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Ultra High Birefringent Hexagonal Photonic Crystal Fibers with Ultra Low Confinement Loss Employing Different Sizes of Elliptical Air Holes in the Core

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ABSTRACT

In this paper a hexagonal microstructure photonic crystal fiber (PCF) is proposed for achieving both ultra high birefringence and large nonlinearity in a high speed transmission system. The full vector Finite Element Method (FEM) is used to study the characteristics of our proposed PCF. In this structure, circular air holes are arranged in the cladding and elliptical air holes are arranged in the core region. According to simulation, the proposed PCF structure has ultra high birefringence of 4.048×10^{-2}, negative dispersion coefficient of - 817.3 ps/(nm.km) and nonlinear coefficient of 67.9 $W^{-1}km^{-1}$ at 1550 nm wavelength. Due to ultra high birefringence, large nonlinearity and low dispersion, the proposed structure can be used for sensing, super-continuum generation and dispersion compensation, respectively.

Keywords: Photonic crystal fiber; Nonlinear coefficient; Ultra-high birefringence

1. Introduction

In recent years, Photonic crystal fiber have drawn significant attention due to their extraordinary optical properties such as ultra high birefringence, large effective mode area, large nonlinearity and low confinement loss [1-12] as compared to conventional fiber. Recently, many articles with different types of air holes arrangements are proposed for achieving high birefringence characteristics [13-14]. For example, Chen et al. have proposed an ultrahigh birefringent PCF of 1.5×10^{-2} by arranging elliptical air holes as hexagonal lattice in the fiber core but circular air holes as hexagonal lattice in the fiber cladding [13]. Wang et al. have designed

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highly birefringence PCF (1.83×10^{-2}) with rectangular air holes in the core region [14]. Recently we reported high birefringence of 3.37×10^{-2} by using four elliptical air holes and two semi circular air holes in the core region [15].

In high speed transmission systems and wavelength division multiplexing (WDM) dispersion is one of the major problem due to pulse broadening. Dispersion compensating fiber (DCF) is used to maintain the dispersion. Photonic crystal fibers have much flexibility for controlling the dispersive properties by changing the size of air-holes [16-19]. Conventional fiber offers negative dispersion coefficient of - 100 to – 300 ps/(nm.km) at operating wavelength of 1550 nm [20]. So far, several attempts have been taken by different groups to achieve high negative dispersion as well as low confinement loss. For example, Razzak et. Al. have reported an Octagonal MOF structure with negative dispersion coefficient of - 239.5 ps/(nm.km) and a hexagonal MOF structure with negative dispersion coefficient of - 562 ps/(nm.km) [21]. Habib et al. have designed a hexagonal PCF which offers negative dispersion coefficient of - 300 ps/(nm.km) at operating wavelength of 1550 nm [22].

Furthermore, highly birefringent PCFs with nonlinear properties have received much attention in sensing and super-continuum (SC) applications. In this paper, we propose a ultra high birefringence (4.048×10^{-2} at 1550 nm) photonic crystal fiber with large nonlinearity of $67.9W^{-1}km^{-1}$, low dispersion of - 817.3 ps/(nm.km) and ultra low confinement loss of 1.861×10^{-10} dB/m by introducing six elliptical air holes as hexagonal lattice in the core region, which is suitable for the application of high bit rate transmission network, sensing and super-continuum generation. In this study, the finite element method with perfectly matched boundary layer condition is used to analyze the various properties of PCF.

