

DESIGN OF HEXAGONAL PHOTONIC CRYSTAL FIBER WITH ULTRA-HIGH BIREFRINGENT AND LARGE NEGATIVE DISPERSION COEFFICIENT FOR THE APPLICATION OF BROADBAND FIBER

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ABSTRACT

The purpose of this paper is to design a hexagonal microstructure photonic crystal fiber (PCF) which gives ultra-high birefringence and very low confinement loss for sensing application. To characterize the modal properties of the proposed photonic crystal fiber, finite element method is used. We found ultra-high birefringence of 3.34×10^{-2} at operating wavelength 1550nm by using simulation software comsol multiphysics. Our proposed PCF gives large value of nonlinear coefficient of $63.51 \text{ W}^{-1}\text{km}^{-1}$, large value of negative dispersion coefficient of $-566.6 \text{ ps}/(\text{nm.km})$, and also ultra-low confinement loss which is in the order of 10^{-7} .

Keywords: Photonic Crystal Fiber (PCF); Ultra-High Birefringence; Nonlinear Coefficient.

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1. INTRODUCTION

Nowadays the researchers are very interested in photonic crystal fibers (PCFs) because of their remarkable characteristics such as large nonlinearity, high birefringence and large negative value of dispersion, because its design parameter is flexible than ordinary optical fiber. Recently for the application of sensing and high bit rate communication system lots of research paper are published [1-11]. Birefringence is one of the most interesting characteristics among the features of PCFs. By getting large index difference and flexible photonic crystal fibers design high birefringence can easily establish. Up to now, various designs of highly birefringent PCFs have been reported. Different types of air hole arrangement in the core as well as cladding are presented for achieving ultra- high birefringence. A high birefringence of 1.83×10^{-2} , by using the

complex unit cells in cladding the photonic crystal fiber (PCF) has been proposed by Wang et.al [9].

So many attempts have been taken to achieve ultra- high birefringence and large negative dispersion by different groups. With the high birefringence of 1.67×10^{-2} and large value of negative dispersion of -239.5 ps/ (nm.km) an octagonal MOF have been offered. Another group also offered a new PCF structure with large value of negative dispersion of -300 ps/ (nm.km) without considering birefringence. A new design which covers all three communication band designed by Matusi et al. but it needs large fiber for dispersion compensation because of its low dispersion value [12]. Besides in sensing and application of super-continuum (SC) ultra-high birefringence photonic crystal fiber including large nonlinearity have draw a very good awareness. For SC generation along with the fiber the well-preserved polarization is an exceptional feature because to enhance nonlinear interaction less power is needed [13].

This paper offers hexagonal photonic crystal fiber which has circular air-holes in the fiber cladding which cause simplification of the fabrication process. Our proposed structure leads in the design flexibility accompanying ultra-high birefringence and large nonlinearity for sensing application. The photonic crystal fiber we offered has a large negative dispersion value, which is very significant for high-bit-rate communication network. Also in our proposed PCF we have used circular air holes in the cladding region to make less complexity of fabrication process. After simulating we found, The PCF presents ultra-high birefringence of 3.34×10^{-2} and large negative dispersion of -566.6 ps/ (nm.km) at excitation wavelength 1550 nm.

2. MATERIALS AND METHODS

In fig. 1 the proposed photonic crystal fiber air hole distribution contains five air hole layers. First layer made up with elliptical and semicircular air holes and second, third, fourth and fifth layers made up with circular air holes. To obtain ultrahigh birefringence and large nonlinearity semicircular and elliptical air holes is used. The diameters of air holes of three rings are equal expressed by d_1 in the proposed PCF which consists of five rings. In our proposed design we used silica as a principle material and air holes are sorted in hexagonal shape. Six air holes in first ring along the y axis construct in elliptical shape to get high birefringence. Major axis of

