Wideband Dispersion Compensation in Square Lattice Photonic Crystal Fiber

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Abstract- **In the present study, a new structure has been suggested for dispersion compensating photonic crystal fibers in order to broaden the chromatic dispersion compensation band, effectively. In the proposed structure, putting a combinations of circular holes and a star structure in the inner clad causes the dispersion profile to be broadened. Also, this photonic crystal fiber comprising a negative dispersion coefficient in the whole S to U telecommunication bands. In this fiber, the minimal dispersion coefficient is -653ps/(nm.km). Furthermore, in this structure by increasing the diameter of the circular holes of the inner clad, a relatively flat dispersion profile is obtained in the whole E to U telecommunication bands with maximum variation of 46ps/(nm.km). In the S to C telecommunication bands, the dispersion variation is 17ps/(nm.km). The simulations are all done using the finite difference time domain (FDTD) numerical method.**

Index Terms- Chromatic dispersion, Dispersion compensation, Negative dispersion, Photonic crystal fiber.

I. INTRODUCTION

Every structure in which the refractive index changes periodically is called photonic crystal. For the first time, the idea of photonic crystal was introduced and supported by John [1] and Yablonovitch [2] in two separate articles. So far, many optical devices have been designed based on photonic crystals such as beam-splitters [3], filters [4], wavelength de-multiplexers [5] and optical fibers [6]-[7]. In the optical communication systems, the dispersion is one of the important problem. Therefore, the different methods of dispersion compensation like dispersion compensation gratings, optical phase conjugation, and electronic dispersion compensation have been widely investigated. As the different methods of dispersion compensation, the dispersion compensation fiber (DCF) is the only method widely used around the world [8]-[9].

The holey photonic crystal fibers (PCFs) have microscopic arrays of air channels running along the length of the fiber causing a reduction in the index of the clad around the core [10]. The idea of using

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PCF for dispersion compensation was first introduced by Birks et al [11]. The photonic crystal fibers are capable of flexibility in adjusting the dispersion [12], which is of considerable importance in designing the dispersion compensating fibers. In fact if a dispersion compensating fiber (DCF) has a negative dispersion in a wavelength range, it can be able to do dispersion compensation within that wavelength range. To minimize the losses and reduce the costs, the DCF should be made as short as possible, and the negative dispersion should be as large as possible [13]. The available wavelength bandwidth for dispersion compensation of DCFs is very narrow because of the concave dispersion profile of dual concentric core fibers. Therefore, it is also necessary to compensate for the dispersion slope of DCFs for broadband operation.

Several structures are proposed for wideband dispersion compensating photonic crystal fibers. The DCF introduced by Fujisawa et al [14] is capable of dispersion compensation throughout the whole band C. The other structure is an octagonal PCF, which is capable of dispersion compensation in the bands S to L [15]. The wideband DCF introduced by Ehteshami et al [16] has a dispersion coefficient of -193.2 ps/(nm.km) at wavelength of 1.55 μm and negative dispersion coefficient over E to L wavelengths. Also, the structure introduced by Siddique et al in 2013 [17] has a dispersion coefficient of -897ps/(nm.km) capable of dispersion compensation in a wide range of wavelengths.

In the present research, a square lattice wideband dispersion compensating photonic crystal fiber is presented. By placing a combination of circular holes and a star structure in the inner clad of the fiber, the dispersion compensation band of the fiber is broadened and resultes in a negative dispersion coefficient throughout the S to U telecommunication bands in the fiber. The results of numerical simulation indicate that the proposed DCF design has wider wavelength range, compare to the other structures presented earlier. Additionally, by increasing the diameter of the circular holes in this structure, a relatively flat dispersion profile is obtained.

In the second section, theoretical calculations on dispersion are discussed briefly and then the geometry of the proposed structure is introduced. In the third section, the simulation and the results of the finite difference time domain (FDTD) numerical method are shown. The fourth section is the conclusion section.

