Designing Dispersion Compensating Microstructure Optical Fiber

Feroza Begum*,AbulKalam Azad, Saifullah Abu Bakar and Iskandar Petra
Faculty of Integrated Technologies
Universiti Brunei Darussalam, Gadong BE 1410, Brunei Darussalam
*feroza1972@gmail.com

Kazuya Miyagi and Yoshinori Namihira
Graduate School of Engineering and Science
University of the Ryukyus, Okinawa 903-0213, Japan

***Abstract*—We design a hexagonal model of dispersion compensating photonic crystal fiber using finite element method with perfectly matched layer as an analysis tool. In this case, we change different parameters-diameter of air holes and pitch to observe the effects of different properties of dispersion compensating photonic crystal fiber such as effective area, confinement loss and chromatic dispersion. We have achieved large negative chromatic dispersion, and low confinement loss. Moreover, numerical results show that small length of the proposed dispersion compensating photonic crystal fiber is achieved. The proposed microstructure fiber can be used for wide band high speed optical transmission systems.**

***Keywords*—**Photonic crystal fiber; chromatic dispersion; confinement loss; dispersion compensation

I. INTRODUCTION

Photonic crystal fiber (PCF) is a fiber that was first demonstrated in 1996 and has been popular since then. It is periodic microstructures that affect the motion of photons like as that ionic lattice affect electrons in solids. It occurs in nature in the form of structure coloration. It is made from the concept of photonic crystal and is very flexible. The core of this particular fiber is made of single material such as silica and can either be solid or empty. The core is surrounded by air holes which runs through the fiber hence it is known as 'holey' or 'micro-structured' fiber. Due to this structure the core acts as a cavity where the light is confined and transmitted [1,2]. The PCF is divided into two different fibers: one is index guiding photonic crystal fiber and other one is photonic band gap fiber. In index guiding PCF light is guided by the total internal reflection between the solid core and multiple air holes cladding. Photonic band gaps are that the periodicity of the crystal induced a gap in its band structure. No electromagnetic modes are allowed to have frequency in the gap. Its effect is exhibited in photonic crystal band gap fiber where the wavelength guides light in a low index core region.

To increase the capacity of the long haul optical communication system and control the detrimental nonlinear effects such as self-phase modulation, cross phase modulation and four wave mixing in wavelength division multiplexing (WDM) system of single mode by use the dispersion compensating PCFs (DC-PCFs). Dispersion compensating fibers have a larger negative dispersion to compensate the main fiber dispersion [3]. The more negative value of chromatic dispersion is achieved the shorter length that one we get for dispersion compensating fiber [4]. If the length is shortened it is cost effective. The conventional optical fiber negative dispersion coefficient is about D=100 to 130 ps/nm/km at 1.55 μm wavelength with high losses [5]. Different types of dispersion compensating photonic crystal fibers (DC-PCFs) have been reported to date such as dual-concentric-core PCFs without doping have been proposed [4, 6] with very narrow bandwidth, doped PCFs [7, 8] which have good dispersion compensating characteristics, but their fabrication can be difficult. Reference [9] designed an elliptical holes octagonal configuration DC-PCFs, and a negative dispersion of −400 to –725ps/nm/km in the wavelength range of 1460–1625 nm can be achieved, but this structure is more difficult to be controlled during fabrication process.

In this paper, we present solid core DC-PCFs for optimizing the dispersion compensation of standard single mode fibers (SMFs) in the entire S and C telecommunication band. The fabrication of this proposed DC-PCFs could be more efficient and easier for the relatively fewer geometrical parameters are need to be optimized compared with formerly presented PCFs. From the numerical simulation results, it is found that it is possible to obtain larger negative chromatic dispersion value approximately around – 1000 ps/nm/km to – 1250 ps/nm/km in the entire S and C band, better residual dispersion, small dispersion compensating fiber length of 0.51 km and low confinement loss in the entire S and C telecommunication band by altering the hole size and spacing.

