Results in Physics 10 (2018) 374–378

Contents lists available at ScienceDirect

Results in Physics

journal homepage: www.elsevier.com/locate/rinp

Nanoscale GaP strips based photonic crystal fiber with high nonlinearity and high numerical aperture for laser applications

Bikash Kumar Paul[a,b,c], Md. Golam Moctader[d], Kawsar Ahmed[a,b,*], Md. Abdul Khalek[a]

[a] Department of Information and Communication Technology (ICT), Mawlana Bhashani Science and Technology University (MBSTU), Santosh, Tangail 1902, Bangladesh
[b] Group of Bio-photomatiχ, Bangladesh
[c] Department of Software Engineering (SWE), Daffodil International University, Shukrabad, Dhaka 1207, Bangladesh
[d] Department of Physics, Mawlana Bhashani Science and Technology University, Santosh, Tangail 1902, Bangladesh

ARTICLE INFO

Keywords:
Photonic crystal fiber
Nonlinearity
Numerical aperture
Scattering loss
Power fraction

ABSTRACT

A novel design of circular hybrid photonic crystal fiber (CH-PCF) with highly nonlinearity and high numerical aperture (NA) is introduced in this paper. The numerical simulation results are obtained by employing the finite element method (FEM) and selecting finer mesh. The investigated parameters are nonlinearity, effective area, scattering loss, power fraction and NA for the two fundamental polarized modes. Significant improvement of PCFs in terms of the non-linearity and numerical aperture are demonstrated by carefully investigation of the structure geometrical parameter. The reported design has high nonlinearity of 62448.64 $W^{-1} km^{-1}$ and 63435.74 $W^{-1} km^{-1}$ at the operating wavelength of 1.00 μm along with numerical aperture of 0.783 and 0.784 at the operating wavelength of 2.00 μm for both fundamental x-polarization mode and for y-polarization mode, respectively. So, the obtained extraordinary outcomes make the proposed PCF a strong candidate in super continuum generation and biomedical imaging applications.

Introduction

Photonic crystal fiber (PCF) is a sort of optical fiber that uses photonic crystals to shape the cladding around the core of the cable. Photonic crystal is a low-loss periodic dielectric medium built by utilizing a periodic array of tiny air holes that run along the whole fiber length. Photonic crystal fibers or microstructure holey fibers show broadened properties which outfit some new applications, for example, super continuum generation, fiber sensors and capacity to maintain high polarization, broadband dispersion controlling and so on. Nonlinearity is one of the fundamental possessions of photonic crystal fibers filaments for some, helpful applications including optical switching, optical regeneration, super continuum generation, optical parameter amplification, and optical wavelength change [1–3]. Contrasted with standard single mode fibers (SMFs), PCFs have numerous tunable properties, for instance; air hole distance diameter, pitch, cladding, background material, doped core and so on. These adaptabilities give better control over nonlinearity, confinement loss, dispersion slope and birefringence so on. These are just conceivable in PCF which are unachievable in SMFs. PCFs are characterized into two gatherings, photonic band gap and index guiding PCFs. In these two sorts of PCFs, high refractive index contrast is maintained in the middle of core and cladding photonic crystal fibers (PCFs), known as key parts to accomplish proficient nonlinear procedures, for example, optical parametric amplification, all optical wavelength transformation and super continuum generation [3,4], have attracted incredible interests in the previous decade [5,6].

To accomplish high nonlinearity scientists have considered the conduct of PCFs by utilizing nanostructure with huge refractive index in the core area. Utilizing pure silica core, nonlinear coefficient is just around 100 $W^{-1} km^{-1}$ because of little nonlinear refractive index of silica, nominally $29.6 \times 10-^{21} W^{-1} m^2$. In this way, higher nonlinear refractive index materials are utilized as a part of the core to enhance nonlinearity. Recently, Liao et al. [7] proposed a PCF of high nonlinearity utilizing nano scale slot core. The PCF displays a high nonlinearity up to $3.5739 \times 10^4 W^{-1} km^{-1}$. Be that as it may, confinement loss issue is disregarded. Huang et al. proposed a slot coiled silicon PCF having a high nonlinear coefficient up to 1068 $W^{-1} km^{-1}$ [8]. Li and Zhao utilized nano wires of gold in center and accomplished supported polarization dependent coupling and transmission [9]. Liao et al. [10] recommended a winding PCF of high nonlinearity showing nonlinear coefficient of 226 $W^{-1} km^{-1}$ at the communication band. Amin et al. [11] proposed a spiral high nonlinear photonic crystal fiber utilizing gallium phosphide (GaP) strips in the core. The fiber demonstrates a