II. Theory and Introducing the Proposed Structure

The chromatic dispersion is the most important factor of dispersion in the single-mode fibers and is calculated with the equation (1).

$$D_C = \frac{1}{L}\frac{\Delta t_C}{\Delta\lambda} = -\frac{\lambda}{C}\frac{d^2 n_{eff}}{d\lambda^2} \tag{1}$$

Where D_c, Δt_c and $\Delta\lambda$ are the chromatic dispersion coefficient, chromatic dispersion and the spectral width. L is the fiber length, λ is the wavelength in vacuum, C is the speed of light in vacuum and n_{eff} is the effective index of the fiber [18]. DCFs contain two spatially separated asymmetric concentric cores which support two supermodes: inner mode and outer mode. The effective refractive index of the inner core mode and outer core mode matches with each other at phase matching wavelength (λp). Before the phase matching wavelength (λ<λp), the field distribution of the inner core mode is confined within the central core and is a Gaussian shape. After the phase matching wavelength (λ>λp), the fundamental mode field distribution is in the outer core region. By an appropriate design, mode matching of these two supermodes can be achieved at a specified wavelength λp with a high negative dispersion coefficient. The proposed DCF design is based on the square lattice with circular holes. The transverse cross-section of the PCF is shown in Fig. 1. This fiber has one ring of the inner clad and two rings of the outer clad. The outer core is created through a reduction in the diameter of the air holes of the second ring. In this fiber, a combination of a star structure and circular holes in the inner clad is used. In DCFs, the chromatic dispersion is related to the additional design parameters like the geometry of the air holes, lattice constants, and the sizes of air holes. By optimizing these parameters, suitable guiding properties can be obtained. The optimum parameters of the structure are presented in Table. 1. The background material is pure silica and the refractive index of background material is given by Sellmeier's equation [19].

$$n^2 = 1 + \frac{A_1\lambda^2}{\lambda^2 - \lambda_1^2} + \frac{A_2\lambda^2}{\lambda^2 - \lambda_2^2} + \frac{A_3\lambda^2}{\lambda^2 - \lambda_3^2} + ... \tag{2}$$

Where n is the refractive index, λ is the wavelength, A_1, A_2, A_3, λ_1, λ_2 and λ_3 are Sellmeier coefficients. The finite difference time domain (FDTD) numerical method is used to investigate the guiding property. In this method, Yee algorithm [20] get the electric and electromagnetic field through solving Maxwell equations directly. FDTD solves Maxwell's curl equations in non-magnetic materials:

$$\frac{\partial D}{\partial t} = \nabla \times H \tag{3}$$

$$D(\omega) = \varepsilon_0 \varepsilon_r(\omega) E(\omega) \tag{4}$$

$$\frac{\partial H}{\partial t} = -\frac{1}{\mu_0} \nabla \times E \tag{5}$$

Where H, E, and D are the magnetic, electric, and displacement fields, respectively, while $\varepsilon_r(\omega)$ is the complex relative dielectric constant ($\varepsilon_r(\omega)=n^2$, where n is the refractive index).

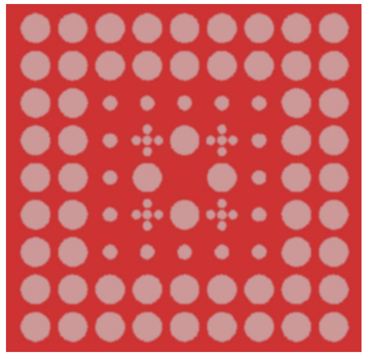

Fig. 1. The proposed square lattice wideband DCF

Table I. The parameters of the proposed structure.

Parameter	**Value (µm)**
Square lattice constant (□)	1.00
Star structure lattice constant (□$_s$)	0.30
Hole diameter of star structure (d_s)	0.26
Circular hole diameter of inner clad (d_1)	0.80
Hole diameter of outer core (d_2)	0.40
Hole diameter of outer clad (d_3)	0.80

The time domain methods usually need a longer time for calculation compared to the other methods. However, they give information of propagation in a wide wavelength range. Memories of the computers are improved rapidly. Although this improvemente also enhancess the efficiency of the other methods, it is specifical for the finite difference time domain numerical method. This method depends on making the space discrete and requires a high memory capacity.