II. METHODS FOR SIMULATING PROPAGATION CHARACTERISTICS

Various numerical simulation methods have been developed to analyze the different characteristics of PCFs, such as the beam propagation method, localized function method, plane wave expansion method, finite element method, finite difference method, multipole method, boundary element method[10]. Comsolmultiphysics commercial package is used as a simulation tool using finite element method (FEM) with anisotropic perfectly matched layer (PML) boundary condition for designing and simulating proposed photonic crystal fiber [11]. It is considered the most efficient boundary condition for the DC-PCFs simulation. We have achieved real part and the imaginary part of effective mode index after simulation which is then used to calculate confinement loss and chromatic dispersion. Using the real part of the effective mode index we have calculated the chromatic dispersion and the imaginary part of the effective mode index are used to calculate the confinement loss of DC-PCFs. The effective area can be calculated directly using the software by solving the appropriate equation.

A. Chromatic Dispersion, D(λ)

Chromatic dispersion contributes as the major technique for controlling the loss in the index-guiding photonic crystal fiber. Control of chromatic dispersion in PCF is a very important problem for our practical application to optical communication system. Chromatic dispersion can be controlled or modified by varying few parameters such as the air hole diameter *d*, the hole to hole spacing also known as the pitch Λ and the shape of the air holes. Moreover, the real part of effective mode index has an effect on chromatic dispersion. Effective mode index for a given wavelength is obtained by solving Eigen value problem from Maxwell equation. Effective mode index is a complex values and it has a real and imaginary part [11-14]. So the effective mode index, $n_{eff}$is obtained as

$$n_{\text{eff}} = \frac{\beta}{\text{k}_0} \qquad (1)$$

whereβ is the propagation constant and k_0 is the free space wave number.

Sellmeier equation is an empirical relationship between refractive index and wavelength for particular transparent and non-transparent medium. This equation is used to determine the dispersion of light. So the equation is define as

$$n_{\text{eff}}{}^2 = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3} \qquad (2)$$

wheren_{eff} is the refractive index, λ is the wavelength, and $B_{1,2,3}$ and $C_{1,\,2,\,3}$ are the coefficients of Sellmeier equation. The coefficients and values of Sellmeier equations are shown in Table I [15].

TABLE I:COEFFICIENTS AND VALUES OF SELLMEIER EQUATION

Coefficient	Value
B_1	0.6961663
B_2	0.4079426
B_3	0.8974794
C_1	0.0684043e-6
C_2	0.1162414e-6
C_3	9.896161e-6

Dispersion is a general term that transmitted optical signal causes boarding of the transmitted light pulses as they travel along the fiber. Total dispersion or chromatic dispersion D consists of two components one is material dispersion D_m and another one is waveguide dispersion D_w.

$$D = D_m + D_w \qquad (3)$$

To control the chromatic dispersion in PCFs, dispersion compensation and linear or nonlinear optics the waveguide dispersion D_m of the PCF is obtained from the n_{eff} value against the wavelength using the following equation. The material dispersion is taken into account during the calculation by the Sellemier formula.

$$D = -\frac{\lambda}{\text{c}} \frac{\text{d}^2 \text{R}_\text{e}(n_{\text{eff}})}{\text{d}\lambda^2} \qquad (4)$$

B. Confinement Loss, L_C

Confinement loss, L_c is due to the finite air holes in cladding. The confinement loss is calculated from the imaginary (Im) part of the complete effective mode index n_{eff}, using the following equation [11-14].

$$L_C = \frac{40}{\text{Im}(n_{\text{eff}})} = 8.686\ \text{k}_0\, \text{Im}(n_{\text{eff}})\ [\text{dB/km}] \qquad (5)$$

C. Effective Area,A_{eff}

The effective area is an important parameter. It is originally introduce as the non-linear measurement. For non-linear measurement the low effective area gives a high density of power and also non-linear effects are dependent the intensity of the electromagnetic field [11-14]. The intensity I, over the core area A_{core}can be calculated from the power, P_{means} define as:

$$I = \frac{P_{means}}{A_{core}} \tag{6}$$

We can calculate the effective area by using the following equation-

$$A_{\mathrm{eff}} = \frac{2\pi(\int_0^{\infty}|E_a(r)^2|rdr)^2}{\int_0^{\infty}|E_a(r)|^4 rdr} \tag{7}$$

where$E_a(r)$ is the field amplitude at radius r.

