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THEORETICAL ANALYSIS OF SQUARE STRUCTURED PHOTONIC CRYSTAL FIBRE USING THE GOLDEN RATIO

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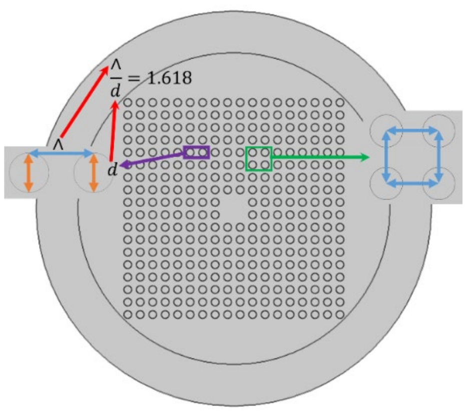
Graphical abstract



Abstract

Square photonic crystal fibre (PCF) is proposed in this study using the principle of the golden ratio; by taking inspiration from nature. Simulations and analyses of the proposed design are used to examine different optical properties. Research findings show that the proposed square photonic crystal fibre exhibits a flattened chromatic dispersion, with a chromatic dispersion value of around 60 ps/(km.nm). At the critical 1.55 μm operating wavelength window, the fibre structure has a low effective area of less than 8 μm^2 and confinement loss of less than 10^{-5} dB/km. These characteristics show that the proposed PCF design is suitable to be used for data communication systems. Subsequently, confinement of light occurs within the core of the proposed PCF at the optimum wavelength of 1.55 μm.

Keywords: Effective area, golden ratio, photonic crystal fibre, chromatic dispersion

1.0 INTRODUCTION

Photonic crystal fibre (PCF) has increased popularity among researchers and manufacturers since its first introduction in 1996 [1]. The main reason is that PCF has structural design flexibility over conventional optical fibre; allowing the designers to design PCFs using air holes with different shapes, sizes, and structures, to produce fibre with interesting properties depending on its needs and applications. In contrast with conventional optical fibres, which are limited in manipulating the refractive indexes of the core and cladding to produce fibre of specific desired properties. Photonic crystal fibre can either be photonic bandgap guiding or index guiding [2,3]. The former has a hollow low-index core with periodic small-scaled air holes surrounding the core. On the other hand, the latter comprises a single background material, such as silicon dioxide, and hollow air holes surround the axes of the fibre. Index guiding PCF has numerous advantages and attractive properties over the conventional optical fibre such as endlessly single-mode range [4], large effective area [5], large negative dispersion [6,7], high nonlinear coefficient [8], high birefringence [9,10], low attenuation [11], near-zero and flattened dispersion [12–19] and so on.

Different models of photonic crystal fibre have been proposed in the literature, with some models exhibiting flattened dispersion over the desired wavelength range [12–19], one of the essential properties for data communication medium. A three-core photonic quasi-crystal fibre with twelve-fold symmetry using a silica doped germanium material is proposed [12]. It has been shown that ultra-flattened chromatic dispersion at a wavelength between 1.4 μm and 1.6 μm is achievable with the design, with dispersion values ranging between 22.1 and 23.01 ps/(km.nm). However, no confinement loss is reported in the paper [12], another vital property that needs to be kept low for data communication. Two PCF designs are proposed [13,14], with cladding containing air holes adhering to hexagonal shapes with varying diameters of air holes [13,14]. Although an ultra-flattened near-zero dispersion is reported in reference [13], high confinement loss is reported from the three-fold symmetric hybrid core PCF. In contrast, low confinement loss and ultra-flattened near-zero dispersion are reported for the PCF designs with elliptical shape rings of different diameter circular air holes in reference [14]. A group of researchers introduced index-guiding PCFs [15,16] implementing four cladding air holes positioned in a hexagonal lattice that assessed birefringence, chromatic dispersion and confinement loss. At 1.55 μm operating wavelength, reference [15] obtained dispersion results of 190 ps/(km.nm), whereas, PCF structure in reference [16] has deduced confinement loss of approximately 10^{-2} dB/m and dispersion of 145 ps/(km.nm). Additionally, a similar hexagonal structure but with five layers cladding holes presented in reference [17] has determined low chromatic dispersion of 59 ps/(km.nm) and low loss of 10^{-3} dB/m. These PCFs [12–17] are relatively complicated for fabrication due to their varying diameters of air holes and structural designs [12–17].

