Numerical investigation and analysis of a compact photonic crystal fiber with negative dispersion

GAUTAM NARAYAN NIRALA[1,*], J. B. MAURYA[2], BHUKYA ARUN KUMAR[3], JAYANTA K. BARAL[4,5]
[1]*Electronics & Communication Engg., National Institute of Technology, Patna Campus, Patna, India*
[2]*Electronics & Communication Engg., National Institute of Technology, Patna Campus, Patna, India*
[3]*School of Electronics and Electrical Engineering, Lovely Professional University, Phagwara, Punjab, India*
[4]*ICube Research Institute, University of Strasbourg, CNRS, INSA-Strasbourg, UMR 7357, 23 rue du Loess, 67037 Strasbourg, France*
[5]*Department of Physics, Central University of Jharkhand, Ranchi, Cheri-Manatu, 835 222, Jharkhand, India*

In the prospective of attaining highly negative dispersion, low confinement loss, normalized frequency a micro structured slotted dual-core PCF has been outlined. A four ring hexagonal solid core PCF have dual core that are slotted by four rectangular slots and other rings are filled with air. FEMSIM module of R-Soft software has been accessed to procure simulations. The upshot unfolds that at diameter d=1.5 μm, 1.65 μm and 1.75 μm, the and confinement loss as 0.000025, 0.000029, 0.000033, further it was also found that dispersion is highly negative and normalized frequency is also found to be low. Introduced PCF is applicable for sensing purpose and also for long haul transmission. This PCF is also used like optical sensor and in the security screening.

(Received September 1, 2024; accepted April 3, 2025)

Keywords: Birefringence, Confinement loss, Dispersion, BK7, Photonic crystal fiber, R SOFT, Mode field diameter

1. Introduction

Positioning of air holes in a definite configuration that sprint down complete portion of the cable models a Photonic Crystal Fiber (PCF) [1]. It possess unalloyed silica as framework material with assemblage of air holes in the cladding section [2]. It manifests eccentric trait discrete from typical fibers. By engineering the size, configuration and fashion of air holes or lattice geometry of PCF, it is workable and manageable to govern light procreation in these fibers. PCF can restrict light in the core by employing either of two processes, very first is rooted on total internal reflection and the second is on band gap effect. Generally, when the refractive index of cladding is smaller in account of cladding then on band gap effect the fiber works.

In course of present time PCF are employed in variety of fields including spectroscopy, industrial machining, military automation, biomedical engineering, sensing etc. Subsequent exceptional efforts have been outlined to date: for example Atakaramians et al. conceptualized and modeled a permeable fiber with rectangular air-holes that manifests a birefringence of greater extent [3-5]. Chen et al. came up with the idea of squeezing lattice elliptical-hole in order to achieve high birefringence but it resulted in high confinement loss. Chen et al again experimented of revolving lattice elliptical holes but this he again experienced high birefringence but very high effective absorption loss [6-10]. Little while back Islam et al. put forward a design that constitute a slotted core PCF of circular lattice cladding that manifest high birefringence with low loss [7]. The end result of all these works clearly manifests the fact that because of solid air cladding and complex lattice holey cladding fiber experiences high absorption loss that combine with outside environment that leads to fabrication difficulties causing the fiber to perform below its output.

In this paper a slotted dual-core PCF with hexagonal cladding has been outlined that enlists highly negative dispersion, V- parameter that is below 2.405, effective area that decreases with the increase in diameter and wavelength, mode field diameter that deceases with increase in diameter and wavelength and finally N_{eff} that decreases with increase in wavelength [8]. This has been done using the Finite Element Method (FEM). The reciprocity of unalike geometric parameters like hole-to-hole spacing was scrutinized in detail. The dependence of different geometrical parameters, namely, hole-to-hole spacing and different air-hole diameter was investigated in detail. With these reported guiding properties, this fiber can be used for the application of residual dispersion compensation in high-speed data transmission optical system [9-13]. Proper arrangement and positioning of number of air holes some captivating properties like ultra-flattened chromatic dispersion, very high nonlinearity, lofty sloping negative dispersion [10], small and huge effective mode area (A_{eff}), and is achieved.