D. Residual Dispersion, D_r

The chromatic dispersion of the SMF is positive, therefore, the fundamental requirements of a DC-PCFs for wavelength division multiplexing operation are a large negative dispersion over a broad range of wavelengths [6-9].

$$D_T(\lambda) = D_{SMF}(\lambda)L_{SMF} + D_{DCF}(\lambda)L_{DCF} \tag{8}$$

whereD_{SMF}, L_{SMF} are the chromatic dispersion and length of the SMFs, respectively. D_{DCF}, L_{DCF} are the chromatic dispersion and length of the DCFs, respectively. If the total compensation of the dispersion is required, the length of the L_{DCF} is chosen so that total dispersion coefficient $D_T = 0$. However, full compensation is not always the optimum due to nonlinear effects and possible chirp in transmitter.

III. RESEARCH MODEL

For our research purpose we have designed a model of DC-PCFs where cladding consists of five rings of air holes in hexagonal shape and a silica solid core which is shown in Fig. 1. Air hole diameter is represented as (d) and the distance between two air holes known as pitch is represented as (Λ) respectively. The diameter of all the air holes are same. As we know, all light does not always go through the core of the fiber and some light might reflect and create a distortion, in order to minimize distortion we use perfectly matched layer (PML) outside the cladding so that it can absorb the loss light and not reflect to create distortion. In this work, we have changed the value of pitch and the diameter of air hole to see the effect on effective mode index,the change in confinement loss, the effect on effective area and the change in chromatic dispersion. In this research we have used two pitches (Λ = 0.7 μm and 0.8 μm) and different types of air hole diameters (d = 0.15 μm, 0.20 μm, 0.5 μm, 0.30 μm, 0.35 μm and 0.38 μm).

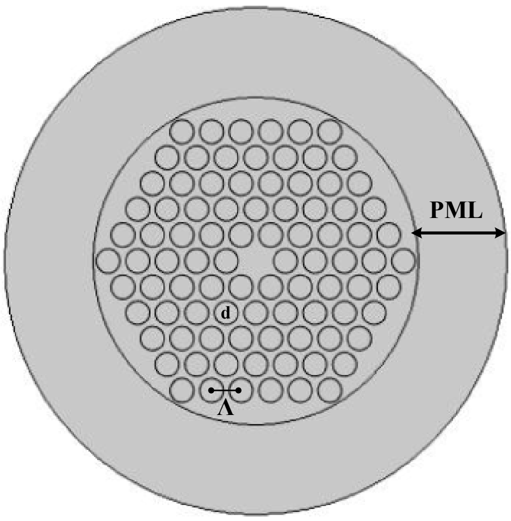
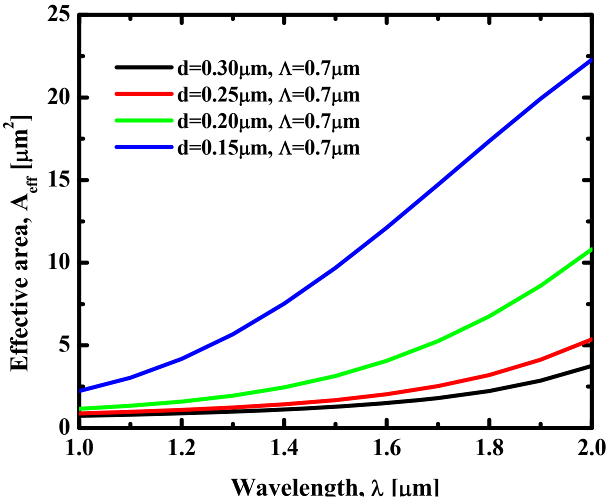


Fig. 1: Proposed PCF with five rings of air hole with diameter d, pitch Λ and PML layer.