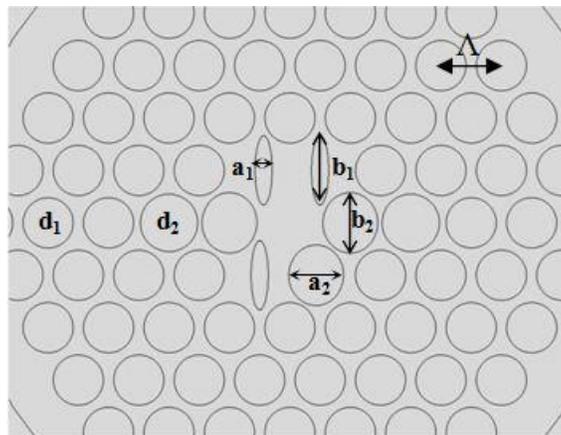


Figure 1: Transverse cross section of proposed H-PCF where, $\Lambda=0.91\mu\text{m}$, $d_1/\Lambda=0.83$, $d_2/\Lambda=0.95$, for elliptical air holes $a_1/\Lambda=0.26$ & $b_1/\Lambda=1$, $a_2/\Lambda=0.83$ & $b_2/\Lambda=0.91$.

Elliptical air holes are denoted as $a_1/\Lambda=0.26$, $a_2/\Lambda=0.83$, and minor axis of six elliptical air holes are denoted as $b_1/\Lambda=1$ & $b_2/\Lambda=0.91$. We get negative characteristic of dispersion because of pitch value is $\Lambda=0.91\mu\text{m}$. To improve the birefringence property all elliptical air holes are used at the core region. Fiber silica's refractive index is 1.45 and air hole's refractive index is 1.

3. NUMERICAL METHOD

To investigate of our proposed hexagonal photonic crystal fiber properties we used finite element method (FEM). Boundary condition of circular perfectly matched layers (PML) is used to achieve the numerical simulation. We used COMSOL- Commercial full-vector finite-element software 4.2 to determine the birefringence, confinement loss and dispersion properties of our proposed PCF. By using Sellmeier equation the refractive index of silica can be obtained. We used silica as our background material in our offered hexagonal PCF. Chromatic dispersion $D(\lambda)$, confinement loss L_c and birefringence B can be determined by the given equations [14].

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

$$L_c = 8.686 \times k_0 \text{Im}[n_{\text{eff}}] \times 10^3 \text{ dB/km}$$

$$B = |n_x - n_y|$$

where, $\text{Re}[n_{\text{eff}}]$ and $\text{Im}[n_{\text{eff}}]$ is real part and imaginary part of effective refractive index n_{eff} , respectively, λ is the wavelength in vacuum, c is the light velocity in vacuum and free space wave number is k_0 .

In the below the effective mode area A_{eff} is established [15]:

$$A_{\text{eff}} = (\iint |E|^2 dx dy)^2 / \iint |E|^4 dx dy$$

Here, the effective mode area A_{eff} in μm^2 and electric field amplitude is E in the medium. For studying nonlinear case of optical fiber, microcavity [16-20] and photonic crystal fiber the effective area is very important. Effective mode area is defined to understand the nonlinear phenomena of photonic crystal fiber. Effective mode area and nonlinearity is inversely proportional to each other i.e light must confined in a short area for better nonlinearity. Photonic crystal fiber nonlinearity can be defined as

$$\gamma = \left(\frac{2\pi}{\lambda}\right) \left(\frac{n_2}{A_{\text{eff}}}\right)$$

4. SIMULATION RESULTS AND DISCUSSIONS

In fig.2 we can see wavelength is depend on dispersion for y polarized mode with optimum design parameters of the proposed design. We set pitch, $\Lambda=0.91\mu\text{m}$, $d_1/\Lambda=0.83$, $d_2/\Lambda=0.95$, for elliptical air holes $a_1/\Lambda=0.26$ & $b_1/\Lambda=1$, $a_2/\Lambda=0.83$ & $b_2/\Lambda=0.91$, in our proposed PCF. In fig.2 we also can see the figure is affected by the variation of global diameter of pitch Λ , $\pm 1\%$ to $\pm 2\%$ while other parameters are kept constant. During fabrication $\pm 1\%$ variation in global diameters may be occurred in PCF [21]. With the consideration of difficulty of fabrication, we analyzed the dispersion effect and birefringence with changing of pitch value from $\pm 1\%$ to \pm

2%. The optimum value of negative dispersion is $-566.6 \text{ ps}/(\text{nm}\cdot\text{km})$ at excitation wavelength 1550nm .