2. Design Methodology

Fig. 1 exhibits the distribution of air holes of the proposed PCF with elliptical air holes in the

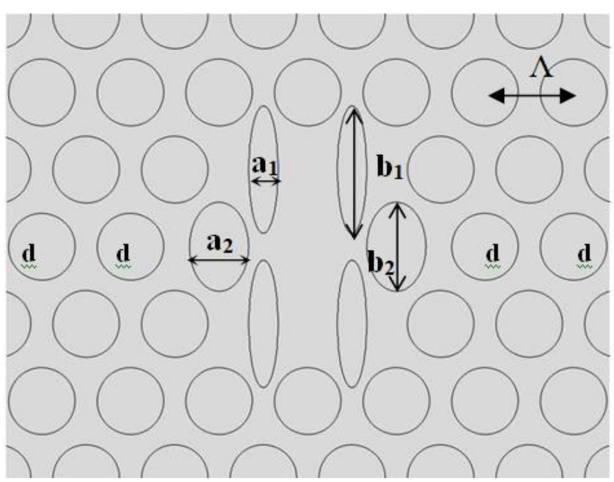


Fig. 1 Transverse cross section of proposed PCF where, pitch Λ=0.9µm, air hole diameter d/Λ=0.75 and for elliptical air holes a_1/Λ =0.15, b_1/Λ=0.64, a_2/Λ =0.3 & b_2/Λ=0.45

core region which is designed using the tool Comsol 4.2. The structure has a hexagonal lattice of circular air holes in the cladding region. Where *d* is the air hole diameter of the 2^{nd} to 8^{th} ring. In PCF, air hole to air hole spacing is called pitch, which is represented by Λ. The key material in our proposed structure is fused silica. To control the birefringence six elliptical air holes are proposed in the first ring with major axis $b_1/\Lambda = 0.64$ and $b_2/\Lambda = 0.45$, & the minor axis $a_1/\Lambda= 0.15$ and $a_2/\Lambda= 0.3$. The outer region is designed with circular air holes with diameter d=0.75Λ.

3. Numerical Method

The To calculate the confinement loss, chromatic dispersion, effective area and nonlinear coefficient of the proposed PCFs, Finite Element Method (FEM) with perfectly matched layers (PML) boundary condition is used. We used Commercial full-vector finite-element software (COMSOL) 4.2 to find an accurate solution to boundary value problem. The effective refractive index corresponding to the operating wavelength of the fused silica is given by the following equation, known as Sellmeier equation.

$$n^2 - 1 = \sum_{k=1}^{3} \frac{b_k \lambda^2}{\lambda^2 - \lambda_k^2}$$

Where b_k is the Sellmeier coefficient.

Dispersion is a common phenomenon in all type of fibers. For high speed transmission system, one of the major limiting factors is chromatic dispersion due to pulse broadening. The birefringence *B*, chromatic dispersion *D(λ)*, and confinement loss L_c can be calculated by the following equations [23].

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

$$L_c = 8.686 \times \mathrm{k}_0 \mathrm{Im}[\mathrm{n}_{\mathrm{eff}}] \times 10^3\, dB/km \tag{2}$$

$$B = \left| n_x - n_y \right| \tag{3}$$

where, n_x and n_y are the effective refractive index of x polarization and y polarization fundamental mode respectively, Re[n_{eff}] and Im[n_{eff}] is the real part and imaginary part of effective refractive index n_{eff} respectively, k_0 is the free space number, λ is the wavelength in vacuum, and c is the velocity of light in vacuum.

The effective area A_{eff} of a photonic crystal fiber is expressed as [24]:

$$A_{eff} = (\iint |E|^2 dxdy)^2 / \iint |E|^4 dxdy \tag{4}$$

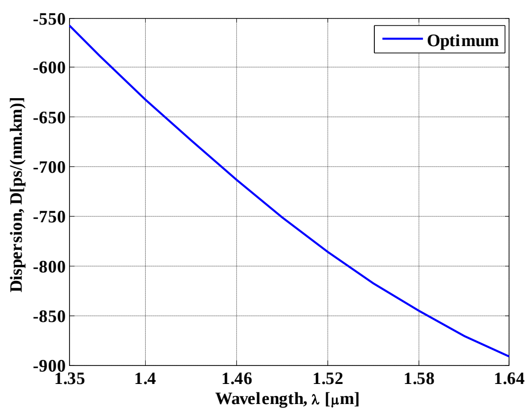
where, A_{eff} is the effective mode area in μm^2. Effective area is important for studying nonlinear case in optical fiber, microcavity [25-27] as well as photonic crystal fiber. The strength of nonlinearity in a photonic crystal fibers is the ratio between the nonlinear refractive index coefficient, n_2 (Kerr constant), and the effective area for a given wavelength. The effective mode area, A_{eff} is inversely proportional to the nonlinear coefficient, γ and can be expressed as follows [28]:

$$\gamma = (\frac{2\pi}{\lambda})(\frac{n_2}{A_{eff}}) \tag{5}$$

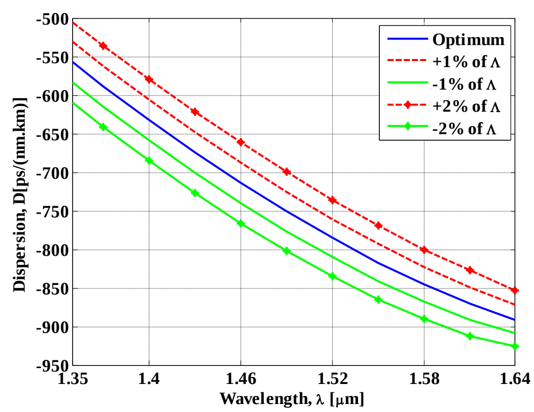
Depending on PCF structure and use of different materials, enhanced nonlinearity can be achieved.

4. Simulation Results and Discussions

Fig. 2 shows the chromatic dispersion characteristics as a function of wavelength of both x and y polarization with pitch Λ=0.9μm and d/Λ =0.75, where six elliptical air holes in 1st ring along the y axis is chosen as a_1/Λ =0.15, b_1/Λ=0.64, a_2/Λ =0.3 & b_2/Λ=0.45. From figure it has been observed that, our proposed PCF demonstrates large negative value of dispersion coefficient about – 817.3 ps/(nm.km) along the y polarization at operating wavelength 1550 nm. Due to large negative value of dispersion coefficient as compared with conventional fiber, our proposed PCF could be suitable contender for dispersion compensating in high speed transmission system.



(a)



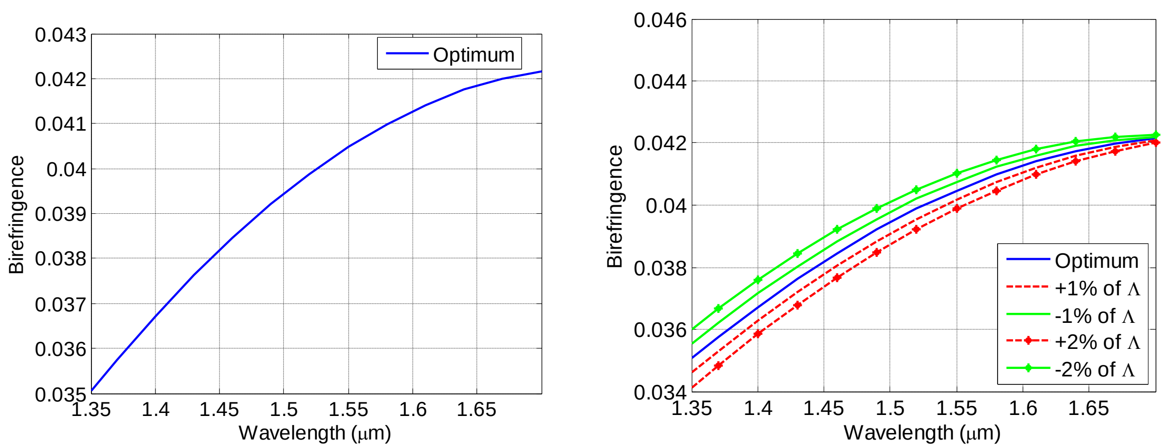
(b)

Fig. 2 (a) Wavelength dependence dispersion curve for slow axis (b) Effect of dispersion by varying the value of pitch Λ from ± 1% to ± 2%

In PCF, during fabrication process ± 1% variation in pitch may be considered [29]. By considering fabrication difficulty, we have studied the impact on birefringence and dispersion by varying air hole to air hole spacing ± 1% to ± 2%, which is also discussed in this paper in the following section.