III. Simulations and Results

In order to show the effect of the proposed structure on the broadening of the chromatic dispersion compensation band more observable, first, a square lattice fiber with simple clad and the same parameters as the proposed structure is simulated and its chromatic dispersion profile is calculated. Then, the structure of Fig. 1. is simulated. Fig. 2. shows the structure of the DCF of the simple square lattice. The optimum parameters of the fiber are presented in Table. 2. The background material is pure silica. The mode field distribution of the simple fiber at the wavelength of 1.55 µm and the effective index of the fiber for the fundamental mode are presented in Figs. 3 and 4, respectively. As one can see in Fig. 5, the dispersion profile of the DCF of the simple square lattice is narrow and capable of dispersion compensation in a narrow wavelength range.

Table II. The quantities of the parameters of simple DCF

Parameter	**Value (µm)**
Square lattice constant (□)	1.00
Circular 36hole diameter of inner clad (d_1)	0.80
Hole diameter of outer core (d_2)	0.40
Hole diameter of outer clad (d_3)	0.80

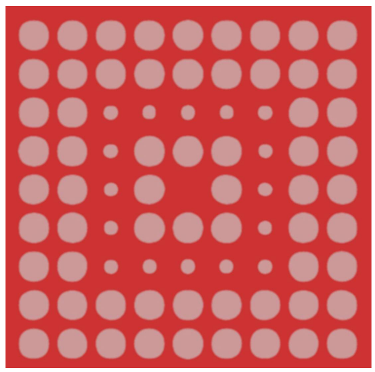

Fig. 2. The simple square lattice DCF.

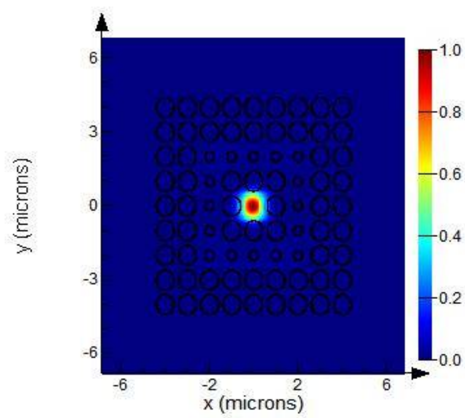

Fig. 3. The mode field distribution of the simple fiber at wavelength 1.55µm.

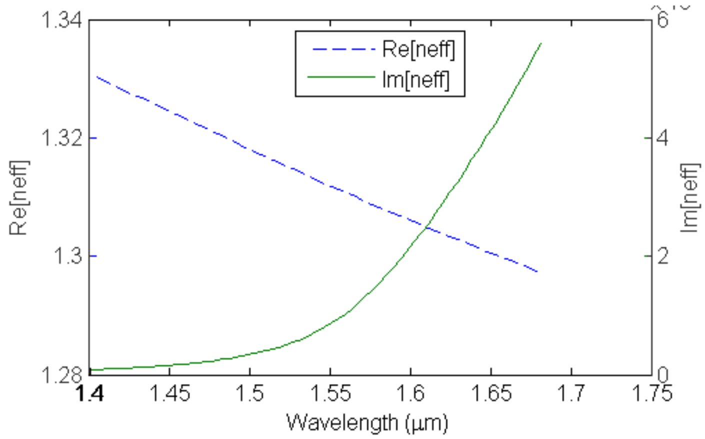

Fig. 4. The curve of simple square lattice fiber effective index versus wavelength.

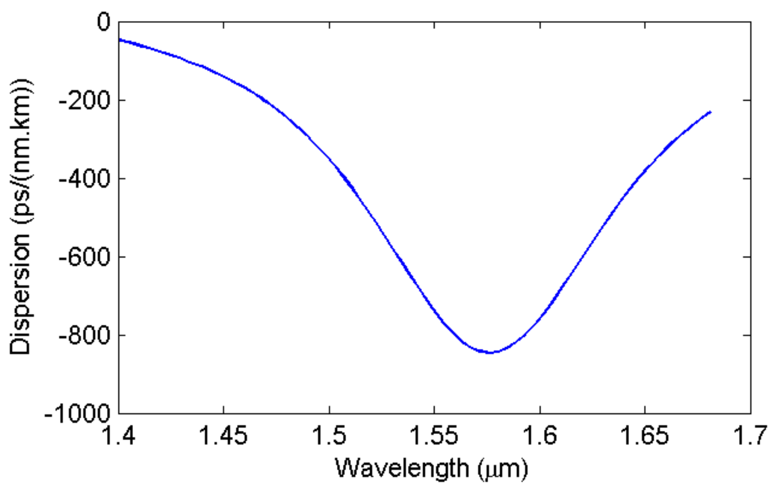

Fig. 5. The chromatic dispersion coefficient curve of the simple square lattice fiber.