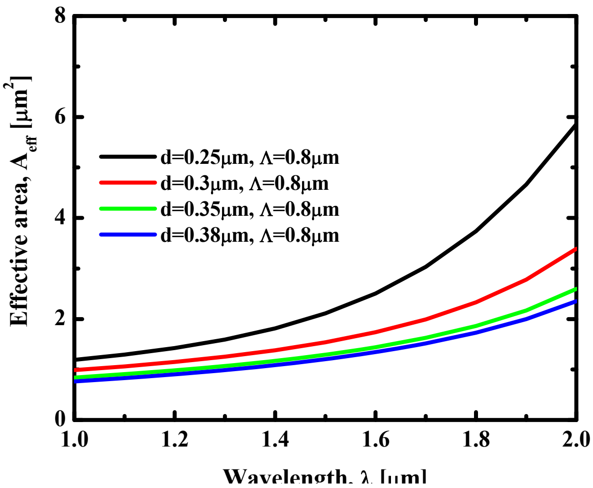
IV. RESULTS ANDDISCUSSION

A. Effective Area

Figure 2 (a) and (b) represents the wavelength response of the effective area of hexagonal DC-PCFs for the parameters pitch, Λ = 0.7 μm, and 0.8 μm, respectively. The diameter of the air hole, d is changed from 0.15 μm to 0.38 μm for all cases keeping the pitch value constant. It is seen that pitch and the diameter of the air hole has an effect on the effective area. We have seen from the Fig. 2 that higher the value of pitch larger the value of effective mode index. It is because as the value of pitch increases the Gaussian function radius increases which increase the effective area. Moreover, it is also observed that for larger value of diameter the value of effective

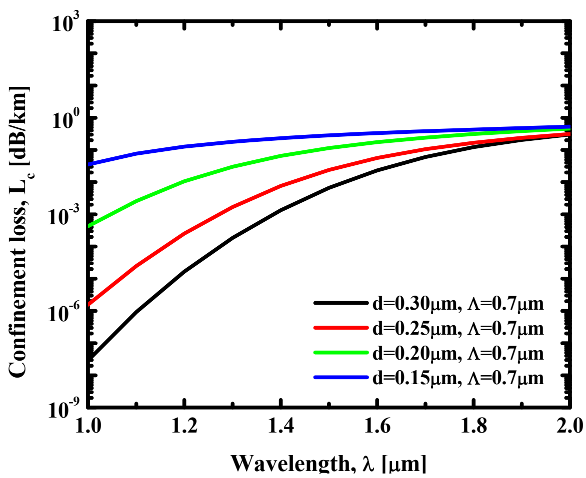


(a)



(b)

Fig. 2: Wavelength dependence effective area for (a) Λ = 0.7μm, *d* = 0.30 μm, 0.25 μm, 0.20 μm, 0.15 μm, and (b) Λ = 0.8μm, *d* = 0.38 μm, 0.35 μm, 0.3 μm, 0.25 μm of the proposed DC-PCF.



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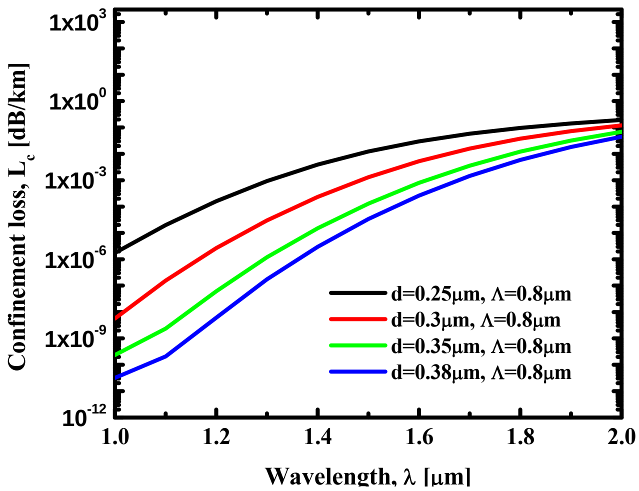