---

* Corresponding author.
E-mail address: kawsar.ict@mbstu.ac.bd (K. Ahmed).

https://doi.org/10.1016/j.rinp.2018.06.033
Received 2 May 2018; Received in revised form 5 June 2018; Accepted 14 June 2018

high nonlinearity of $10^4 W^{-1} km^{-1}$. In any case, fiber shows confinement loss of 10^3 and 10^{-10} dB/km for x and y polarization modes, individually at 1550 nm wavelength. To create strands having huge nonlinearity with nanoscale slot core, recently article [12] is published. Slot bismuth PCFs are proposed by K. Saitoh et al. [13]. It is demonstrated that high nonlinear coefficient of 11 $W^{-1} m^{-1}$ at 1.55 µm and straightened dispersion of 2 ps/(nm.km) over a 67 nm wavelength range can be accomplished in these slot liquid PCFs. Another sort of all-strong space winding silicon PCF is presented in article [10] which gained ultrahigh nonlinear coefficient of 224.36 $W^{-1} km^{-1}$ at 1.55 µm wavelength. None of above mentioned articles are analyzed numerical aperture (NA). Furthermore, nonlinearity is not so high like 10^5 $W^{-1} km^{-1}$.

In our article, CH-PCF is being proposed which demonstrates a high nonlinearity up to 62448.64 $W^{-1} km^{-1}$ and 63435.74 $W^{-1} km^{-1}$ at wavelength of 1 µm for x-polarization and for y-polarization respectively. As far as anyone is concerned this is the best outcome contrasted with recently published articles. In this manner, proposed fiber can be helpful super continuum generation, optical parameter amplification and broadband dispersion compensation.

Fiber design and theory

The geometric perspective of the proposed CH-PCF with amplified sight of slot core is exhibited in Fig. 1. The outline is kept as basic as could reasonably be expected. The cladding area contains hybrid shape air hole rings. In cladding, the outer two rings are formatted in circular shape and entry three rings are formatted in hexagonal shape The air gap distance across in cladding distance, d = 1.40 µm and 1.50 µm with the pitch estimation of Λ = 1.60 µm. Air filling portion in cladding is d/Λ which fabrication is practical. Here the moderate level of air filling fraction of 0.88 has been strictly maintains. The foundation material is GaP which is mechanically available. Reliance of the powerful mode on wavelength of the proposed fiber is clarified in Fig. 2. From Fig. 2, it is comprehended that viable territory at wavelength is 1 µm, which is little. Moreover, the arrow surface by red color denoting the direction of the electric field. This little zone of the compelling mode gives ascent of huge nonlinearity. Besides, the value of convergence error is very low of 3.6×10^{-11}.

Numerical methods and analysis

Numerical analysis is the part and parcel of characterization designed PCF. In this work, the state and art of the suggested PCF and numerical outcomes have been carried out by FEM based commercially available software package COMSOL Multiphysics® version 4.2.There are many numerical methods such as Finite-difference time-domain (FDTD), full vector Partial wave expansion (FV-PWE), Boundary element methods, FEM are well established. Among these numerical methods FEM is highly suitable for microstructure electromagnetic investigations. Number of degrees-of-freedom (DOF) is fixed here and 48530are found from the suggested model. Due to the fixed number of degree freedom FEM best suited for electromagnetic probe. By solving the matrix eigenvalue problem, FEM provides the propagation constant spontaneously providing more accurate result even the structural menstruation is more complex. Moreover it takes less computational memory and less computational time then other numerical method. The base material is pure silica. The refractive index of a silica is dependent on EM wave. There is also established an imperial relationship for determination of the refractive index. In the year of 1871, Wilhelm Sellmeier developed an equation as follows

$$n_{silica}^2(\lambda) = 1 + \sum_{i=1}^{3}\frac{B_i\lambda^2}{\lambda^2 - C_i} \tag{1}$$

where, A_i and B_i are the sellmeier coefficient of silicaat the standard temperature T = 25 °C and λ is the controlling wavelength in µm unit.

