design freedom in PCF to choose the suitable number of air-hole rings and hence we can keep the confinement loss within the desired value. The confinement loss in dB/km can be defined as

$$L_c = 8.686 \times \frac{2\pi}{\lambda} \times \text{Im}[n_{eff}] \tag{2}$$

Finally, the effective area A_{eff} in μm^2 is calculated by the following equation where E is the electric field vector in the medium.

$$A_{eff} = \frac{\left(\iint |E|^2 dxdy \right)^2}{\iint |E|^4 dxdy} \tag{3}$$

IV. REQUIREMENT FOR DISPERSION AND DISPERSION SLOPE COMPENSATION

Dispersion compensation is a technique to nullify the positive dispersion caused by the standard single mode fibers. The equation of broadband dispersion compensation is given by [12]

$$D_m L_m + D_n L_n = D_t \tag{4}$$

where D_m and D_n are dispersion coefficient of SMF and DCF, L_m and L_n are the length of SMF and DCF respectively. For full compensation of the dispersion caused by SMF, the length of the DCF is selected such that total dispersion coefficient $D_t = 0$. Under this condition, the length of DCF will be as follows

$$L_n = -\frac{D_m L_m}{D_n} \tag{5}$$

The equation clearly shows that the length of DCF will be short only for high negative value of D_n. On the other hand, dispersion compensation over a wide range of wavelength requires dispersion and dispersion slope compensation at the same time for broadband communication system. Hence, the total dispersion slope DS_t is given as follows

$$DS_t = DS_m L_m + DS_n L_n \tag{6}$$

where DS_m, DS_n are the dispersion slopes of the SMFs and the DCFs respectively. From Eq. (6) it is obvious that a negative dispersion slope of the DCF is necessary in order to achieve slope compensation. Thus, the condition for full slope compensation is that the relative dispersion slope (RDS) of both fibers would have to be equal

$$RDS_m = RDS_n \tag{7}$$

where RDS_m and RDS_n are the relative dispersion slope of the standard SMF and the DCF. It should be pointed out that standard SMF exhibits RDS value of about 0.0036 nm^{-1} at λ=1.55 μm [23]. Once the RDS value of DCF is close to that of the SMF, the design of the broadband DCF is accomplished. Another parameter is the compensation ratio which indicates the fraction of the SMF dispersion which the DCF compensates at a wavelength, λ and is represented by [23].

$$CR(\lambda) = \frac{|D_m(\lambda) \times L_m|}{|D_n(\lambda) \times L_n|} \tag{8}$$

V. DISPERSION PROPERTIES OF THE PROPOSED C- PCF

Fig. 2 shows the variation of chromatic dispersion against wavelength for the five rings C-PCF where solid line corresponds to the variation in dispersion properties for optimum parameters (Λ =1.0, d_1/Λ =0.95, d_2/Λ =0.81, d_3/Λ =0.98, d_4/Λ =0.60). In our work, all the dispersion curves are presented only for fundamental modes of the proposed C-PCF.
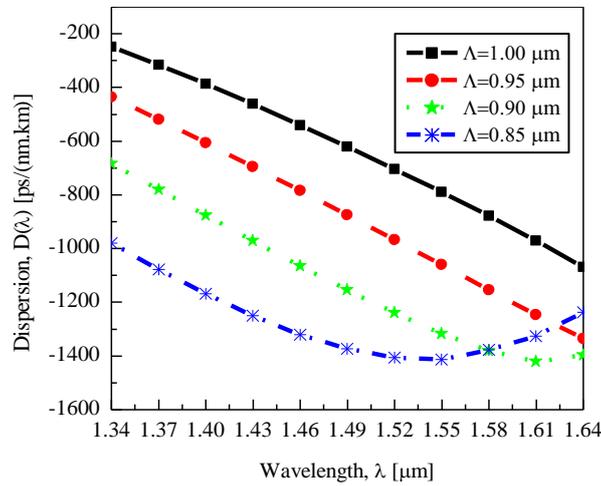