According to Fig. 1, a combination of the star structure is used instead of the circular holes in the inner clad of the fiber. Fig. 6 shows the mode field distribution of the proposed fiber at the wavelength of 1.55 µm and Fig. 7 shows the effective index of the fiber for the fundamental mode. Group velocity versus wavelength demonstrates in Fig. 8.

According to Fig. 9, the new inner clad causes the fiber to have a negative dispersion in a wide wavelength range and therefore be capable of dispersion compensation in this range. This range includes the S to U and a part of E telecommunication bands, which is capable of dispersion compensation in a wider wavelength range compared to the other structures mentioned earlier, for example, it includes a wider wavelength range compare to the square lattice DCF presented by Siddique et al (2014), and also it includes a wider wavelength range and a larger negative dispersion coefficient compare to the square lattice structure presented by Ehteshami et al (2012). The minimum dispersion coefficient of this structure is -653ps/(nm.km) at wavelength 1.67µm (phase matching wavelength λp), and has a dispersion coefficient of -176ps/(nm.km) at wavelength 1.55µm.

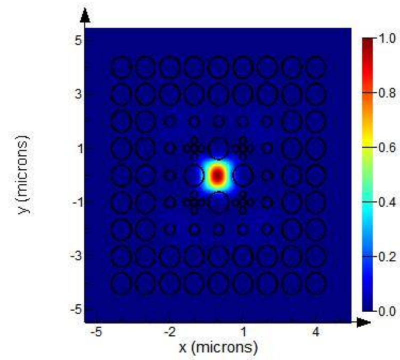

Fig. 6. The mode field distribution of the proposed DCF at the wavelength 1.55μm.

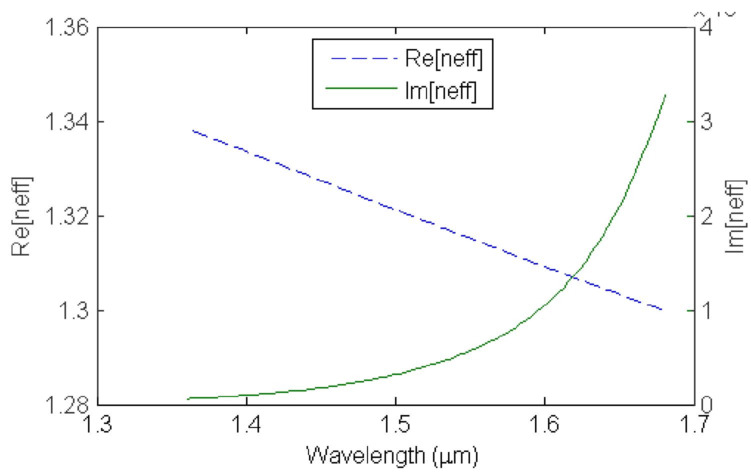

Fig. 7. The curve of the effective index of the proposed DCF versus wavelength.