The golden ratio has been widely used to obtain a reliable and strong structure, through inspiration from nature. The same principle may be adopted for PCF designs demonstrated in these two pieces of literature [18,19]. In reference [18], a hexagonal lattice PCF is introduced by keeping the the proportion of the major and minor axis of the elliptical core holes equal to the golden ration; to exhibit steep chromatic dispersion at the 0.5 to 2.0 wavelengths. Another design [19] uses a golden spiral structure with different spiral radius, giving zero chromatic dispersions at a different wavelength for different spiral radius [19]. However, both references [18,19] report slightly high confinement loss to fortify their claim of the applicability of their designs for usage in the telecommunication system. Furthermore, the fabrication of the design [19] is complex; due to its complicated spiral designs [19].

This paper introduces simple square PCF designs using the principle of the golden ratio. The finite element method with a 3 μm thickness perfectly match layer is used to analyse the design using simulation software. It is shown that flattened dispersions at the 1.3 to 1.84 μm wavelength range are possible, with one of the pitch values exhibiting near-zero dispersion value and confinement loss of less than 10^{-5} at 1.55 μm wavelength. Effective area is also shown to be less than 8 μm^2. These properties justify the usage of the PCF design for data communication systems.

2.0 ARCHITECTURE OF THE PROPOSED PCF

Figure 1 reveals the proposed PCF design in x and y axes, composed of a square design with a length of 18 air holes with identical diameters. The design originates by arranging two air holes side by side whilst abiding by the golden ratio principle; fixing the ratio of pitch distance Λ to air holes' diameter d, to the golden ratio value of 1.618, i.e. Λ/d = 1.618. Square patterns are iteratively formed by adding two air holes, and the process continues until the finalised PCF design is obtained. The 4 innermost cladding holes are absent in design to provide an index-guiding core for propagation of light. A total of 320 hollow cladding holes of identical diameter were imposed in the region. Finally, a 3 μm thickness PML is added to the outermost region to absorb light rays that may pass through from the core of the PCF through its cladding and thereby, preventing reflections; to achieve interference-free light in the core of the proposed square-structured PCF. The proposed design is simulated by varying the pitch value between 0.9 μm to 1.3 μm whilst fixing Λ/d to the golden ratio value, resulting in the automatic change of diameters of the air holes and, consequently, the core and the cladding. The proposed PCF design is considered non-complex due to the uniform dimensions and configurations, thus, there shall be ease of fabrication in the manufacturing process. Various fabrication methods that have been introduced can be implemented for this PCF design such as stacking and drawing [20], sol-get casting [21] and extrusion [22].

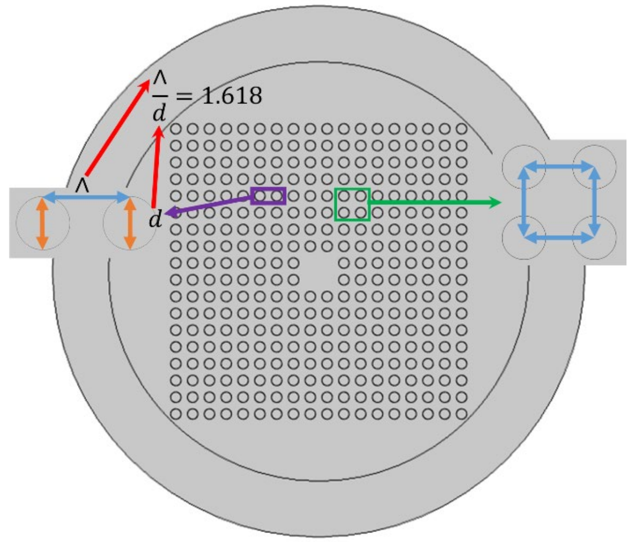


Figure 1 The architecture of the proposed eight-ring highly nonlinear PCF

3.0 METHODOLOGY

The simulation method by implementing the Finite Element Method (FEM) with imposed Perfectly Matched Layer (PML) is used to evaluate the functionality of the proposed PCF design. Based on the simulation, the results are then used to compute optical properties of effective refractive index n_{eff}, chromatic dispersion D, confinement loss L_c, effective area A_{eff} and V-parameter V_{eff}.