Fig. 2. Dispersion properties of C-PCF showing the effect of pitch, Λ .
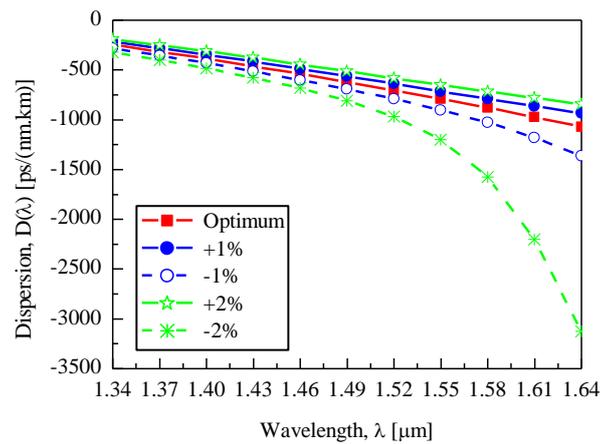
Fig. 3. Dispersion properties of C-PCF: optimum dispersion and effects of changing pitch Λ keeping all d/Λ constant.
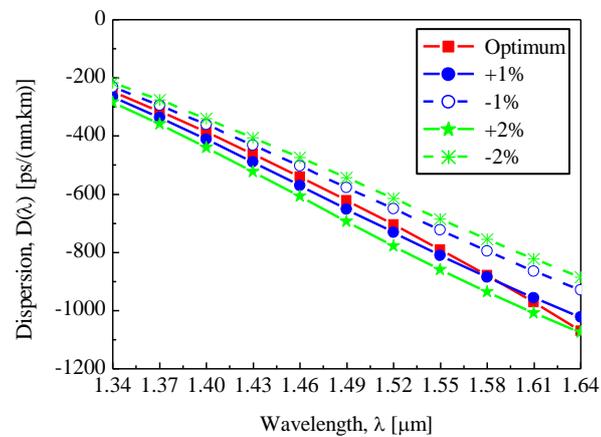

Fig. 4. Dispersion properties of C-PCF: optimum dispersion and effects of changing d_1.

From numerical simulation, it is found that the proposed dispersion compensating C-PCF shows large negative dispersion coefficient of about -248.65 to -1069 ps/(nm.km) for optimum parameter values in the wavelength range 1.34-1.64 µm (270 nm band). Fig. 3 shows dispersion accuracy of the proposed fiber for pitch, Λ along with the optimum dispersion curve while keeping all d/ Λ constant. Fig. 4-6 shows the dispersion accuracy of the proposed C-PCF for air hole diameters d_1, d_2 and d_4 along with the optimum dispersion curve. From dispersion properties obtained from Fig. 3-6, it is clearly shown that the proposed C-PCF maintains the desired dispersion characteristics. It is also observed that the effect of pitch, Λ and then first air hole diameter, d_1 on dispersion properties of the proposed C-PCF is more significant than other parameters. It is to be mentioned here that d_1 largely controls field confinement and hence dispersion, while the air-hole diameter, d_2 controls the dispersion slope. Fig. 7-10 show the residual dispersion, dispersion slope, relative dispersion slope, and compensation ratio respectively against wavelength for the proposed five rings C-PCF. Solid line represents the variation in dispersion properties for optimum parameters. Fig. 7 shows the residual dispersion after compensating the positive dispersion of 40 km SMF by the proposed C-PCF for optimum parameters. It is noted that the residual dispersion should be lower than ±64 ps/nm [12] to compensate for a 40 Gbps signal.
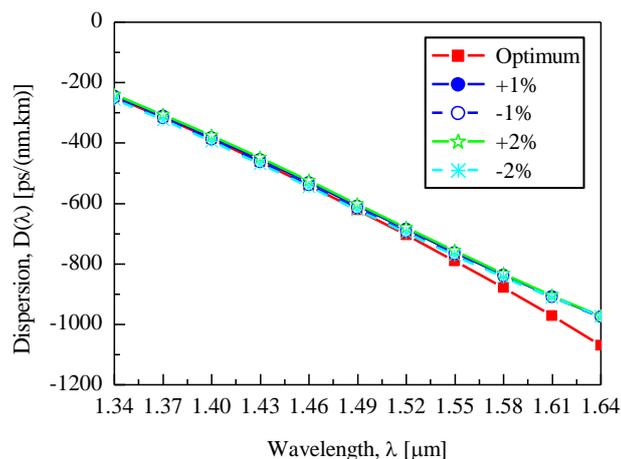

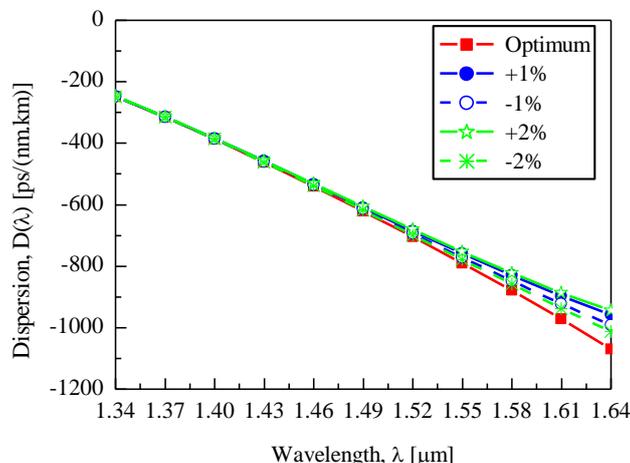Fig. 5. Dispersion properties of C-PCF: optimum dispersion and effects of changing d_2.