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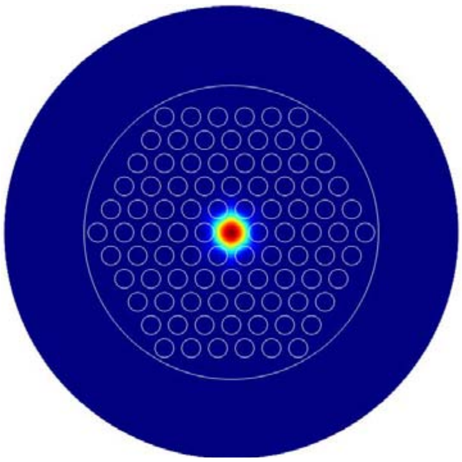
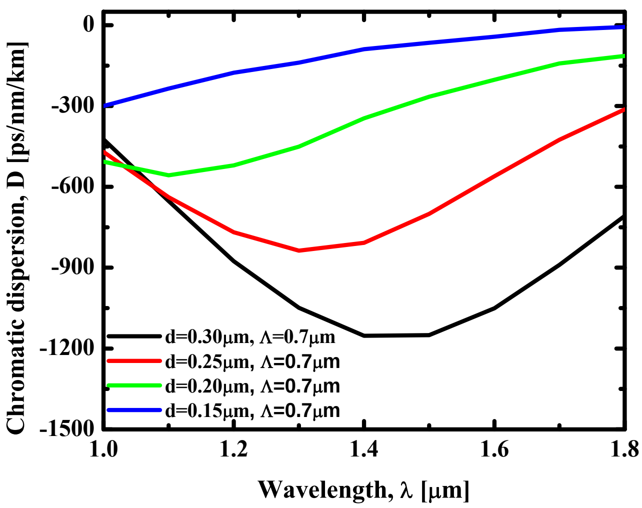


(c)

Fig. 3: Wavelength dependence confinement loss for (a) Λ = 0.7μm, *d* = 0.30 μm, 0.25 μm, 0.20 μm, 0.15 μm, (b) Λ = 0.8μm, *d* = 0.38 μm, 0.35 μm, 0.3 μm, 0.25 μm, and (c) simulated figure of the proposed DC-PCFs with light passing through the center of the core of the fiber.



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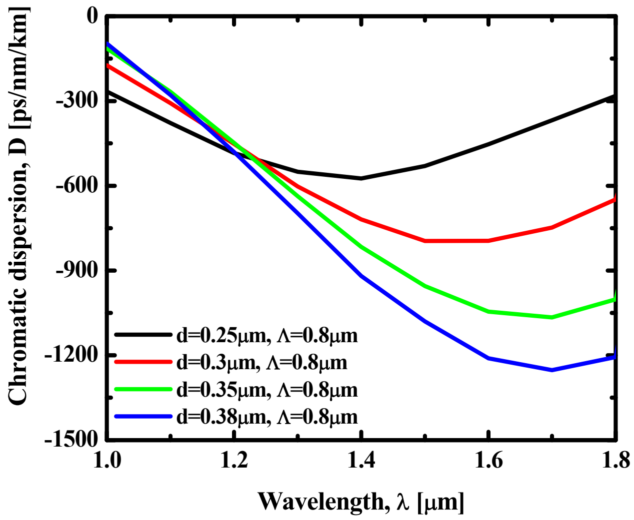


(b)

Fig. 4: Wavelength dependence chromatic dispersion for (a) Λ = 0.7μm, *d* = 0.30 μm, 0.25 μm, 0.20 μm, 0.15 μm, and (b) Λ = 0.8μm, *d* = 0.38 μm, 0.35 μm, 0.3 μm, 0.25 μm of the proposed DC-PCFs.

areadecreases. This is because as we increase the diameter of the air hole the value of Gaussian response decreases, hence effective area decreases with increase in value of diameter of air hole.Furthermore, it is seen that wavelength also has an effect on the effective mode index, with the increase in the wavelength the value of effective mode index increases. The optimum parameters are considered Λ = 0.8 μm and *d* = 0.38 μm and obtained 1.25 μm^2 effective area at 1.55 μm wavelength which is shown in Fig. 2(b).