Chromatic dispersion D is the scattering attribute of the waveguide in transmitting signal through pulses. Scattering of pulses reduces the integrity of the signal and calculated with the real part of the effective refractive index. This property is defined as [11,23–25]:

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2 Re[n_{eff}]}{d\lambda^2} \quad (1)$$

Confinement loss L_c is an avoidable property of the propagating light that emerges from the core region of the fibre into the surrounding matrix. It is computed from the imaginary part of the effective refractive index, and defined as [11,23–25]:

$$L_c = \frac{2\times 10^7}{\ln(10)\lambda}\frac{2\pi}{\lambda}\mathrm{Im}[n_{eff}] \quad (2)$$

Effective area is the quantitative computation of the waveguide covers the dimensions of the fibre. The property is determined by the amount of electric field covering the radial distance of the structure, and it is defined as [11,23–25]:

$$A_{eff} = \frac{2\pi(\int_0^\infty |E_a(r)^2| \, rdr)^2}{\int_0^\infty |E_a(r)|^4 rdr} \quad (3)$$

To determine whether the fibre is operating in single mode or multimode, the V-parameter shall be observed. V-parameter is the used to clarify the propagation modes of the fibre through calculation from the refractive indices of the core and cladding, and it is defined as [26–28]:

$$V_{eff} = \frac{2\pi}{\lambda}\sqrt{n_{co}^2 - n_{cl}^2} \quad (4)$$

where, Re(n_{eff}) and Im(n_{eff}) are the real and imaginary parts, respectively, of the complex refractive effective index n_{eff} derived by solving Maxwell's equations. λ is the operating wavelength, c is the velocity of light in a vacuum, E_a is the electric field, r is the radial distance of the PCF, n_{co} is the refractive index of the core, and n_{cl} is the refractive index of the cladding. The derivative in equation (1) is the second differential of the real part of the complex refractive index with respect to operating wavelength.

These three parameters, chromatic dispersion D, effective area A_{eff}, and confinement loss L_c, need to be kept at considerably low values to ensure the suitability of the fibre to be used as a means of data communication. On the other hand, to deduce the functioning of the PCF structure in a single-mode or multi-mode region is determined by V-parameter.

4.0 RESULTS AND ANALYSIS

Simulations of the proposed design are performed. Results from the simulations and calculations are plotted in Figures 2 to Figure 6, depicting effective refractive index n_{eff}, chromatic dispersion D, confinement loss L_c, effective area A_{eff}, and V-parameter V_{eff} against different wavelength λ, respectively. Lines in the figures represent different values of pitch Λ. As shown in Figure 2, effective refractive index n_{eff} is higher for PCF with high pitch values overall range of wavelengths under consideration. Generally, the effective refractive index n_{eff} decreases with increasing operating wavelength and produces a steeper gradient for PCF with low pitch values. These results are used to determine chromatic dispersion D and confinement loss L_c using equations (1) and (2), respectively.

Chromatic dispersion properties for the proposed PCF with different pitch values in Figure 3 show that flattened and near-zero dispersions are achievable, with flatter chromatic dispersion observed as pitch values increase. Overall pitch values considered, highest pitch value at 1.3 μm gives the flattest line with chromatic dispersion value at around 60 ps/(km.nm). Pitch value of 1.3 μm offers the possibility of application of the fibre in data communication, especially for long-distance data communication, due to its flat, near-zero chromatic dispersion property. It can also be observed that for a pitch value of 0.9 μm, chromatic dispersion nearing zero may be obtained at the critical 1.55 μm window, the wavelength with the lowest attenuation commonly used in optical communication systems.

For applicability in data transmission system, the effective area of the PCF needs to be considerably low [2], with an effective area of lower than 86 μm^2 is required to reduce the effect of non-linearity. Furthermore, confinement loss needs to be limited to less than 0.2 dB/km. Figures 4 and 5 show the effective areas and confinement losses assessed by the proposed structure for different wavelengths at different pitch values, respectively. Low effective area A_{eff} of below 8 μm^2 may be obtained using the proposed design for all pitch values, illustrated in Figure 4. These values are far lower than the 86 μm^2 effective area requirement. From Figure 5, confinement losses over the range of wavelength under consideration are also kept under 10^{-2} dB/km, well under the 0.2 dB/km confinement loss required for a data transmission system. Particularly at the 1.55 μm window, it can be seen from Figure 5 that confinement loss of lower than 10^{-5} dB/km is obtainable.