Fig. 2(b) shows the effect of chromatic dispersion by varying the value of pitch Λ from ± 1% to ± 2%, while other parameters are kept constant. It has been observed that the value of dispersion is increased negatively with decrease in the global diameter of pitch Λ. For the variation of pitch, Λ of +1%, the dispersion is -517.3 ps/(nm.km) at 1.34 μm and -871.9 ps/(nm.km) at 1.64 μm. At, 1.55 μm for the variation of pitch Λ of +1%, a dispersion of -793.1 ps/(nm.km) is obtained. The proposed structure offers optimum dispersion of -817.3 ps/(nm.km) at operating wavelength of 1550 nm.

Fig. 3(a) indicates the modal birefringence characteristics of the proposed PCF as a function of wavelength with the pitch 0.9 μm. From the figure it is observed that our proposed PCF shows ultra high birefringence about 4.048×10^{-2} at wavelength 1550 nm. Our proposed PCF is very effective in signal processing and sensing applications, and more specifically in high speed optical communication system due to having ultra high birefringence. The impact of pitch on birefringence is also shown in fig. 3(b). It can also be noted from figure that birefringence increases with the air hole to air hole spacing decreases, which is important for the application of polarization maintaining fiber. However, current conventional polarization maintaining fibers show a modal birefringence about 5×10^{-4} [30]. Moreover our proposed hexagonal PCF offer ultra high birefringence about 4.048×10^{-2} at the operating wavelength of 1550 nm, which could be a suitable choice in sensing applications.