2. Design methodology

Fig. 1 shows geometry of proposed dual-core rectangular slotted PCF. The slotted dual-core is occupied by regular hexagonal lattice structure consisting of four rings of air holes. The proposed PCF structure four rectangular slots whose dimensions are chosen in such a way that the lengths L_1=L_4 both the cores are 1.55 µm and L_2 = L_3 is 1.75 µm respectively and the width of all the slots are taken to be 0.1 µm as common from centre slots are 0.8 µm in upward and downward direction and the distance between two adjacent slots are 0.4 µm. The background material is chosen as silica having the refractive index of 1.45 [11]. The diameter of air holes is same throughout the structure for ease in fabrication. The rectangular slot are filled with BK_7 whose refractive index is 1.534 and are placed in core area [13-14]. The distance between two air holes, which is known as pitch (Λ) is considered same in proposed structure i.e. 2 µm. We analise all the results with with different diameter value of the purposed structure. For the PCF we considered value d=1.5 µm, 1.65 µm, 1.75 µm.

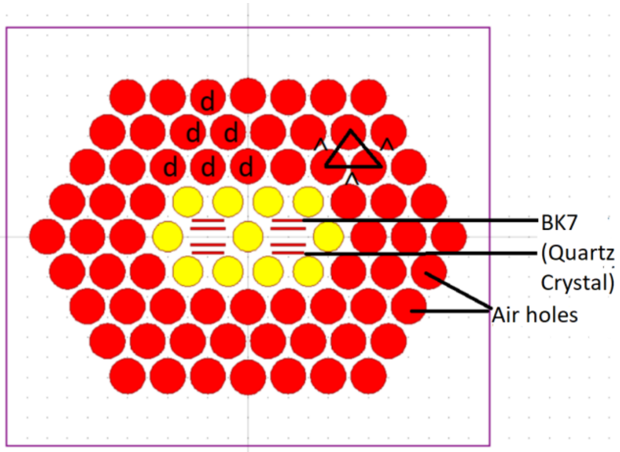

Fig. 1. Cross sectional view of proposed structure (colour online)

3. Results & discussions

Fig. 2 illustrates that light is perfectly confined in both the cores. The proposed work consists of micro-structured fiber whose air holes are of the same size. Also, the diameter of air holes of cladding region to has been varied from 1.5 µm to 1.75 µm and keeping the pitch (Λ) constant at 2 µm throughout to compare and analyzed the results of the effect of air holes size [14-18]. The proposed work is stimulated using FEMSIM module of R-Soft software and further all the requisite optical parameters are calculated and performance analysis has been done and further all the requisite optical parameters are calculated and performance analysis has been done [19].

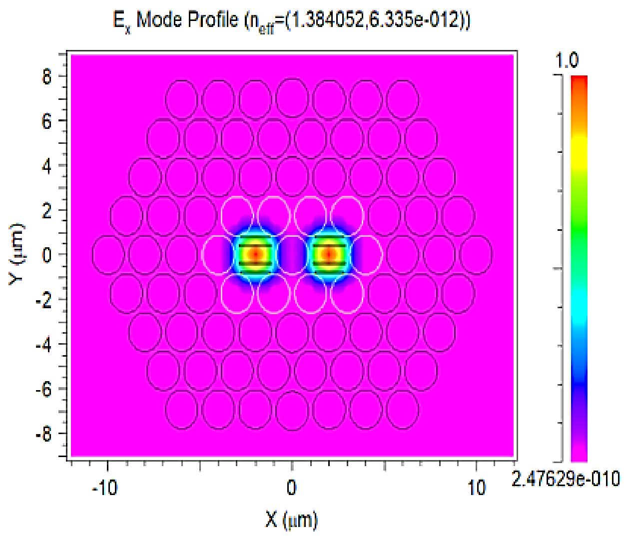

Fig. 2(a). Light confinement in dual –core for d=1.5 µm (colour online)

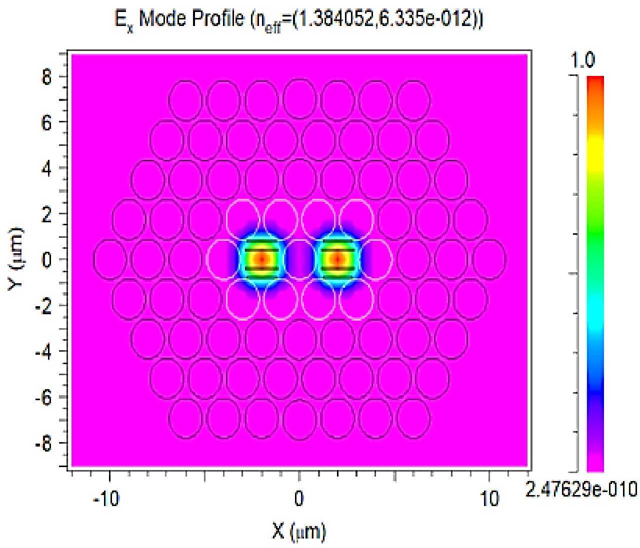

Fig. 2(b). Light confinement in dual –core for d=1.65 µm (colour online)