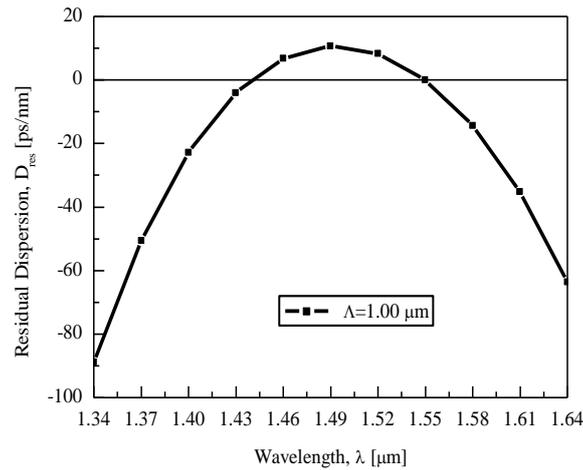Fig. 6. Dispersion properties of C-PCF: optimum dispersion and effects of changing d_4.

Fig. 7. Variation of residual dispersion against wavelength of 818.4 m long optimized C-PCF to compensate for a 40 km long standard SMFs.
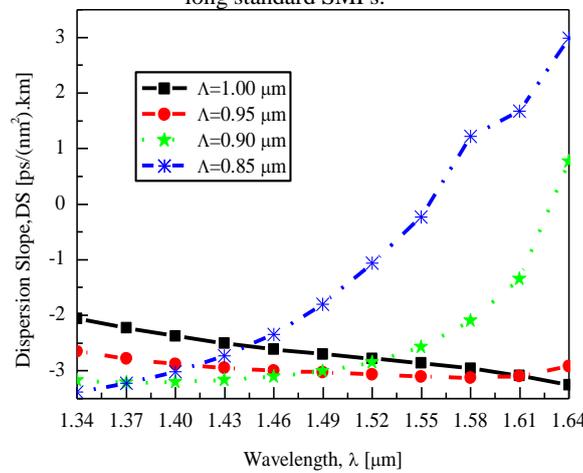

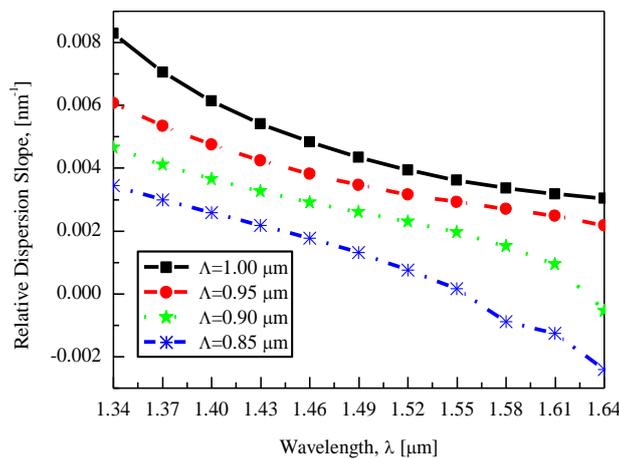Fig. 8. Spectral variation of dispersion slope for different pitch, Λ .

Fig. 9. Effect of changing pitch, Λ on relative dispersion slope (RDS).