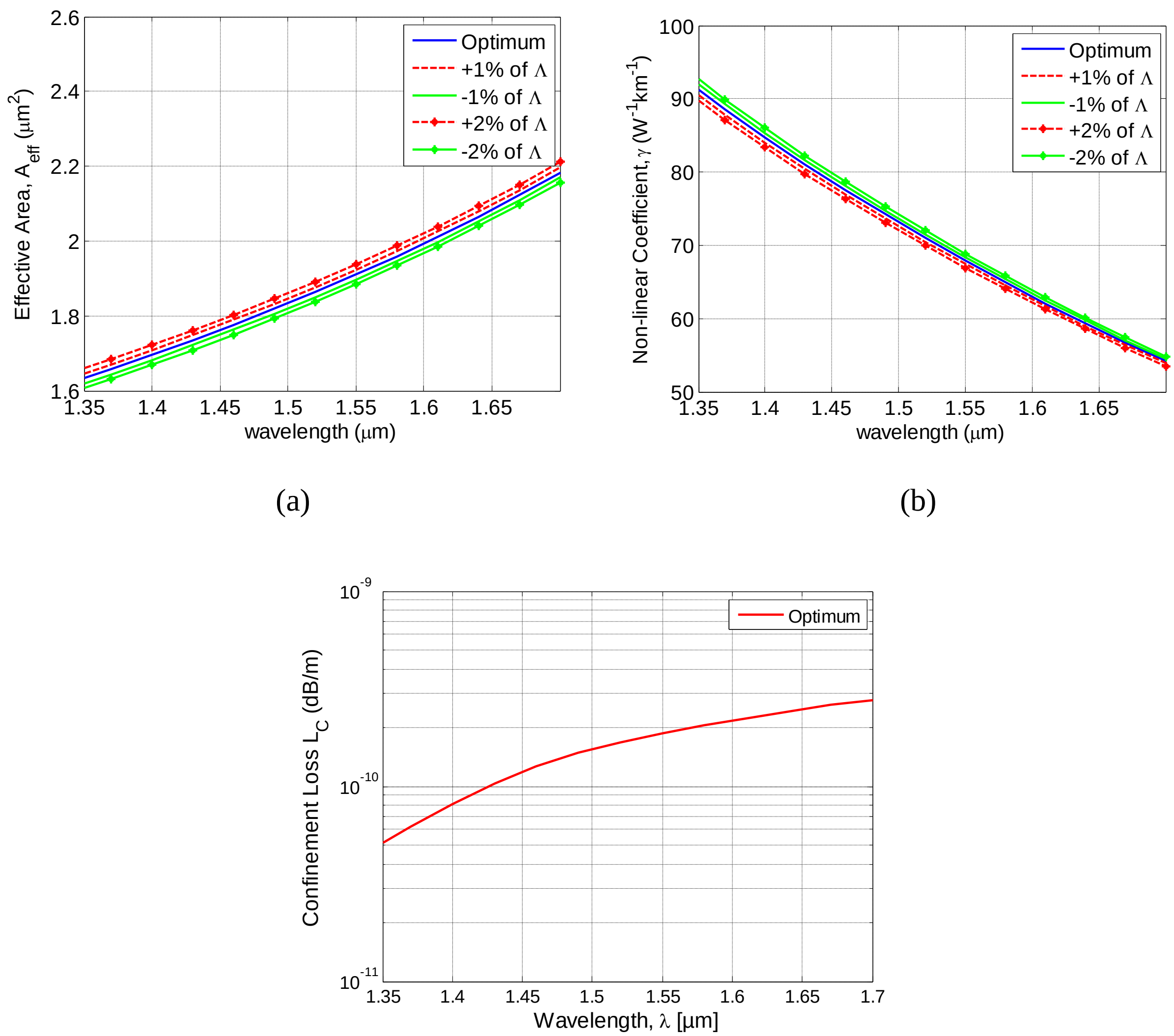


(a) (b)

Fig. 3 Birefringence as a function of wavelength for (a) optimum design parameters (b) by varying the value of pitch Λ from ± 1% to ± 2%

Fig. 4(a) and 4(b) shows the effects of pitch variation on effective area and nonlinearity for wavelength range 1.34 μm to 1.7 μm. The optimum value of effective mode area of the proposed PCF is 1.91 μm^2 at 1550 nm wavelength. The effective area increases with increase in the pitch. At 1550 nm the effective area is calculated to be 1.924 μm^2, 1.938 μm^2, 1.897 μm^2, and 1.885 μm^2 for the variation of pitch +1%,+2%, -1%, and -2%, respectively.

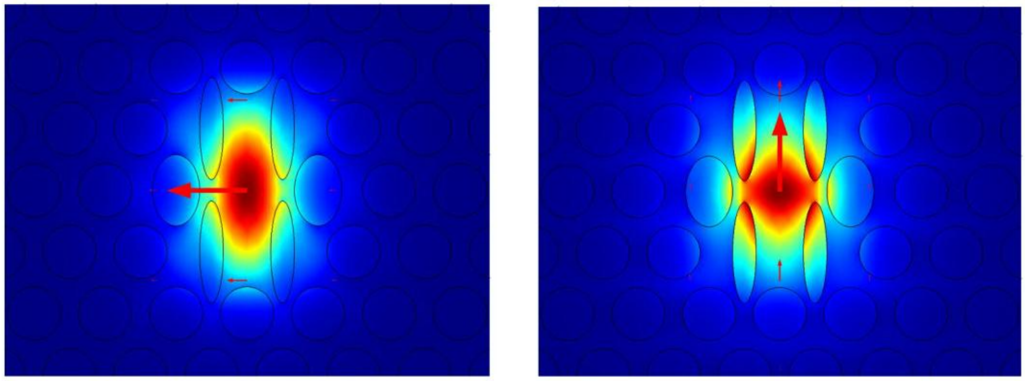
The proposed structure shows large nonlinearity as effective area is inversely proportional to nonlinearity. Large nonlinearity of $67.9 W^{-1}km^{-1}$ is achieved at 1550 nm wavelength which increases with decreasing the air hole to air hole spacing. The large value of nonlinearity is remarkably well enough for the application of super continuum generation [25].