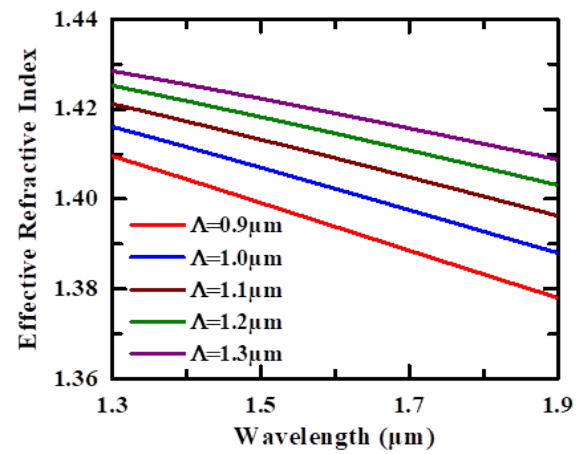


Figure 2 Effective refractive index against wavelength for proposed square PCF

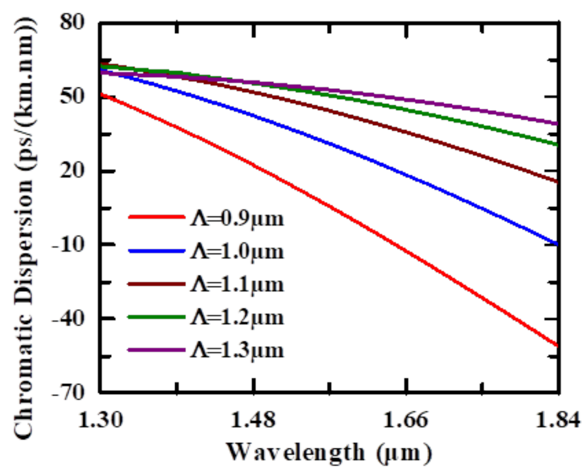


Figure 3 Chromatic dispersion against wavelength for proposed square PCF

Figure 6 represents the V-parameter in regard to the operating wavelength for the proposed PCF. For single-mode operated fibre, the V-parameter should be equal to or lower than 2.405 and exceed this specific value; the fibre shall be operating as a multi-mode fibre. For varying the pitch distance from 0.9 µm to 1.3 µm of the proposed design, the V-parameter is below 1.75 from 1.3 µm to 1.9 µm operating wavelength.