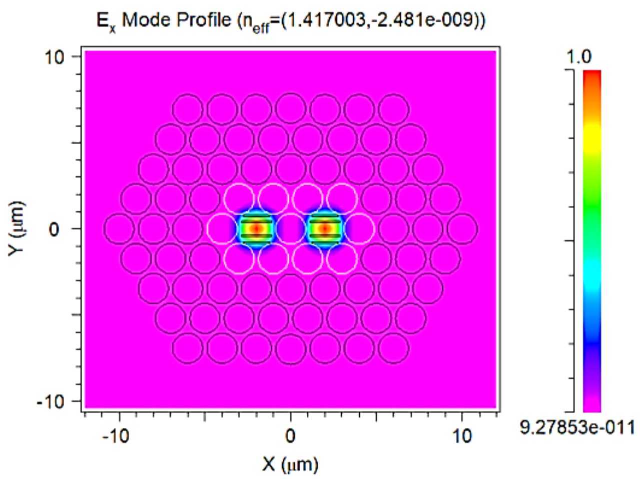

Fig. 2(c). Light confinement in dual –core for d=1.75 µm (colour online)

Fig. 2 illustrates that light is perfectly confined in both the cores in all the three diameters. The light confinement decreases as the diameter increases. The effective refractive index (N_{eff}) versus wavelength can be seen from Fig. 3 [20].

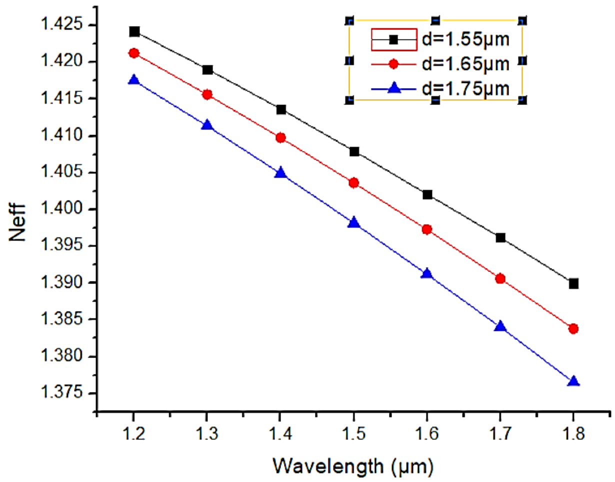

Fig. 3. N_{eff} versus wavelength of solid dual-core slotted PCF (colour online)

It can be seen that with increment in wavelength for hexagonal solid dual-core slotted PCF with quartz crystal filled in inner rectangular slots. Effective refractive index decreases significantly as the wavelength increases the same value of wavelength [15-17]. The dispersion D can be calculated as:

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

where D is the dispersion, λ is the wavelength, n_{eff} is effective refractive index, c is the speed of light [21].

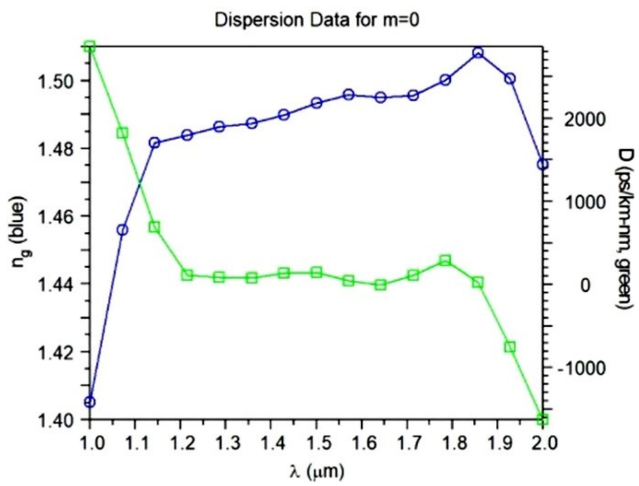

Fig. 4(a). Dispersion curves of the proposed design at d= 1.5 µm (colour online)