B. Confinement Loss

Figure 3 (a) and (b) reveals the wavelength response of the confinement loss of hexagonal DC-PCFs. From the Fig. 3 above it is seen that higher the value of pitch larger the value of confinement loss. It is because as the value of pitch increasesthe leakage of light increases, hence we have seen that the value of confinement loss increases. Moreover, it is also observed thatwhen we have changed the diameter of the air hole keeping the pitch constant,for larger value of diameter the value of confinement loss decreases. This is because as we increase the diameter of the air hole the amount of leakage light decreases, henceconfinement loss decreases with increase in value of diameter of air hole.From Fig. 3(b), it is seen that the confinement loss isless than 10^{-4} dB/kmin the entire S and C bands for the Λ = 0.8 μm and *d* = 0.38 μm. Figure 3 shows the simulated proposed

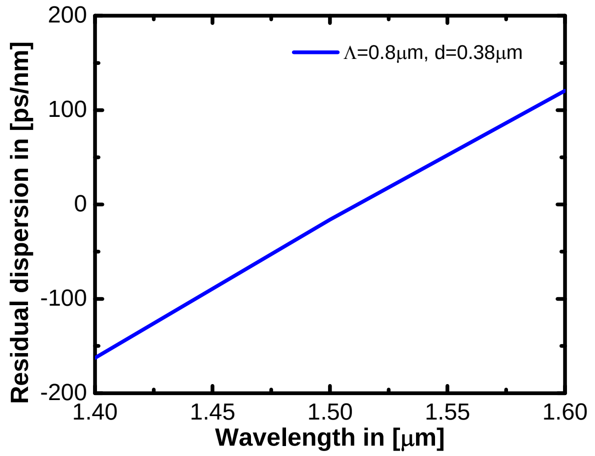
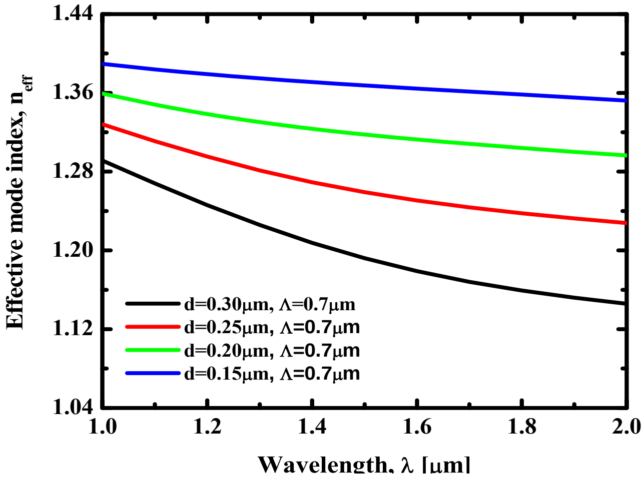
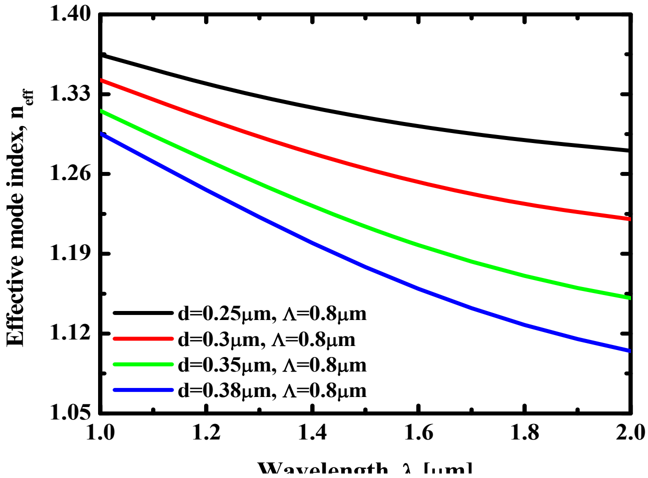


Fig. 5: The wavelength dependence residual dispersion of the proposed DC-PCF for the optimum parameters Λ = 0.8 μm and *d* = 0.38 μm.