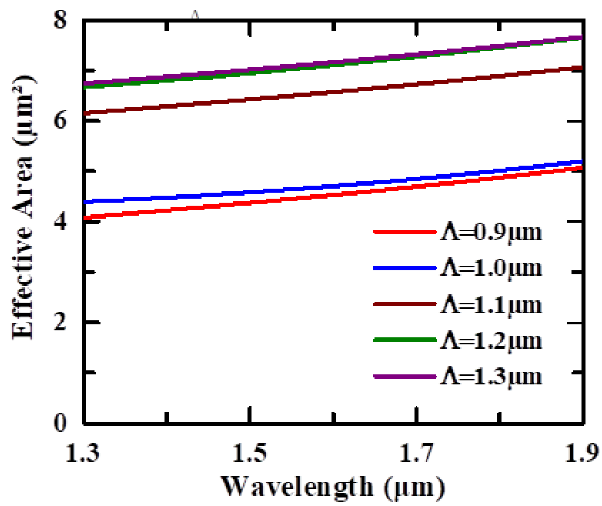


Figure 4 Effective area against wavelength for proposed square PCF

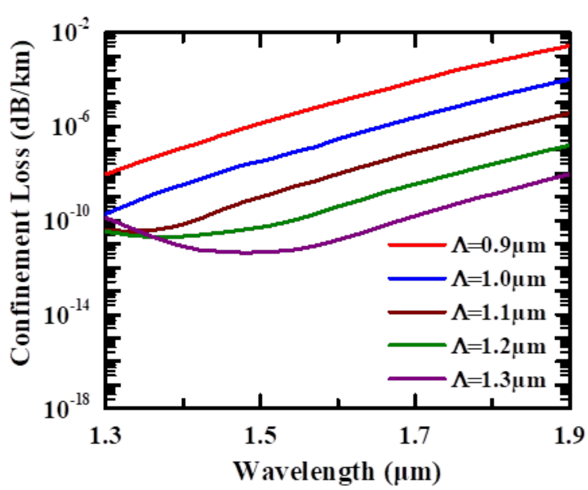


Figure 5 Confinement loss against wavelength for proposed square PCF

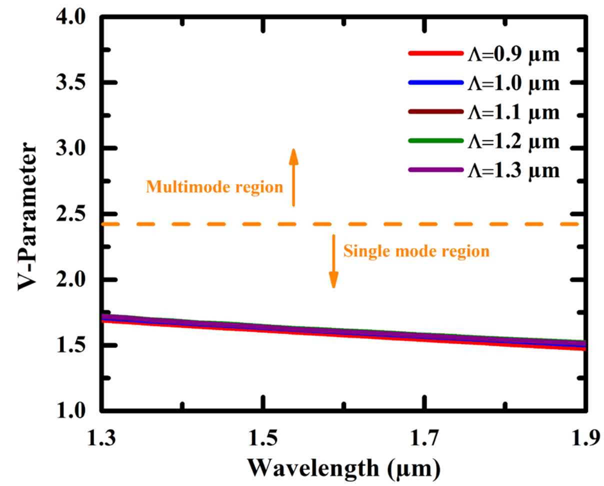


Figure 6 V-Parameter wavelength proposed square PCF

Figure 7 shows the normalised electric field at the wavelength of 1.55 µm for the proposed PCF with a pitch value of 1.3 µm. Pitch value of 1.3 µm is chosen as it has been previously shown that it is suitable for long-distance data communication. From this figure, it can be clearly observed that light is confined inside the core region.

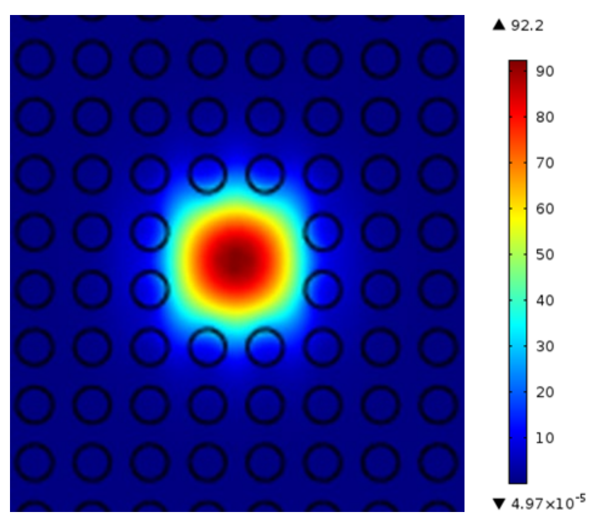


Figure 7 The normalized electric field at a wavelength of 1.55 µm

Additionally, a comparison table is presented in Table 1 shows the performance between previous PCFs and the proposed PCF at operating wavelength of 1.55 µm. As observed from the table, the proposed PCF displays lower chromatic dispersion and confinement loss.

Table 1 Comparison table on the performance of proposed PCF against prior PCFs at λ = 1.55 µm

References	Structure	Dispersion (ps/(km.nm))	Confinement Loss (dB/km)
Ref. [15]	Hexagonal lattice	190	-
Ref. [16]	Hexagonal lattice	145	~10^{-2}
Ref. [17]	Hexagonal lattice	59	~10^{-3}
Proposed PCF	Hexagonal lattice	53.8	~10^{-12}

5.0 CONCLUSION

This paper proposes a novel design of photonic crystal fibre based on the golden ratio. It has been shown that the proposed fibre has a flattened chromatic dispersion at around 60 ps/(nm.km) for a pitch value of 1.3 µm. This flattened chromatic dispersion for a higher pitch value of 1.3 µm corresponds to the flatten effective refractive index shown in this paper. Subsequently, it has been demonstrated that the fibre design confines light properly within the core region with a pitch value of 1.3 µm at the 1.55 µm wavelength. With a low effective area of less than 8 µm^2 and confinement loss of less than 10^{-5} dB/km at the 1.55 µm window, the proposed PCF has the potential to be used as a data transmission medium. The symmetrical structure of the proposed PCF and the consistent size of all air holes in the design allow the PCF to be fabricated with relative ease.

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References

[1] Knight, J. C., Birks, T. A., Russell, P. S. J. and de Sandro, J. P. 1998. Properties of Photonic Crystal Fiber and the Effective Index Model. *Journal of the Optical Society of America A.* 15(3): 748. https://doi.org/10.1364/JOSAA.15.000748.