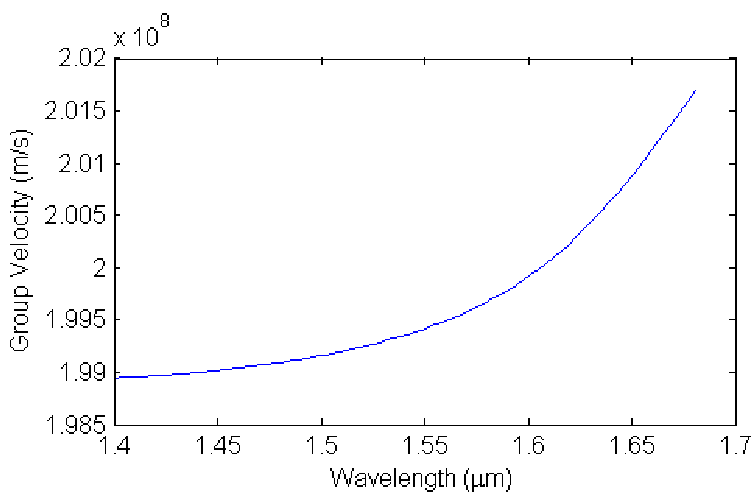

Fig. 8. The group velocity versus wavelength

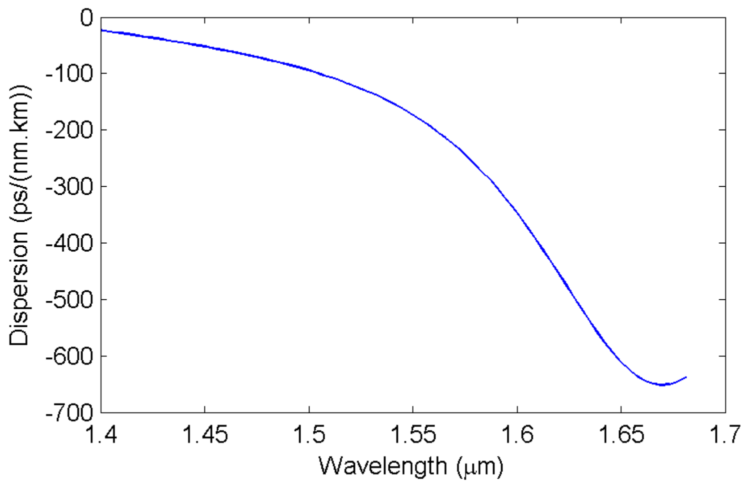

Fig. 9. The dispersion profile of the proposed square lattice DCF.

As shown in Fig. 10, as the diameter of the star structure holes decreases, the dispersion profile gets closer to the positive values and the minimum dispersion is transmitted to the higher wavelengths, which shows its capable of dispersion compensation in a wider wavelength range. On the other hand, since the negative dispersion at the wavelengths of higher than 1.675μm (the end of U telecommunication band) is not of much use, the diameter of the hole is set to be 0.26μm for the optimum structure. It should be noted that the optimum structure has a larger negative dispersion coefficient compared to the fiber with the hole diameter of 0.24μm. As the diameter of the star structure holes increases, the dispersion coefficient gets more negative and the minimum dispersion is transmitted to the smaller wavelengths. If the distance between inner core and outer core is small (or decrease of the diameter of the air-holes in the inner clad), the guided modes of both cores are strongly coupled and the effective refractive index of the coupled mode is gradually changed with wavelength resulting in smaller negative dispersion coefficient.

As shown in Fig. 11, the dispersion profile of the fiber is sensitive to any changes in the diameter of the circular holes of the inner clad. With a reduction in the diameter of the holes to 0.78μm, the dispersion profile in the wavelength range gets closer to the positive values and even has a positive dispersion in some wavelength ranges, and the minimum dispersion is shifted to the higher wavelengths. With an increase in the diameter of the holes to 0.82μm, the dispersion profile gets more negative, and the minimum dispersion is shifted to the smaller wavelengths.

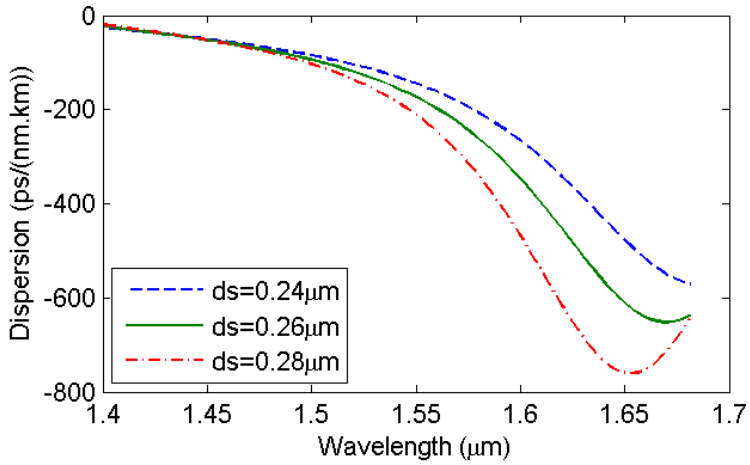

Fig. 10. The effect of the change in the diameter of the star structure holes on the dispersion profile.