(a) (b) (c)

Fig. 4 (a) Wavelength dependence effective area (b) nonlinear coefficient (c) confinement loss curve of our proposed H-PCF for optimum design parameters

Fig.4(c) shows the wavelength dependence properties of confinement loss with the optimum parameter of the pitch 0.9 μm. The confinement loss is very small in the order of 10^{-10} for the proposed structure. At 1550 nm wavelength, the optimum value of confinement loss is 1.861×10^{-10} dB/m. The obtained value of confinement loss is better than in [13].



(a) (b)

Fig. 5 The optical Field distributions of fundamental modes at 1550 nm for (a) x-polarization and (b) y-polarization

Fig. 5 shows the electric field distribution of our proposed PCF with pitch 0.9 μm at the excitation wavelength of 1.55μm for both x and y polarization modes. It is clearly seen from fig. 5. that both x and y polarization modes are strongly confined inside the core region due to that the core of our proposed structure is more effectively enclosed by the 1st ring elliptical air holes.

Thus our proposed design is unique as compared with others design because rectangular PCF have higher birefringence, compared to our results, but the confinement loss reported in our case is very small and low dispersion is obtained. We also found large nonlinearity in our proposed PCF. The combination of large nonlinearity and low dispersion is an added advantage for the generation of super-continuum.

Table 1 Comparison between properties of the proposed PCF and other PCF at 1550 nm

PCFs	**Comparison of modal properties**			
	D(λ) Ps/(nm.km)	**B=$\|n_x – n_y\|$**	**A_{eff} (μm^2)**	**γ ($W^{-1}km^{-1}$)**
Ref. [22]	-300	------	1.55	----
Ref. [30]	-588	$1.81×10^{-2}$	3.41	------
Ref. [31]	-474.5	------	1.60	------
Ref. [32]	-562	$3.06×10^{-2}$	2.08	63.3
Ref. [33]	-----	$1.75×10^{-2}$	3.248	39.933
Proposed PCFs	- 817.3	$4.048×10^{-2}$	1.91	67.9

5. Conclusion

In conclusion, we have proposed a novel hexagonal PCF to obtain both ultra-high birefringence and large nonlinearity with low confinement loss. From the numerical results, negative dispersion coefficient of about – 543.2 to – 891 ps/(nm.km) is successfully achieved for wavelength range 1.34 μm to 1.7 μm. The noble feature of our proposed designed fiber is that it offers ultra high birefringence as 4.048×10^{-2} along with the property of large nonlinearity of about 67.9 $W^{-1}km^{-1}$ and relatively very small confinement loss of about 1.861×10^{-10} dB/m at the operating wavelength of 1550 nm. Due to having ultra high birefringence, large nonlinearity and low confinement loss, our proposed PCF would be a suitable candidate for nonlinear optical applications including sensor applications, super-continuum generation, dispersion compensation and high bit rate transmission network.

References

[1] Abdullah, M. I. H., Hasan, M. I., Rahman, M. N. A., & Aseer, M. (2017). Ultra-high Birefringent Photonic Crystal Fiber for Sensing Applications. Asia Pacific J. Eng. Sci. Tech., 3(3), 121-128.

[2] Biswas, S. K., Hasan, M. I., Awsaf, M. A., Rahman, M. N. A., Iqbal, M., Abdullah, H., & Mia, M. M. A. (2017). Design and Analysis of Hexagonal Photonic Crystal Fiber with Ultra-high Birefringent and Large Negative Dispersion Coefficient for the Application of Sensing and Broadband Dispersion Compensating Fiber. Asian J. Appl. Sci. Tech., 1(8), 147-151.