For propagation mode, optical power flows through the fiber core. But the internal structure of the crystal lattice and PCF is not so homogenous. As a result the power flow distribution is not same for core cladding and material. Besides there founds fundamental two X-polarization and Y-polarizations. Due to the very small variation in refractive index for these two orthogonal polarizations the power fraction is not same. The power fraction can be calculated by the following relationship.

$$Power\ Fraction\,(\eta') = \frac{\int_X S_z dA}{\int_{All} S_z dA} \tag{2}$$

where "x" is the area of interest (i.e. core, cladding, and material) and "*all*" means cross sectional the total area of PCF. It is very essential to estimate the effective mode area because it helps to evaluate the other optical parameters such as nonlinearity, numerical aperture etc. The effective mode area highly in influences the nonlinearity. The effective mode area of the proposed PCF can be evaluate by the following relation in Eq. (3) followed by the article [3].

$$Effective\ mode\ area\ A_{eff} = \frac{(\int\int |E(x,y)|^2 dxdy)^2}{\int\int |E(x,y)|^4 dxdy}[\mu m^2] \tag{3}$$

Here, E is the electric field. But A_{eff} is the prerequisite for resolving nonlinearity as well as NA. A high value of nonlinear coefficient is derived from the small size core area with comparative larger size air hole in the outer boundary of cladding region. The nonlinearity of the PCF can be computed by the following Eq. (4).

$$Nonlinearity\ (\gamma) = \frac{2\pi}{\lambda} \times \frac{n_2}{A_{eff}} \tag{4}$$

Here, n_2 is the nonlinear coefficient of the core material, in the unit m^2/W. Highly nonlinear PCFs are emergent for all optical signal processing, super continuum generation, high power applications. The amount of optical power collection or gathering is realize by the optical parameter know as numerical aperture. It is unit less parameter and dependent on the effective area. Numerical aperture can be calculated by the following Eq. (5) as follows.

$$Numerical\ Aperture\ (NA) = \sin\theta \approx \left[1 + \frac{\pi A_{eff}}{\lambda^2}\right]^{-\frac{1}{2}} \tag{5}$$

A dimension less parameter NA is also indispensable for non-invasive medical imaging as well as OCT.

The base material is silica and there exist some microscopic

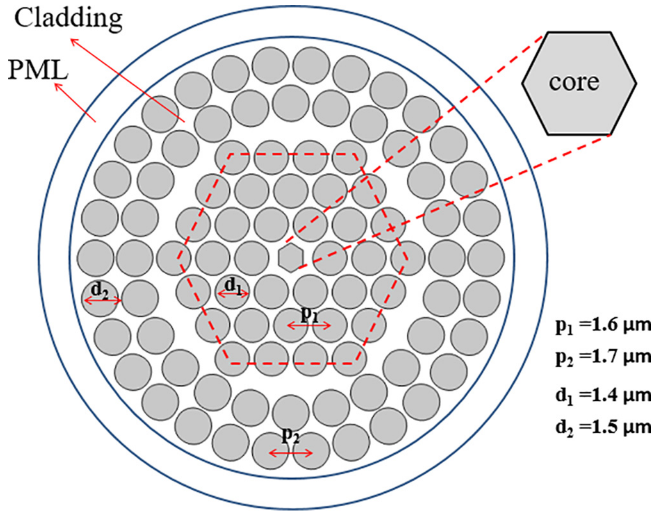

Fig. 1. Cross sectional view of CH-PCF structure of (a) cladding region (b) core region filled with nanoscale gallium phosphide.