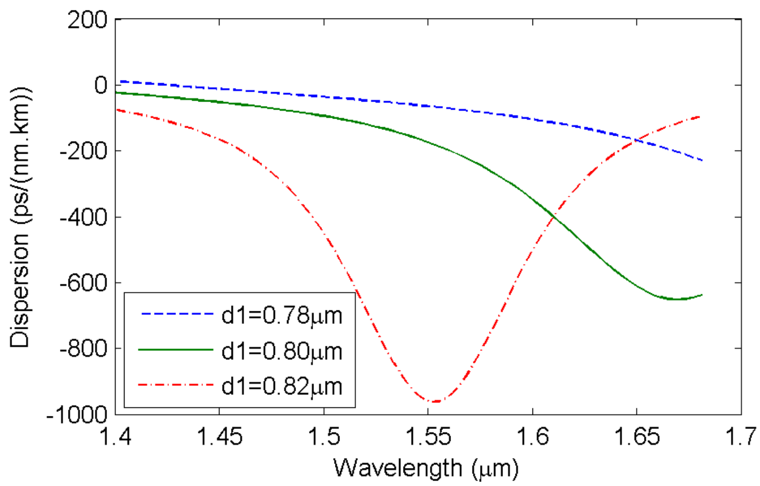

Fig. 11. The effect of the change in the diameter of the circular holes of the inner clad on the dispersion profile.

According to Fig. 12, the dispersion profile of the fiber is sensitive to the changes in the diameter of the holes of the outer core. With a reduction in the diameter of the holes to 0.38μm, the dispersion profile gets more negative and the minimum dispersion gets closer to the smaller wavelengths. With an increase in the diameter of the holes to 0.42μm, the dispersion profile gets closer to the positive values and the minimum dispersion gets closer to the higher wavelengths.

As shown in Fig. 13, with a reduction in the diameter of the holes of the outer clad to 0.78μm, the dispersion profile gets more negative and the minimum dispersion gets closer to the smaller wavelengths. Besides by increasing the diameter of the holes of the outer clad to 0.82μm, the dispersion profile gets closer to the positive values and the minimum dispersion is shifted to the higher wavelengths.

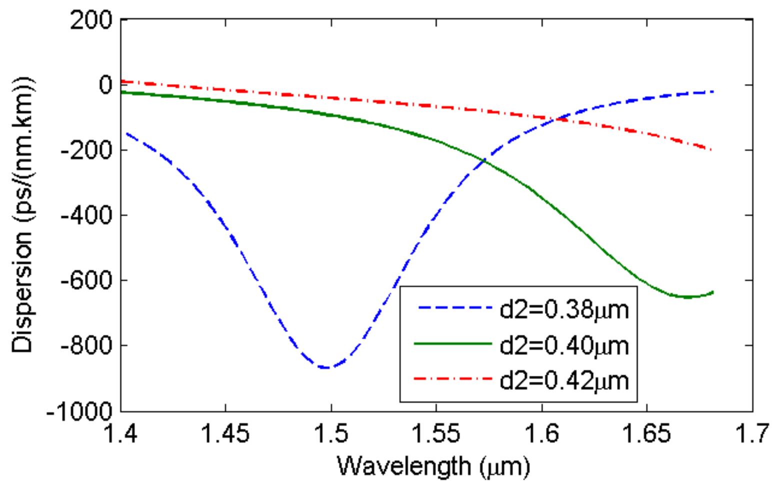

Fig. 12. The effect of the change in the diameter of the holes of the outer core on the dispersion profile.