[2] Begum, F., Zaini, J. H., Petra, I., Namihira, Y. and Zou, N. 2017. Microstructured Fiber for Optical Communications and Medical Applications. *Advanced Science Letters.* 23(6): 5098–5101. https://doi.org/10.1166/asl.2017.7318.

[3] Wang, Y. Y., Wheeler, N. V., Couny, F., Roberts, P. J. and Benabid, F. 2011. Low Loss Broadband Transmission in Hypocycloid-Core Kagome Hollow-Core Photonic Crystal Fiber. *Optic Letters.* 36(5): 669. https://doi.org/10.1364/OL.36.000669.

[4] Russell, P. S. J. 2006. Photonic-Crystal Fibers. *Journal of Light Technology.* 24(12): 4729–4749.

[5] Begum, F., Azad, A. K., Abu Bakar, S., Petra, I., Miyagi, K. and Namihira, Y. 2017. Large Effective Area Square Photonic Crystald Fiber for Optical Communications. *Journal of Engineering and Applied Sciences.* 12(16): 4016–4021. https://doi.org/10.36478/jeasci.2017.4016.4021.

[6] Begum, F., Azad, A. K., Bakar, S. A., Petra, I., Miyagi, K. and Namihira, Y. 2016. Designing Dispersion Compensating Microstructure Optical Fiber. *International Journal of Engineering and Technology.* 8(2): 995–1002.

[7] Chen, M., Yang, Q., Li, T., Chen, M. and He, N. 2010. New High Negative Dispersion Photonic Crystal Fiber. *Optik.* 121(10): 867–871. https://doi.org/10.1016/j.ijleo.2008.09.039.

[8] Liao, J., Sun, J., Qin, Y. and Du, M. 2013. Ultra-Flattened Chromatic Dispersion and Highly Nonlinear Photonic Crystal Fibers with Ultralow Confinement Loss Employing Hybrid Cladding. *Optical Fiber Technology.* 19(5): 468–475. https://doi.org/10.1016/j.yofte.2013.05.013.

[9] Hasan, M. I., Abdur Razzak, S. M. and Habib, M. S. 2014. Design and Characterization of Highly Birefringent Residual Dispersion Compensating Photonic Crystal Fiber. *Journal of Lightwave Technology.* 32 (23), 4578–4584. https://doi.org/10.1109/JLT.2014.2359138.

[10] Lee, Y. S., Lee, C. G. and Kim, S. 2017. Dispersion Compensating Photonic Crystal Fiber Using Double-Hole Assisted Core for High and Uniform Birefringence. *Optik.* 147: 334–342. https://doi.org/10.1016/j.ijleo.2017.08.121.

[11] Begum, F., Namihira, Y., Razzak, S. M. A. and Zou, N. 2007. Novel Square Photonic Crystal Fibers with Ultra-Flattened Chromatic Dispersion and Low Confinement Losses. *IEICE Transactions onf Electronics.* E90-C (3): 607–612. https://doi.org/10.1093/ietele/e90-c.3.607.

[12] Guimarães, Á. de O., Silva, J. P. da and Dantas, E. R. M. 2015. Chromatic Dispersion of an Optical Fiber Based on Photonic Quasicrystals with Twelve-Fold Symmetry and Its Application as Directional Coupling. *Journal of Microwaves, Optoelectronics and Electromagnetic Application.* 14(2): 170–183. https://doi.org/10.1590/2179-10742015v14i2481.

[13] Hansen, K. 2003. Dispersion Flattened Hybrid-Core Nonlinear Photonic Crystal Fiber. *Optics Express*. 11(13): 1503. https://doi.org/10.1364/OE.11.001503.

[14] Hao, R., Li, Z., Sun, G., Niu, L. and Sun, Y. 2013. Analysis on Photonic Crystal Fibers with Circular Air Holes in Elliptical Configuration. *Optical Fiber Technology.* 19(5): 363–368. https://doi.org/10.1016/j.yofte.2013.04.005.

[15] Agbemabiese, P. A. and Akowuah, E. K. 2020. Numerical Analysis of Photonic Crystal Fiber of Ultra-High Birefringence and High Nonlinearity. *Scientific Reports.* 10(1): 21182. https://doi.org/10.1038/s41598-020-77114-x.