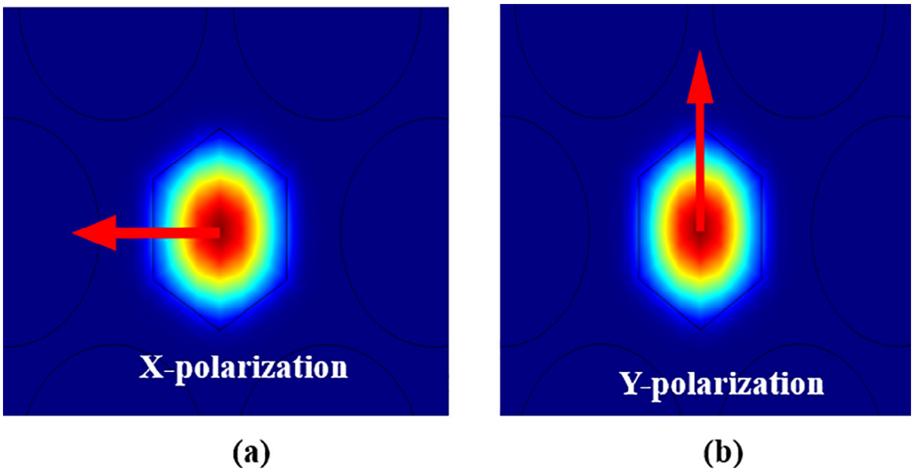

Fig. 2. Mode filled distributions of proposed CH-PCF with nanoscale gallium phosphide (b) X-polarization (c) Y-polarization at the optical wavelength λ = 1.55 μm. The arrow surface denoted the direction of the electric field.

variation due to some material density and non-uniform geometric configuration. As a result of such types of configuration light are scattered whereby produces some scattering loss. The scattering loss of any PCF leads to the total loss of any fiber. It can be evaluated by the following Eq. (6).

Due to microscopic variation in the material density and inhomogeneous geometric configuration of the fiber structure light are scattered and caused scattering loss. It is one kind of channel impairments which leads to total loss of the fiber. For the proposed PCF this loss has been analyzed and plotted with for the operated frequency spectrum. The scattering loss of the PCF has been calculated using the following Eq. (6) as follows

$$\alpha_R = C_R \times \left(\frac{1}{\lambda}\right)^4 \tag{6}$$

where, C_R is the scattering coefficient of the background material and is the range from 0.8×10^{-5} to 1.0×10^{-5} (dB/cm). (μm)^4. The value of C_R is chosen 1.0×10^{-5} (dB/cm) (μm)^4 here for the investigation process.

Results and discussions

Fig. 3 demonstrates the impact of nonlinearity for wavelength go between 1 μm and 2 μm. The structure demonstrates extensive nonlinearity as effective area is little. The high nonlinearity is a direct result of high nonlinear refractive index of the material. The nonlinearity decreases as the wavelength expands on account of decreased confinement of light in the core. The higher the confinement of light in the center region the higher the estimation of the nonlinearity, thus high nonlinearity can be accomplished. Extensive nonlinearity found for x-polarization 62448.64 W^{-1} km^{-1} and for y-polarization 63435.74 W^{-1} km^{-1} are at 1 μm which diminishes with ellipticity proportion of the air gaps. They got estimation of nonlinearity is superior to that in [8,10].

The effective area is little as appeared in Fig. 4 for the proposed structure. The esteem is exceptionally littler than that in conventional fiber. The effective area is little in the order (10^{-13}) for the proposed structure. The effective area is incremented with ellipticity ratio. For the proposed structure, 8.14×10^{-13} m^2 and 8.06×10^{-13} m^2 effective area are found for x-polarization and y-polarization at the wavelength of 2 μm.

Besides, the nonlinearity and effective Area, the scattering loss is examined on Fig. 5 which reveals that, the light is firmly confine through the core and induce low scattering loss. The low scattering loss are founded for the proposed structure 1.32599×10^{-08} dB/km and 1.32625×10^{-08} dB/km for x-polarization and y-polarization respectively at the wavelength of 1 μm.