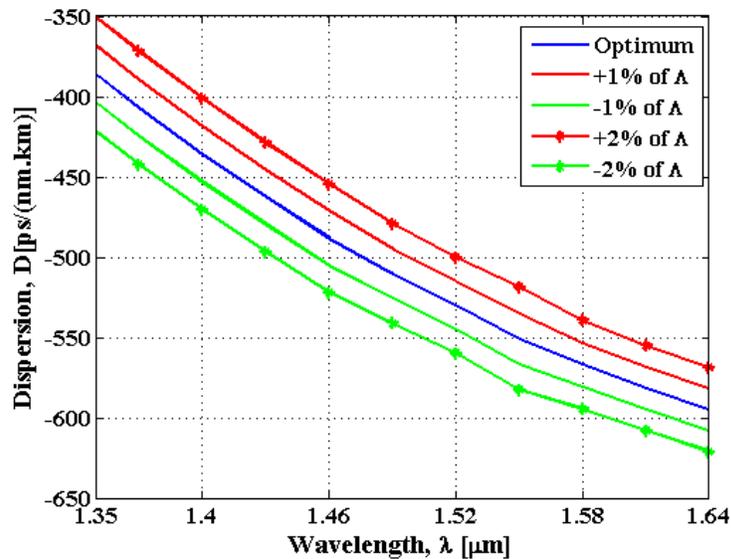


Figure 2: Wavelength dependence dispersion curve for y polarization

Figure 3 shows the ultra-high birefringence characteristics of our proposed design. This figure shows that birefringence about 3.34×10^{-2} at excitation wavelength 1550 nm . The presented design reveals ultra-high birefringence because the asymmetrical design of the core, which is necessary in applications of polarization maintaining. Birefringence at 1550 nm becomes 0.03362 , 0.0343 , 0.03328 and 0.03464 respectively because the variation of the pitch is $\pm 1\%$ to $\pm 2\%$ from ideal value.