However, the maximum value of residual dispersion in usable bandwidth (1.360-1.625 μm) for the proposed C-PCF after compensating is about ±62 ps/nm for optimum parameters and particularly at 1.55 μm, it is zero. Thus, it is clearly proved that our proposed C-PCF with optimized parameters is suitable for systems with high bit rates transmission systems covering entire E to L telecommunication bands. Fig. 8 represents the dispersion slope whose values are in-between -2.06 to
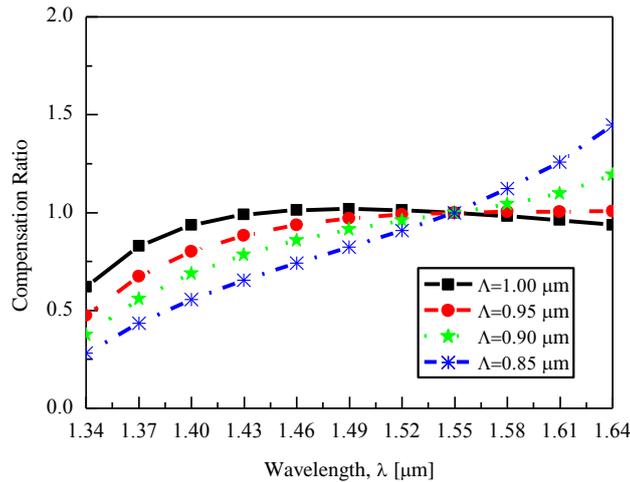
Fig. 10. Compensation ratio as a function of wavelength for the proposed five rings C-PCF with different pitch, Λ.
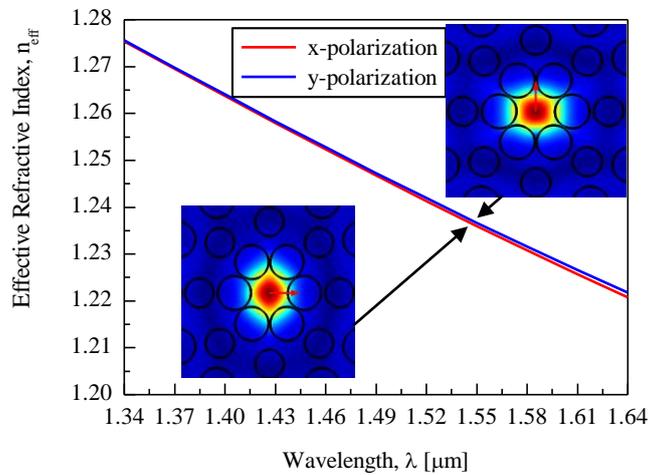

Fig. 11. Variation in the effective refractive index for optimized C-PCF for each polarization. (The insets are fundamental electric field distributions at λ = 1.55 μm for each polarization for optimum parameters).

-3.25 ps/(nm^2.km) over E to L wavelength bands for optimum parameters which shows less variation in magnitude than [12]. Fig. 9 shows the relative dispersion slope against wavelength and it is seen that at λ=1.55 μm, the RDS value of the proposed C-PCF for optimum parameters is $0.0036\,nm^{-1}$ which perfectly matches to the RDS of SMF. Compensation ratio of the proposed C-PCF is evaluated as a function of wavelength and best compensation is obtained for the optimum parameters as shown in Fig. 10. Variation in the effective refractive index for optimized C-PCF for each polarization is shown in Fig. 11. The fundamental mode of electric field pattern at λ = 1.55 μm for each polarization is shown for optimum parameters in the insets of Fig. 11. The proposed C-PCF also exhibits a birefringence of order 1.64×10^{-4}.

VI. EFFECTIVE AREA

Fig. 12 represents the effective area of the proposed five rings C-PCF at λ=1.55 μm is 1.574 μm^2 for the optimum parameters which is higher than that obtained for eight ring DC-MOF [23] but lower than [13]. However, low effective area causes splice loss and as a solution, tapered intermediate PCF
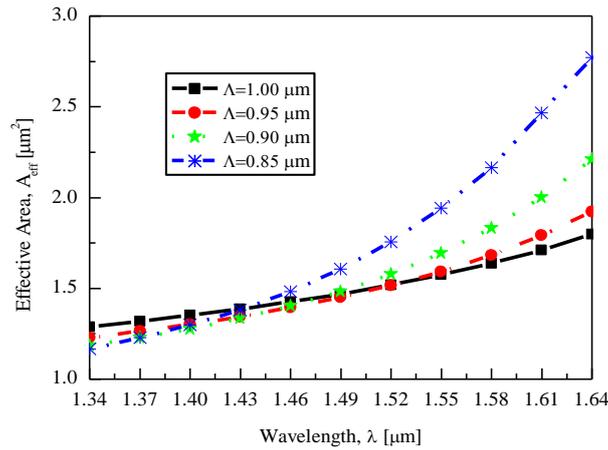
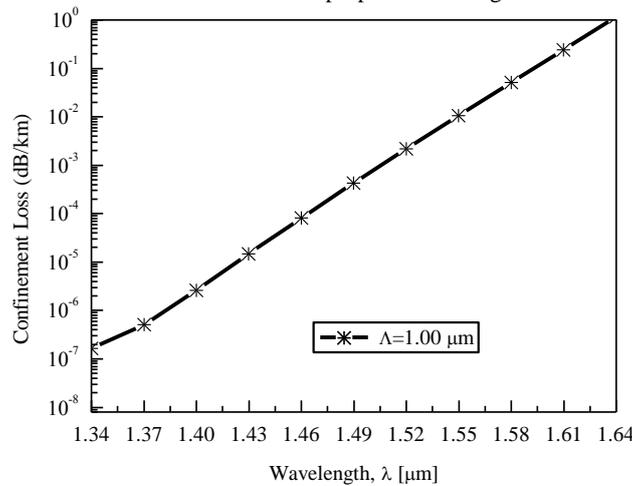Fig. 12. Spectral variation of effective area of the proposed five rings C-PCF for different pitch, Λ .