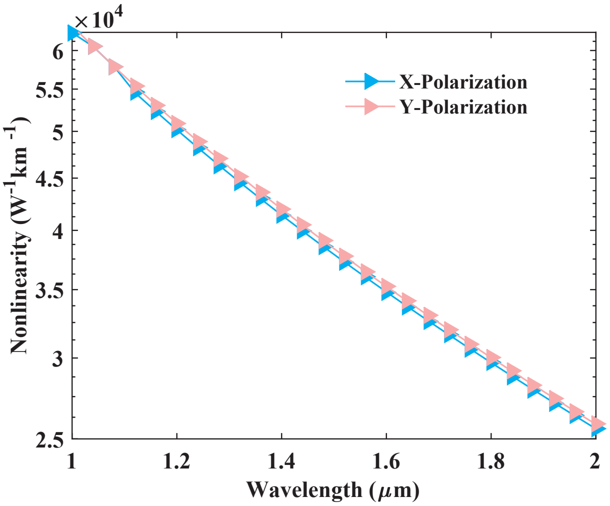

Fig. 3. Nonlinearity of optimum structure for two fundamental polarization X-polarization and Y-polarization modes as a function of optical wavelength.

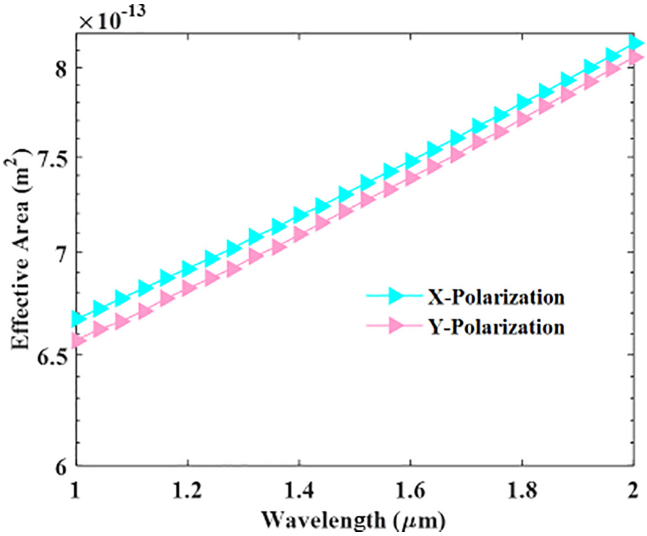

Fig. 4. Effective area of optimum structure for two fundamental polarization X-polarization and Y-polarization modesas a function of optical wavelength.

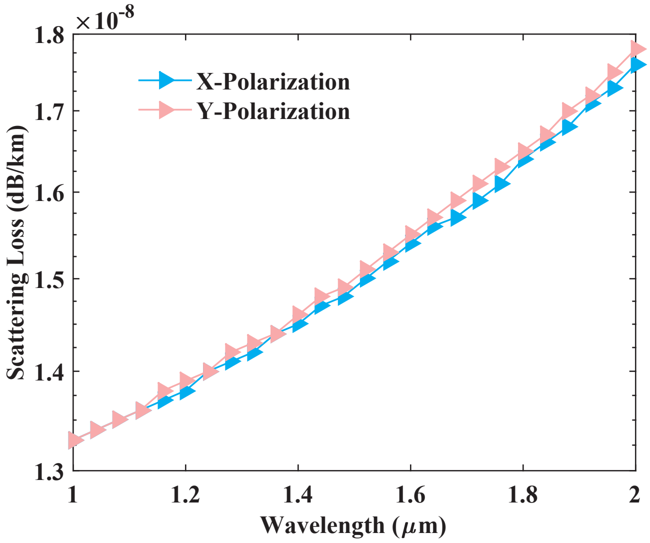

Fig. 5. Scattering loss of optimum structure for two modes as a function of optical wavelength.

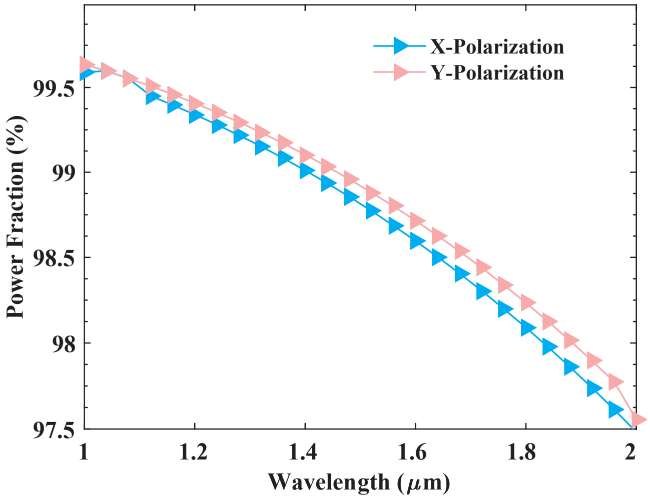

Fig. 6. Power fraction of optimum structure for two modes as a function of optical wavelength.