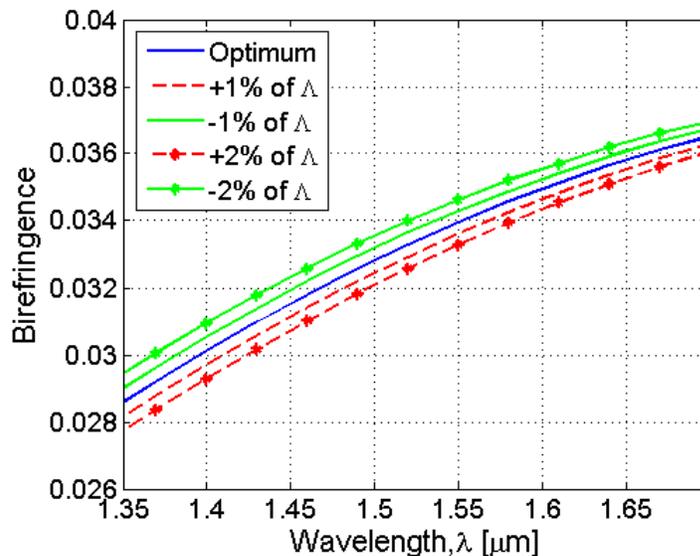
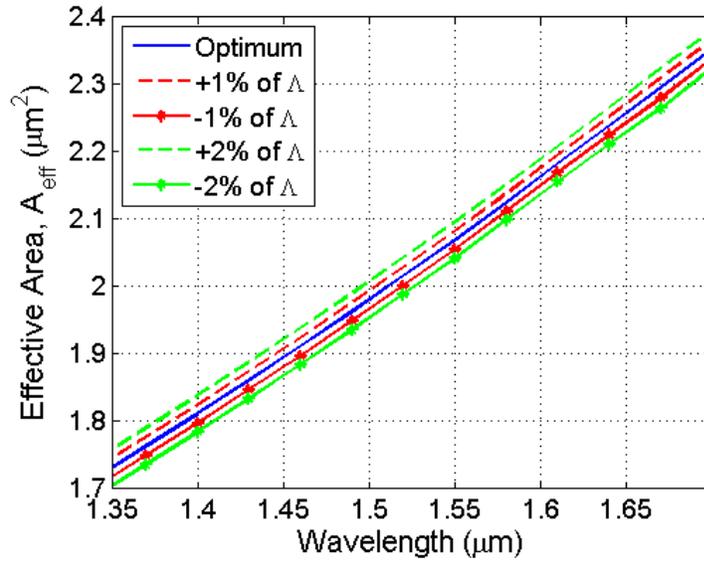
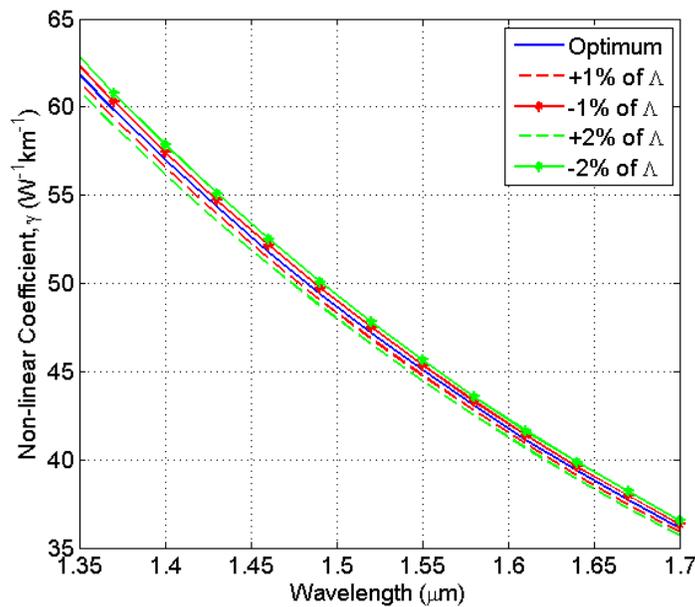


Figure 3: Birefringence as function of wavelength by varying pitch value.

In figure 4(a) shows that our presented PCF viewing small effective mode area. At excitation wavelength 1550 nm the ideal value of effective mode area of the presented H-PCF is $2.069 \mu\text{m}^2$. The nonlinearity vs wavelength for most favorable design parameter in addition with the variation of pitch from $\pm 1\%$ to $\pm 2\%$ shows in figure 4(b). At excitation wavelength 1550nm the result of nonlinear coefficient is $63.51 \text{ W}^{-1}\text{km}^{-1}$. For the sensing and super continuum generation application large nonlinear coefficient value is very well [22].



(a)



(b)