Fig. 13. Confinement loss as a function of wavelength for optimum design parameters and N_r=8.

can be used for interfacing between proposed C-PCF and SMFs successfully [13]. So, we believe that our proposed C-PCF can be interconnected with SMF without any major complications.

VII. CONFINEMENT LOSS

Fig. 13 describes the wavelength dependence properties of the confinement loss of the proposed C-PCF. Confinement loss only for optimum parameters is shown. From figure, it is observed that the confinement loss is about 10^{-2} dB/km at λ=1.55 μm considering eight air-hole rings which is the acceptable level for the transmission fiber. In contrast, confinement loss is not the major concern because the length of DCF is short compared to transmission fiber. Hence confinement loss will not be high due to short length of DCF. However 20, 11, 13 and 9 air hole rings are considered by [25-26,10,12] to keep the confinement loss below 10^{-4} dB/m to cover S band [10], C band [25] and wavelength ranging from 1.46 to 1.64 μm [12, 26]. Therefore the design complexity of the proposed C-PCF is lower than mentioned above in terms of number of rings used. Finally a comparison is made between properties of the proposed C-PCF and some other PCFs designed for broadband dispersion compensation. The comparison between those fibers is presented in terms of magnitude of negative dispersion (ND), RDS, length of dispersion compensating fiber (LDCF) and number of design

parameters (NDP) including number of rings in the cladding, N_r, pitches, N_Λ different sized air hole diameter, N_d in Table 1. Ref. [12] considers two optimum design parameters such as Λ =0.85, d_1/Λ =0.3, d/Λ =0.76 and Λ =0.90, d_1/Λ =0.3, d/Λ =0.76 which shows negative dispersion of -230 to -435 and -190 to - 405 ps/(nm.km) respectively in the wavelength ranging from 1.46-1.64 μm but the RDS value is 0.0037 and 0.0043 nm^{-1}. However, negative dispersion of -239.5 and -204.4 ps/(nm.km) are reported at λ=1.55 μm in [13, 15] respectively. Although Ref. [15] obtains RDS of 0.003543 nm^{-1} which is close to SMF's RDS but significant deviation is noticed in Ref. [13]. Ref. [23] shows accurate RDS value at λ=1.55 μm but still negative dispersion is not enough. On the other hand, the proposed C-PCF shows higher negative dispersion value of -790.12 ps/(nm.km) at 1.55 μm wavelength that is higher that all mentioned in the Table 1 with 100% RDS matching . As a result, the length of the proposed C-PCF is lower than those presented in Table 1.

TABLE I. COMPARISON BETWEEN PROPERTIES OF THE PROPOSED C-PCF AND OTHER DC-PCF

PCFs	Wavelength Band (μm)	ND (ps/nm/km)	ND (ps/nm/km) at λ=1.55 μm	RDS (nm^{-1}) at λ=1.55 μm	LDCF (km)	NDP (N_r, N_Λ, N_d)
Ref. [12]	1.46-1.64	-230 to -435	-	0.003700	-	9, 1, 2
		-190 to -405	-	0.004300	-	
Ref. [13]	1.53-1.625	-226 to -290	-239.5	0.003000	2.77	6, 1, 2
Ref. [15]	1.35-1.65	-	-204.4	0.003543	3.2	5, 1, 3
Ref. [23]	1.40-1.60	-130 to -360	-	0.003600	-	5, 1, 1
C-PCF	1.34-1.64	-248.65 to -1069	-790.12	0.003600	0.82	5, 1, 4

VIII. CONCLUSION

In this study, large negative dispersion properties as well as effective area and confinement loss of circular photonic crystal fiber have been investigated using FEM. A simple design of circular PCF has been proposed for dispersion compensation over the entire E to L wavelength band ranging from 1360-1625 nm. It was found that the proposed broadband dispersion compensating C-PCF can be designed to provide large negative dispersion of about -248.65 to -1069 ps/(nm.km) over E to L wavelength and an RDS equal to that of SMF's. It is expected that the proposed C-PCF will be greatly applicable in high-bit-rate optical transmission networks for broadband dispersion compensation.

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