Fig. 6 reveals the power fraction in the core region of the proposed PCF for the variation of wavelength. Large modal area is indispensable of a fiber for high power transmission or high bit rate communications. The obtained maximum power fraction of the raised model is of 99.7% at wavelength 1.00 μm which is comparable to previous works. It nicely visualize that the value of power fraction decreases monotonically when the value of wavelength increases as shown in Fig. 6.

Fig. 7 demonstrates that the highest NA of 0.78 for optimum structure for both polarization at 2 μm wavelength. A PCF with higher value of NA is very useful in practical applications because of its resolving power. The higher value of NA induces by tightly confinement of more light into the core region thorough covering small effective area. Fig. 7 depicts the NA for both x-polarization and y-polarization. It also shows that the value of NA is proportional to the wavelength. That means the value of NA increases as the value of wavelength increases. This value is highly comparable with previously reported result [14–16]. So the proposed PCF is also a potential candidate for medical imaging applications.

From the above discussion and Table 1, it can be easily discovered that the proposed PCF simultaneously offers both desirable optical characteristics high nonlinearity and high numerical aperture. Comparing to the previously reported PCFs with their optical characteristics it can be observed that the proposed PCF gives extraordinary optical characteristics than others.

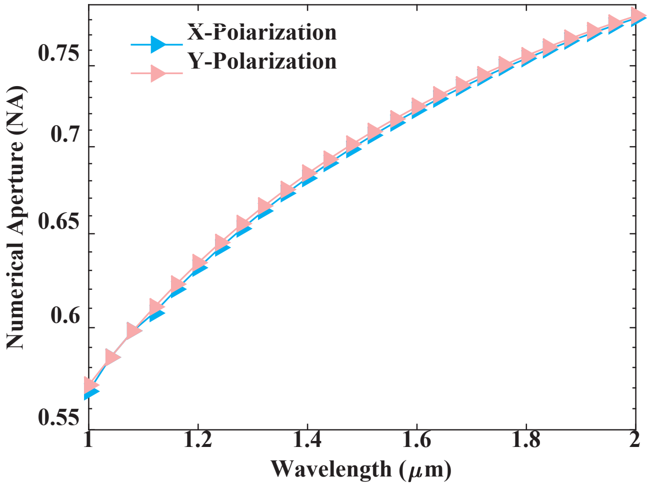

Fig. 7. Numerical aperture (NA) of optimum structure for two modes as a function of optical wavelength.

Table 1
A comparison table on previous PCFs with reported PCF by considering various essential optical parameters.

Prior PCFs	Operating wavelength (μm)	Nonlinearity W^{-1} km^{-1}	NA	Core material
Ref [7]	1.55	3.5739×10^4	–	Si-nc
Ref [11]	1.55	11.34×10^4	–	GaP
Ref [17]	1.55	33.2	–	Silica
Ref [18]	1.55	11,000	–	Bismuth
Ref [19]	1.00	5828	–	SF-57
Ref [20]	0.85	26739.42	–	As_2S_3
This work	1.00	63435.74	0.78	GaP

Conclusion

With highly nonlinearity and high NA, a novel design of circular hybrid photonic crystal fiber (CH-PCF) is presented. The numerical results demonstrate that the reported design offers high nonlinearity of 62448.64 W^{-1} km^{-1} and 63435.74 W^{-1} km^{-1} for both x-polarization and y-polarization, respectively, at the operating wavelength of 1.00 μm. At the operating wavelength of 2.00 μm, the highest numerical aperture of 0.78 is also gained for both polarization modes. So, the proposed PCF will be a strong candidate in super continuum generation and biomedical imaging applications.

Disclosures

The authors have no relevant financial interests in this article and no potential conflicts of interest to disclose.

Conflict of interest

This manuscript has not been published yet and not even under consideration for publication elsewhere. All the authors have read the manuscript and approved this for submission as well as no competing interests.

Acknowledgment

The authors are very grateful to those who participated in this

research work. There is no financial support for this research work.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.rinp.2018.06.033.