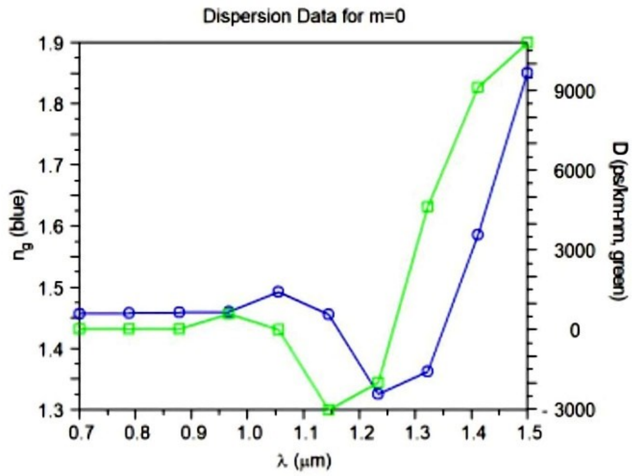

Fig. 4(b). Dispersion curves of the proposed design at d=1.65 µm (colour online)

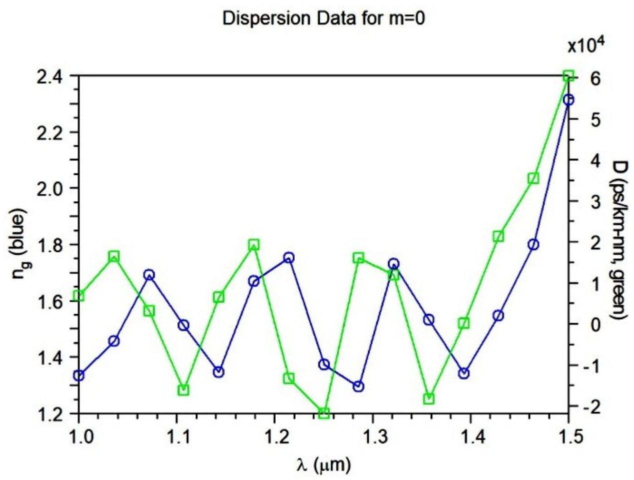

Fig. 4(c). Dispersion curves of the proposed design at d=1.75 (colour online)

Fig. 4 depicts the dispersion curve when air hole diameter d=1.5 µm where positive dispersion occurred 0.7 µm to 1.7 µm wavelength [23]. Fig. 7 shows the dispersion between 0.7 µm to 1.8 µm wavelength where the maximum negative dispersion -300 ps/km-nm is achieved when air hole diameter is 1.8 µm. In Fig. 8 the diameter 2.1 µm is consider achieving better results, shows the dispersion values are 0 ps/km-nm or negative over the entire proposed wavelength. It can be observed from the graph that increasing air holes diameter from d=1.5 µm to 2.1 µm we have more negative values for dispersion which reduces the crosstalk effect and attenuation for better and long-distance communication. In each case the value of dispersion decreases with increase in wavelength [23].

Effective area (A_{eff}) can be calculated as:

$$A_{eff} = \pi[W_{PCF}]^2 \quad (2)$$

where W_{PCF} is the mode field diameter.

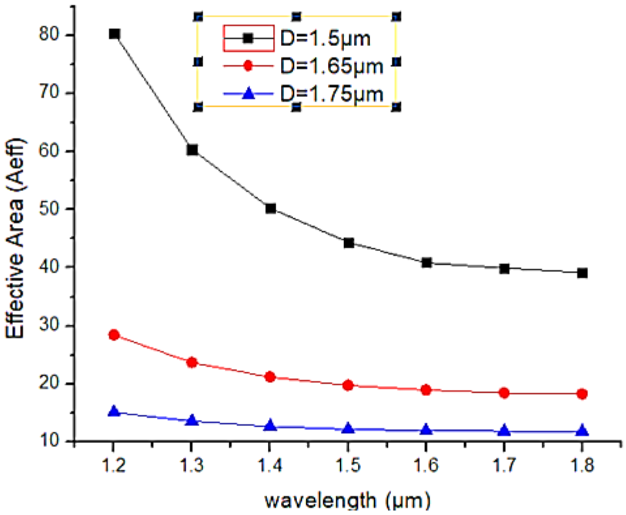

Fig. 5. Effective area versus wavelength of solid slotted dual-core PCF (colour online)

Fig. 5 depicts that with the increase in diameter from d = 1.5 μm to 1.75 μm effective area decreases and further it can also be analyzed that with the increase in wavelength 1.2 μm to 1.6 μm the effective area decreases then at 1.7 μm and 1.8 μm it becomes constant. For D=1.5 μm highest and lowest value of effective area at 1.5 wavelength are 80.4351 and 39.195 respectively similarly for D = 1.65 μm highest and lowest value are encountered as 28.430 and 18.276 further for diameter d = 1.75 it is 15.108 and 11.828, so it can be clearly seen that with the increase in diameter of air holes effective area of PCF decreases significantly [24].