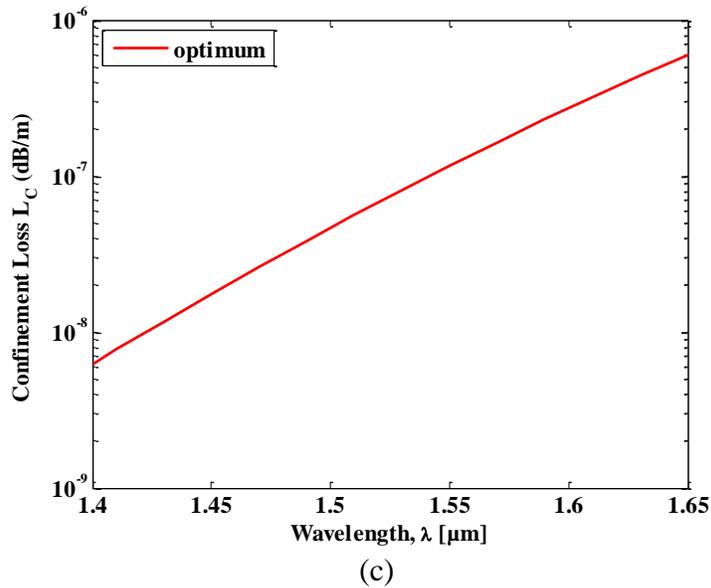


Figure 4: (a) Wavelength dependence effective area (b) nonlinear coefficient (c) confinement loss curve of proposed H-PCF for optimum design parameters

The optimum value of confinement loss of our presented ultra-high birefringence PCF is shown in fig.4 (c) as a function of wavelength. At the wavelength of 1550nm the optimum value of confinement loss is 10^{-7} . With the comparison of ordinary fiber it can easily identify that our presented PCF has excessive low confinement loss. For this reason light is strongly compacted in the central core region.

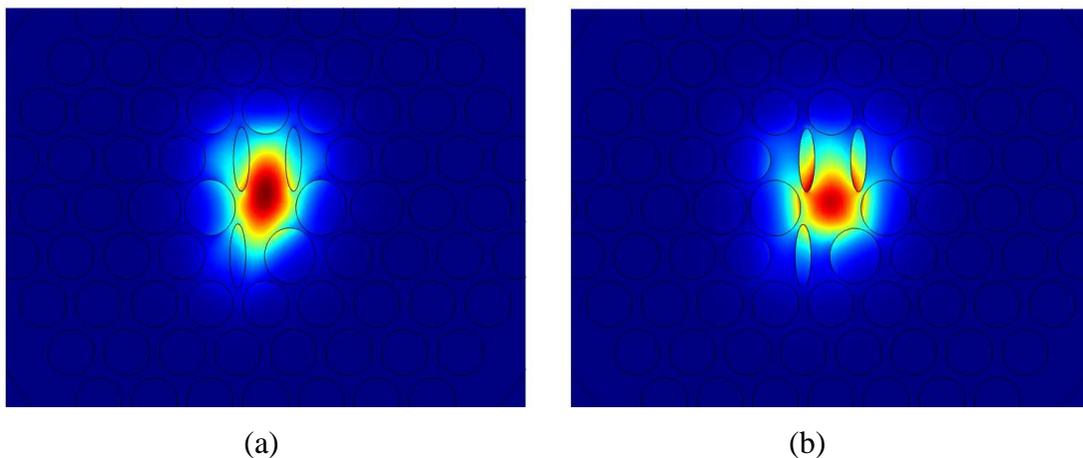


Figure 5: Field distributions of fundamental modes at 1550 nm for (a) x-polarization and (b) y-polarization.

In figure 5 it is shown that the optical field profile for x and y polarization modes at operating wavelength 1550 nm. It can be observed that x and y polarized modes are heavily compacted in the center region of the core because of high-index in the region of the core than the region of the cladding in accordance with numerical simulation.

Comparison between properties of the proposed PCF and other PCFs at 1550 nm is shown in Table 1.

Table 1: Comparison of Modal Properties Between proposed PCF and Other Designs

PCFs	Comparison of modal properties		
	$D(\lambda)$ $Ps/(nm.km)$	$B= n_x-n_y $	A_{eff} (μm^2)
Ref. [9]	-----	1.83×10^{-2}	-----
Ref. [11]	-300	-----	1.55
Ref. [13]	-588	1.81×10^{-2}	3.41
Ref. [21]	-474.5	-----	1.60
Ref. [23]	-----	1.75×10^{-2}	3.248
Ref. [24]	-----	2.62×10^{-2}	-----
Proposed H-PCF	-566.6	3.34×10^{-2}	2.069