References

[1] Wang A, Zhang B, Hou J, Wei H, Tong W, Luo J, Zhang Z. Visible supercontinuum generation with sub-nanosecond 532-nm pulses in all-solid photonic bandgap fiber. IEEE Photonics Technol Lett 2012;24(2):143–5.

[2] Yatsenko YP, Pryamikov AD. Parametric frequency conversion in photonic crystal fibres with germanosilicate core. J Opt A: Pure Appl Opt 2007;9(7):716.

[3] Ahmed F, Roy S, Paul BK, Ahmed K, Bahar AN. Extremely low loss of photonic crystal fiber for terahertz wave propagation in optical communication applications. J Opt Commun 2018. http://dx.doi.org/10.1515/joc-2018-0009.

[4] Tian L, Wei L, Guoying F. Numerical simulation of supercontinuum generation in liquid-filled photonic crystal fibers with a normal flat dispersion profile. Opt Commun 2015;334:196–202.

[5] Hsu JM. Tailoring of nearly zero flattened dispersion photonic crystal fibers. Opt Commun 2016;361:104–9.

[6] Karasawa N. Dispersion properties of transverse anisotropic liquid crystal core photonic crystal fibers. Opt Commun 2016;364:1–8.

[7] Liao J, Huang T. Highly nonlinear photonic crystal fiber with ultrahigh birefringence using a nano-scale slot core. Opt Fiber Technol 2015;22:107–12.

[8] Huang T, Liao J, Fu S, Tang M, Shum P, Liu D. Slot spiral silicon photonic crystal fiber with property of both high birefringence and high nonlinearity. IEEE Photonics J 2014;6(3):1–7.

[9] Li P, Zhao J. Polarization-dependent coupling in gold-filled dual-core photonic crystal fibers. Opt Express 2013;21(5):5232–8.

[10] Liao J, Sun J, Du M, Qin Y. Highly nonlinear dispersion-flattened slotted spiral photonic crystal fibers. IEEE Photonics Technol Lett 2014;26(4):380–3.

[11] Amin MN, Faisal M. Highly nonlinear polarization-maintaining photonic crystal fiber with nanoscaleGaP strips. Appl Opt 2016;55(35):10030–7.

[12] Hou J, Bird D, George A, Maier S, Kuhlmey BT, Knight JC. Metallic mode confinement in microstructured fibres. Opt Express 2008;16(9):5983–90.

[13] Saitoh K, Kakihara K, Varsheney S, Koshiba M, Nonlinearity enhancement and dispersion management in bismuth microstructured fibers with a filled slot defect, Conference on Lasers and Electro-Optics (CLEO) 2008 JTuA82.

[14] Sen S, Islam MS, Paul BK, Islam MI, Chowdhury S, Ahmed K, Asaduzzaman S. Ultra-low loss with single mode polymer-based photonic crystal fiber for THz waveguide. J Opt Commun 2017. http://dx.doi.org/10.1515/joc-2017-0104.

[15] Sultana J, Islam MS, Islam MR, Abbott D. High numerical aperture, highly birefringent novel photonic crystal fibre for medical imaging applications. Electron Lett 2017.

[16] Chowdhury S, Sen S, Ahmed K, Asaduzzaman S. Design of highly sensible porous shaped photonic crystal fiber with strong confinement field for optical sensing. Optik-Int J Light Electron Opt 2017;142:541–9.

[17] Li X, Xu Z, Ling W, Liu P. Design of highly nonlinear photonic crystal fibers with flattened chromatic dispersion. Appl Opt 2014;53(29):6682–7.

[18] Saitoh K, Kakihara K, Varshney S, Koshiba M. May. Nonlinearity enhancement and dispersion management in bismuth microstructured fibers with a filled slot defect. Quantum Electronics and Laser Science Conference (p. JTuA82). Optical Society of America; 2008.

[19] Revathi S, Inabathini S, Sandeep R. Soft glass spiral photonic crystal fiber for large nonlinearity and high birefringence. Opt Appl 2015;45(1):15–24.

[20] Revathi S, Inbathini SR, Saifudeen RA. Highly nonlinear and birefringent spiral photonic crystal fiber. Adv OptoElectronics 2014;2014.