[3] Hasan, M. I., Awsaf, M. A., Rahman, M. N. A., Abdullah, M. I. H., Mia, M. M. A., & Biswas, S. K. (2017). Proposal for Ultra-high Birefringent Photonic Crystal Fiber with Ultra-low Confinement Loss, Large Negative Dispersion and Large Nonlinearity. Asian J. Appl. Sci. Tech., 1(8), 152-156.

[4] S. M. Rakibul Islam, Md. Monirul Islam, Md. Nafiz Ahbabur Rahman, Mohammad Mahmudul Alam Mia, Md Shahrier Hakim, and Shovasis Kumar Biswas. (2017). Design of Hexagonal Photonic Crystal Fiber with Ultra-High Birefringent and Large Negative Dispersion Coefficient for the Application of Broadband Fiber. Int. J. Eng. Sci. Tech., 2(1), 9-16.

[5] Md. Iqbal Hossain Abdullah, Md. Ishtiaq Hasan, Md. Nafiz Ahbabur Rahman, Md. Aseer Awsaf, Mohammad Mahmudul Alam Mia, & Md Shahrier Hakim. (2017). Proposal for an Ultra-high Birefringent Photonic Crystal Fiber with Large Nonlinearity. Int. J. Advance Research Innovative Ideas in Edu., 3(4), 2931-2937.

[6] Ju, Jian, Wei Jin, and M. S. Demokan. "Properties of a highly birefringent photonic crystal fiber." IEEE Photonics Technology Letters 15.10 (2003): 1375-1377.

[7] Yi, N., Liang, A., Yuejian, X., Lei, Z., & Jiangde, P."Confinement loss in solid-core photonic bandgap fibers." Optics communications, 235.4 (2004): 305-310.

[8] Razzak, SM Abdur, Y. Namihira, and F. Begum. "Ultra-flattened dispersion photonic crystal fibre." Electronics Letters 43.11 (2007): 615-617.

[9] Saitoh, Kunimasa, Nikolaos Florous, and Masanori Koshiba. "Ultra-flattened chromatic dispersion controllability using a defected-core photonic crystal fiber with low confinement losses." Optics Express 13.21 (2005): 8365-8371.

[10] Liang, J., Yun, M., Kong, W., Sun, X., Zhang, W., & Xi, S. "Highly birefringent photonic crystal fibers with flattened dispersion and low effective mode area." Optik Int. J. Light and Electron Optics 122.23 (2011): 2151-2154.

[11] Hu, D. J. J., Shum, P. P., Lu, C., & Ren, G."Dispersion-flattened polarization-maintaining photonic crystal fiber for nonlinear applications." Optics Communications 282.20 (2009): 4072-4076.

[12] Hao, R., Li, Z., Sun, G., Niu, L., & Sun, Y."Analysis on photonic crystal fibers with circular air holes in elliptical configuration." Optical Fiber Technology 19.5 (2013): 363-368.

[13] Chen, Daru, and Linfang Shen. "Ultrahigh birefringent photonic crystal fiber with ultralow confinement loss." IEEE Photonics Technology Letters 19.4 (2007): 185-187.

[14] Wang, W., Yang, B., Song, H., & Fan, Y. "Investigation of high birefringence and negative dispersion photonic crystal fiber with hybrid crystal lattice." Optik-International Journal for Light and Electron Optics 124.17 (2013): 2901-2903.

[15] Halder, Amit, and Shaik Asif Hossain. "Design of Ultra-high Birefringent Broadband Dispersion Compensating Photonic Crystal Fiber for High Speed Transmission System." Imperial Journal of Interdisciplinary Research 2.3 (2016): 211-217.

[16] Razzak, S. A., Namihira, Y., & Begum, F. (2007). Ultra-flattened dispersion photonic crystal fibre. Electronics Letters, 43(11), 615-617.

[17] M. Koshiba and K. Saitoh, " Structural dependence of effective area and mode field diameter for holey fibers", Opt. Express 11 (2003) 1746-1756.