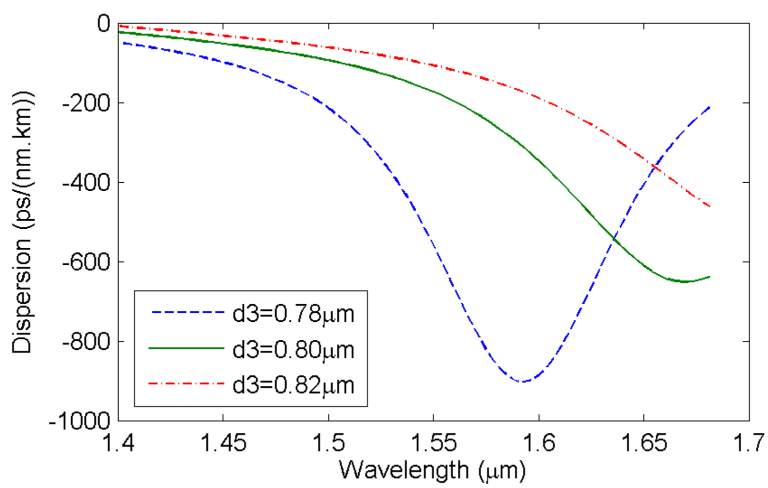

Fig. 13. The effect of the change in the diameter of the holes of the outer clad on the dispersion profile.

An increase in the diameter of the circular holes of the inner clad to 0.98μm results in a relatively flat dispersion profile. This structure, throughout the E to U telecommunication bands (from 1.360 to 1.675μm), has a dispersion variation of 46ps/(nm.km) (from a dispersion coefficient of -239ps/(nm.km) to -285ps/(nm.km)), and throughout the S to C telecommunication bands (from 1.460 to 1.565μm), it has a dispersion variation of 17ps/(nm.km) (from a dispersion coefficient of -258ps/(nm.km) to -275ps/(nm.km).

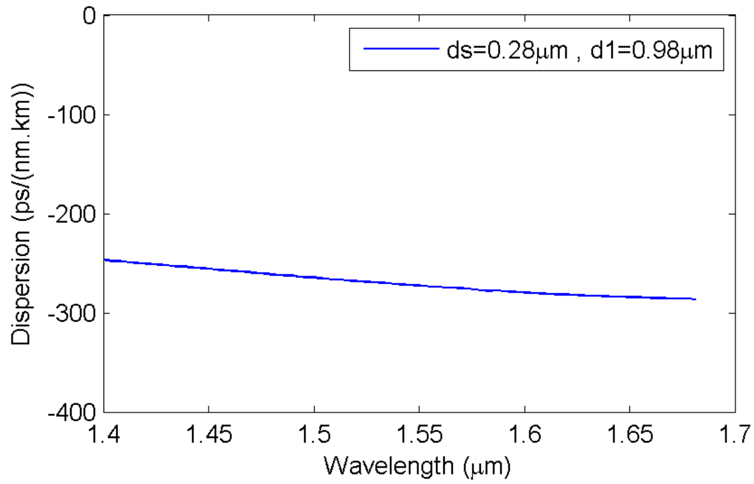

Fig. 14. A relatively flat dispersion profile with the diameter of the circular holes of the inner clad 0.98μm.

IV. CONCLUSION

In this paper, a new structure has been presented for dispersion compensating photonic crystal fibers to broaden the dispersion compensation band, effectively. Placing a combination of the circular holes and the star structure in the inner clad of the fiber causes the dispersion profile to get broadened. Also, this photonic crystal fiber comprising a negative dispersion coefficient in the whole S to U and a part of E telecommunication bands. This structure, compared to the similar structures presented earlier, is capable of dispersion compensation in a wider wavelength range; for example, it includes a wider wavelength range compare to the square lattice DCF presented by Siddique et al (2014). Also, it includes a wider wavelength range and a more negative dispersion coefficient compare to the square lattice structure presented by Ehteshami et al (2012). The minimum dispersion coefficient of this structure is -653ps/(nm.km), and the dispersion coefficient is calculated to be -176ps/(nm.km) at wavelength 1.55μm. With an increase in the diameter of the circular holes of the inner clad to 0.98μm, a relatively flat dispersion profile is obtained. This structure, throughout the E to U telecommunication bands (from 1.360 to 1.675μm), has a dispersion variation of 46ps/(nm.km) (from a dispersion coefficient of -239ps/(nm.km) to -285ps/(nm.km)), and throughout the S to C telecommunication bands (from 1.460 to 1.565μm), it has a dispersion variation of 17ps/(nm.km) (from a dispersion coefficient of -258ps/(nm.km) to -275ps/(nm.km)).

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