5. CONCLUSION

In this paper, a hexagonal microstructure photonic crystal fiber (PCF) has been proposed that simultaneously ensures ultrahigh birefringence for sensing applications and large value of negative dispersion in the broadband telecommunication band. At the operating wavelength of 1550 nm the presented PCF provides high birefringence of 3.34×10^{-2} which is very desirable for the application of sensing. Our designed PCF also offers large negative dispersion coefficient which is -566.6 ps/ (nm.km) and high nonlinearity of $63.51 W^{-1}km^{-1}$. Additionally, our proposed PCF has circular air holes in the cladding region that clarify the process of fabrication much easier.

REFERENCES

- [1] Razzak, S. A., Namihira, Y., & Begum, F. (2007). Ultra-flattened dispersion photonic crystal fibre. *Electronics Letters*, 43(11), 615-617.
- [2] M. Koshiba and K. Saitoh, "Structural dependence of effective area and mode field diameter for holey fibers", *Opt. Express* 11 (2003), 1746-1756.
- [3] 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.
- [4] 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.
- [5] 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.
- [6] L. Gruner- Nielsen, S. N. Knudsen, B. Edvold , T. Veng, D. Magnussen, and C. C. Larsem, "Dispersion compensating fibers," *Opt. Fiber Technol.*, (2000), 164.
- [7] S .G. Li, X. D. Liu, L. T. Hou, "Numerical study on dispersion compensating property in photonic crystal fibers," *Acta Phys. Sin.*, (2004) 1880.

- [8] Z. W. Tan, T. G. Ning, Y. Liu, Z. Tong and S. S. Jian, "Suppression of the interactions between fiber gratings used as dispersion compensators in dense wave length division multiplexing systems," *Chin. Phys.*, (2006) 1819-1823.
- [9] 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.
- [10] 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 applications," *Japan. J. of Appl. Phys.*, vol.48, 052401-052408, 2009.
- [11] 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.
- [12] T. Matsui, K. Nakajima and I. Sankawa, "Dispersion Compensation Over All the Telecommunication Bands with Double-Cladding Photonic-Crystal Fiber," *J. Lightw. Technol.* 25, 757-762 (2007).
- [13] Austin, D. (2005). Supercontinuum in axially varying photonic crystal fibres.
- [14] 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).
- [15] 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.
- [16] Biswas, S. K., & Kumar, S. (2015). Impact of Kerr nonlinearity on the whispering gallery modes of a microsphere. *Optics express*, 23(20), 26738-26753.
- [17] Biswas, Shovasis. Impact of Kerr and Raman nonlinear effects on the whispering gallery modes of a spherical microcavity. Diss. 2016.
- [18] 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.
- [19] Siddique A. B. and Biswas S. K. (2015). Performance analysis of bifacial PV module for the integration in static Sea Shell concentrator," *International Conference on Electrical & Electronic Engineering (ICEEE)*, 65-68.
- [20] A Siddique, SK Biswas, S Sinha, a Pal, RK Mazumder (2013). Performance analysis of bifacial PV module for the integration in static Sea Shell concentrator," *International Conference on Informatics, Electronics & Vision (ICIEV)*, 1-6.
- [21] W. H. Reeves, J. C. Knight and P. S. J. Russell, "Demonstration of ultraflattened dispersion in photonic crystal fibers," *Opt. exp.*, 10(2002) 609-613.
- [22] Benabid, F., & Roberts, P. J. (2011). Linear and nonlinear optical properties of hollow core photonic crystal fiber. *Journal of Modern Optics*, 58(2), 87-124.
- [23] Japatosh Mondal, Mohammad Shaifur 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.
- [24] Chowdhury, Shabbir, and Japatosh Mondal. "Designing of a non-zero dispersion shifted fiber with ultra-high birefringence and high non-linearity." *Electrical Engineering and Information Communication Technology (ICEEICT)*, 2016 3rd International Conference on. IEEE, 2016.

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