[16] Agbemabiese, P. A. and Akowuah, E. K. 2020. Numerical Analysis of Photonic Crystal Fibre with High Birefringence and High Nonlinearity. *Journal of Optical Communications.* https://doi.org/10.1515/joc-2020-0084.

[17] Khalid, M., Arshad, I. and Zafarullah, M. 2014. Design and Simulation of Photonic Crystal Fibers to Evaluate Dispersion and Confinement Loss for Wavelength Division Multiplexing Systems. *The Nucleus*. No.2 June 2014.

[18] A., L. and Geetha, G. 2020. A Novel Hybrid Hexagonal Photonic Crystal Fibre for Optical Fibre Communication. *Optical Fiber Technology.* 59: 102321. https://doi.org/10.1016/j.yofte.2020.102321.

[19] García, A. B., Sukhoivanov, I. A., Lucio, J. A. A., Manzano, O. G. I., Guryev, I., García, J. C. H. and Ortiz, G. R. 2015. Numerical Study of Highly Nonlinear Photonic Crystal Fiber with Tunable Zero Dispersion Wavelengths. *Journal of Electromagnetic Analysis and Applications.* 07(05): 141–151. https://doi.org/10.4236/jemaa.2015.75016.

[20] Azman, M. F., Mahdiraji, G. A., Wong, W. R., Aoni, R. A. and Mahamd Adikan, F. R. 2019. Design and Fabrication of Copper-Filled Photonic Crystal Fiber Based Polarization Filters. *Applied Optics.* 58(8): 2068. https://doi.org/10.1364/AO.58.002068.

[21] El Hamzaoui, H., Ouerdane, Y., Bigot, L., Bouwmans, G., Capoen, B., Boukenter, A., Girard, S. and Bouazaoui, M. 2012. Sol-Gel Derived Ionic Copper-Doped Microstructured Optical Fiber: A Potential Selective Ultraviolet Radiation Dosimeter. *Optics Express.* 20(28): 29751. https://doi.org/10.1364/oe.20.029751.

[22] Cordeiro, C. M. B., Ng, A. K. L. and Ebendorff-Heidepriem, H. 2020. Ultra-Simplified Single-Step Fabrication of Microstructured Optical Fiber. *Scientific Reports.* 10(1): 9678. https://doi.org/10.1038/s41598-020-66632-3.

[23] Begum, F., Namihira, Y., Kinjo, T. and Kaijage, S. 2010. Supercontinuum Generation in Photonic Crystal Fibres at 1.06, 1.31, and 1.55 µm Wavelengths. *Electronics Letters.* 46(22): 1518. https://doi.org/10.1049/el.2010.2133.

[24] Begum, F. and Abas, P. E. 2019. Near Infrared Supercontinuum Generation in Silica Based Photonic Crystal Fiber. *Progress in Electromagnetics Research C.* 89 (December 2018): 149–159. https://doi.org/10.2528/PIERC18100102.

[25] Begum, F., Namihira, Y., Razzak, S. M. A., Kaijage, S. F., Hai, N. H., Miyagi, K., Higa, H. and Zou, N. 2009. Flattened Chromatic Dispersion in Square Photonic Crystal Fibers with Low Confinement Losses. *Optical Review.* 16(2): 54–58. https://doi.org/10.1007/s10043-009-0011-x.

[26] Maidi, A. M., Abas, P. E., Petra, P. I., Kaijage, S., Zou, N. and Begum, F. 2021. Theoretical Considerations of Photonic Crystal Fiber with All Uniform-Sized Air Holes for Liquid Sensing. *Photonics*. 8(7): 249. https://doi.org/10.3390/photonics8070249.

[27] Eid, M. M. A., Habib, M. A., Anower, M. S. and Rashed, A. N. Z. 2020. Highly Sensitive Nonlinear Photonic Crystal Fiber Based Sensor for Chemical Sensing Applications. *Microsystem Technology.* No. September. https://doi.org/10.1007/s00542-020-05019-w.

[28] Rana, S., Saiful Islam, M., Faisal, M., Roy, K. C., Islam, R. and Kaijage, S. F. 2016. Single-Mode Porous Fiber for Low-Loss Polarization Maintaining Terahertz Transmission. *Optical Engineering.* 55(7): 076114. https://doi.org/10.1117/1.OE.55.7.076114.