Mode Field Diameter (WPCF) can be calculated as:

$$W_{PCF} = a\,[0.65 + 1.619 V_{eff}^{-3/2} + 2.879 V_{eff}^{-6}] \quad (3)$$

where a is the radius of the air holes and V_{eff} is the normalized frequency.

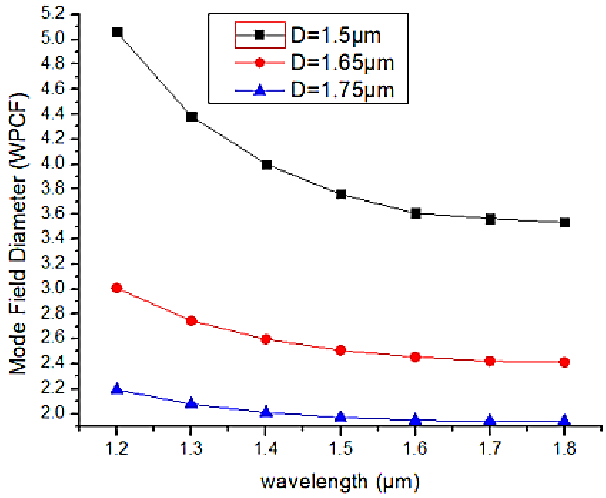

Fig. 6. Mode field diameter versus wavelength of solid slotted dual-core PCF (colour online)

Fig. 6 it can be clearly seen from the following graph with the increase in diameter from d = 1.5 μm to 1.75 μm mode field diameter decreases and further it can also be analyzed that with the increase in wavelength 1.2 μm to 1.6 μm the mode field diameter decreases then at 1.7 μm and 1.8 μm it becomes constant For D=1.5 μm highest and lowest value of mode field diameter at 1.5 wavelength are 5.059 and 3.532 respectively similarly for D = 1.65 μm highest and lowest value are encountered as 3.008 and 2.411 further for diameter d = 1.75 it is 2.192 and 1.9404, so it can be clearly seen that with the increase in diameter of air holes mode field diameter of PCF decreases significantly [21-24].

Normalized frequency (V_{eff}) can be calculated as

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

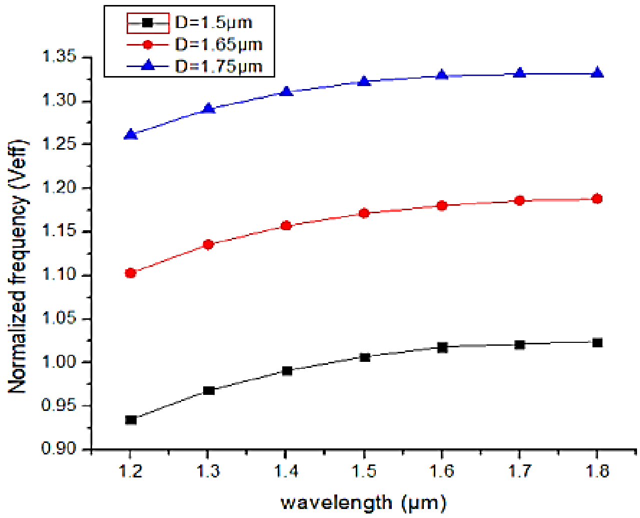

Fig. 7. Normalized frequency (V_{eff}) versus wavelength of solid slotted dual-core PCF (colour online)

As shown in Fig. 7 the normalized frequency is below 2.45 for each diameter (D). For D=1.5 μm, D=1.65 μm and D=1.75 μm, the highest and lowest values of V_{eff} are 1.02399 and 0.9351, 1.1881 and 1.1030 and 1.3322, 1.26166, respectively.

4. Conclusion

In this PCF, important design parameters such as the refractive index, confinement loss and negative dispersion have been thoroughly investigated and presented. By increasing diameters of air holes better results for birefringence, confinement loss and negative dispersion is obtained. It shows that innermost ring has maximum impact on the values of birefringence, confinement loss and dispersion. Moreover, study has shown that it is possible to achieve high birefringence and low confinement loss simultaneously. Methanol as filling material is focused because as it holds applications in chemical industries and in making chemical and biological solutions. Propound PCF holds great latency in optical parameter so it is applicable in chemical sensing applications.