[18] S. M. A. Razzak and Y. Namihira , ‘‘Proposal for highly nonlinear dispersion- flattened octagonal photonic crystal fibers," IEEE photon. Technol. Lett., 20 (2008) 249-251.

[19] K. Saitoh , M. Koshiba , T. Hasegawa and E. Sasaoka, "Chromatic dispersion control in photonic crystal fibers: application to ultraflattened dispersion,"Opt. Exp., 11 (2003) 843-852.

[20] J. Laegsgaard, S. E. BarkouLibori, K. Hougaard, J. Riished, T. T. Lasen, and T. Sorensen, ‘‘Dispersion Properties of photonic crystal fibers- issues and opportunities," Mater. Res. Soc. Symp. Proc., (2004) 797.

[21] S. F. Kaijage , Y. Namihira, N. H. Hai , F. Begum , S. M. A. Razzak, T. Kinjo, K. Miyagi and N. Zou, ‘‘Broadband dispersion compensating octagonal photonic crystal fiber for optical communication apllications,"Japan. J. of Appl. Phy., vol.48, 052401-052408, 2009.

[22] M. Selim Habib , M. Samiul Habib , S. M. A. Razzak , Y. Namihira, M.A. Hossain and M. A. G. khan , "Broadband dispersion compensation of conventional single mode fibers using microstructure optical fibers," Optik, (doi.org/10.1016/j.ijleo.2012.12.014), Feb 2013.

[23] M. Selim habib, M. Samiul Habib, S. M. A. Razzak, M. I. Hasan, R. R. Mahmud and Y. Namihira, ‘‘Microstructure holey fibers as wideband dispersion compensating media for high speed transmission system," Optik (2013)

[24] Guo, S., Wu, F., Albin, S., Tai, H., & Rogowski, R. (2004). Loss and dispersion analysis of microstructured fibers by finite-difference method. Optics Express, 12(15), 3341-3352.

[25] Biswas, S. K., & Kumar, S. (2015). Impact of Kerr nonlinearity on the whispering gallery modes of a microsphere. Optics express, 23(20), 26738-26753.

[26] Biswas, Shovasis. Impact of Kerr and Raman nonlinear effects on the whispering gallery modes of a spherical microcavity. Diss. 2016.

[27] Kumar, S., & Biswas, S. K. (2016). Impact of Kerr nonlinearity and stimulated Raman scattering on the whispering gallery modes of an optical microsphere. JOSA B, 33(8), 1677-1687.

[28] Poli, F., Cucinotta, A., Selleri, S., & Bouk, A. H. (2004). Tailoring of flattened dispersion in highly nonlinear photonic crystal fibers. Photonics Technology Letters, IEEE, 16(4), 1065-1067.

[29] W. H. Reeves, J. C. Knght and P. S. J. Russell, ‘‘Demonstration of ultraflattened dispersion in photonic crystal fibers," Opt. exp., 10(2002) 609-613.

[30] M. Selim Habib , M. Samiul Habib , S. M. A. Razzak and M. A. Hossain, ‘‘Proposal for highly birefringent broadband dispersion compensating octagonal photonic crystal fiber," Opt. Fiber Technol., (dx.doi.org/10.1016/j.yofte.2013.05.014), May 2013.

[31] L .P. Shen , W. P. Huang , G. X. Chen and S. S. Jian , "Design and optimization of photonic crystal fibers for broadband dispersion compensation," IEEE Photon. Technol. Lett., 15(2003) 540-542.

[32] Ahmad, R., Siddique, A. H., Ali, M. S., Islam, A., Nasim, K. M., & Habib, M. S. (2014, February). Design of a photonic crystal fiber for dispersion compensation over telecommunication bands. In Electrical Information and Communication Technology (EICT), 2013 International Conference on (pp. 1-5). IEEE.

[33] J. Mondal, M. S. Rahman, " Design of highly birefringent dispersion compensating spiral photonic crystal fiber" in 2nd Int'l Conf on Electrical Engineering and Information & Communication Technology (ICEEICT) 2015, Bangladesh.