(a)



(b)

Fig. 6: Wavelength dependence effective mode index for (a) Λ = 0.7μm, *d* = 0.15 μm, 0.20 μm, 0.25 μm, 0.30 μm, and (b) Λ = 0.8μm, *d* = 0.25 μm, 0.30 μm, 0.35 μm, 0.38 μm of the proposed DC-PCFs.

DC-PCFs. From this Fig. (c), it is observed that almost all light is passing through the core without any leakage light beyond the first air hole ring.

C. Chromatic Dispersion

Figure 4(a) and (b) embodied the wavelength response of chromatic dispersion of proposed hexagonal DC-PCFs for the parameters pitch, Λ = 0.7 μm and 0.8 μm. The diameter of air hole, *d* is changed from 0.15 μm to 0.38 μm for all cases the pitch is constant. It is seen that the real part of effective mode index has an effect on the chromatic dispersion. It can observe that the dispersion is monotonically decrease with the increase of pitch. From the numerical results, from Fig. 4(b) it is seen that high negative dispersion values of −1000 ps/nm/km to – 1250 ps/nm/km can be achieved between the 1.45 μm to 1.7 μm wavelength range for the optimum parameters Λ = 0.8 μm and *d* = 0.38 μm. It can be clearly seen that the design parameter Λ = 0.8 μm possesses a larger negative dispersion value than the other design parameters.

D. Residual Dispersion

Figure 5 represents the change in residual dispersion with the value of wavelength. Fig. 5 reveals the calculated residual dispersion, D_r obtained after the dispersion compensation by a 0.51 km long optimized DC-PCFs for the one span (40 km long) of SMF. It can be observed that the residual dispersion varies less than ± 64 ps/nm in the entire S and C bands, which enables the proposed DC-PCFs to be a suitable candidate for high-bit-rate transmission systems. The very short fiber length is achieved from this proposed DC-PCFs. This is another advantage of this proposed DC-PCFs.

E. Effective Mode Index

Figure 6 (a) and (b) shows the wavelength response of the real part of the effective mode index of the proposed DC-PCFs for the parameters pitch, Λ = 0.7 μm, and 0.8 μm. The diameter of the air hole, *d* is changed from 0.15μm to 0.38 μm for all cases keeping the value of pitch constant. It is seen that pitch and the diameter of the air hole has an effect on the effective mode index. We have seen from the Fig. 6 that higher the value of the pitch larger the value of effective mode index. It is because as the value of pitch increases the amount of silica index increases, hence we have seen that the value of effective mode index increases. Moreover, it is also observed that when we have changed the diameter of the air hole keeping the pitch constant, forlarger value of diameter the value of effective mode index decreases. This is because as we increase the diameter of the air hole the value of silica index decreases, hence effective mode index decreases with increase in value of diameter of air hole. Furthermore, it is seen that wavelength also has an effect on the effective mode index, with the increase in the wavelength the value of effective mode index decreases.

V. CONCLUSION

In this research, we have proposed hexagonal DC-PCFs with five rings of air hole. Our approach was to achieve negative dispersion for dispersion compensating fiber, which is used for optical communication system. In order to do so we have changed different parameters such as air hole diameter and pitch, and observed the variation of different properties such as effective mode index, effective area, confinement loss and chromatic dispersion. From our research we have concluded that chromatic dispersion varies with the real part of the effective index along with the wavelength. Through our research we obtained the negative chromatic dispersion value approximately around – 1000 ps/nm/km to – 1250 ps/nm/km in the entire S and C band. Large negative dispersion is preferable for high bit rate optical communication purpose. Moreover, higher the negative chromatic dispersionvalue shorter the length of the dispersion compensating fiber.

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