A slotted dual-core PCF has been proposed that exhibits highly negative dispersion, V parameter that is below 2.405, high effective area that deceases with increase in diameter of air holes from 1.5 µm to 1.75 µm. Mode field diameter that decreases with increase in diameter. Hence by varying the diameter of air holes different optical properties can be evaluated that makes the proposed PCF structure applicable in various field like, long haul transmission, optical sensors, medical, security screening etc.

Acknowledgements: Not applicable

Declarations:

Consent to Participate: Consent was obtained from all the authors contributed in the research work.

Consent for Publication: The authors give full consent for publication of this research work.

Availability of data and materials: All data in support of the findings of this paper are available within the article or can be requested from the author.

Competing interests: The authors declare no conflicts of interest

Funding: There is no funding involved in this research work.

Author Contributions: Gautam Narayan Nirala: Performed simulations, Writing - Original draft, Data collection, **Bhukya Arun Kumar:** Data curation, Writing - Original draft. **J B Maurya:** Conceptualization, Review and Editing. **Jayanta K. Baral-**Review and Editing.

References

[1] T.-Y. Yang, E. Wang, H. Jiang, Z. Hu, K. Xie, Opt. Express **23**(7), 8329 (2015).
[2] P. St. J. Russell, J. Lightw. Technol. **24**(12), 4729 (2006).
[3] S. Atakaramiansetal, Opt. Express **17**(16), 14053 (2009).
[4] S. F. Kaijage, Z. B. Ouyang, X. Jin, IEEE Photon. Technol. Lett. **25**(15), 1454 (2013).
[5] K. Wang, D. M. Mittleman, Nature **432**, 376 (2004).
[6] K. Ahmed, Appl. Opt. **56**(12), 3477 (2017).
[7] P. Russel, Proceedings of 2002 4th International Conference on Transparent Optical Networks (IEEE Cat. No. 02EX551) **2**, 7 (2002).
[8] A. Ortigosa-Blanch, J. C. Knight, W. J. Wadsworth, J. Arriaga, B. J. Mangan, T. A. Birks, P. S. J. Russell, Opt. Lett. **25**, 1325 (2000).
[9] T. A. Birks, J. C. Knight, P. S. J. Russell, Opt. Lett. **22**, 961 (1997).
[10] D. C. Tee, M. H. A. Bakar, N. Tamchek, F. R. M. Adikan, IEEE Photonics Journal **5**, 7200607 (2013).
[11] M. F. H. Arif, K. Ahmed, S. Asaduzzaman, M. A. K. Azad, Photonic Sensors **6**, 279 (2016).
[12] D. S. Bomse, Marwood N. Ediger, Conference on Lasers and Electro-Optics (CLEO): Application and Technology, 1-2 (2014).
[13] Q. Xu, M. Wang, S. Lin, Optik **127**, 3427 (2016).
[14] D. Lu, J. Liu, Journal of Lightwave Technology **34**(10), 2452 (2016).
[15] A. M. Heikal, F. F. K. Hussain, M. F. O. Hameed, S. S. A. Obayy, Journal of Lightwave Technology **33**, 2868 (2015).
[16] R. R. Mahmuda, S. M. A. Razzaka, M. I. Hasanc, M. S. Habib, Optik **127**, 8670 (2016).
[17] S. Asaduzzaman, K. Ahmed, M. F. H. Arif, M. Morshed, 2015 18th International Conference on Computer and Information Technology (ICCIT) (2015).
[18] Yongqin Yu, Xuejin Li, Xueming Hong, Yuanlong Deng, Kuiyan Song, Youfu Geng, Huifeng Wei, Weijun Tong, Optics Express **18**, 15383 (2010).
[19] J. C. Knight, T. A. Birks, P. St. J. Russell, D. M. Atkin, Optics Letters **22**, 484 (1997).
[20] Q. Xu, M. Wang, S. Lin, Optik **127**, 3427 (2016).
[21] P. A. Agbemabiese, E. K. Akowuah, Sci. Rep. **10**, 21182 (2020).
[22] E. Khoobjou, H. Khalesi, V. Ghods, Opt. Quant. Electron. **53**, 361 (2021).
[23] B. K. Paul, K. Ahmed, M. T. Rani, K. P. S. Pradeep, F. A. Al-Zahrani, Alexandria Engineering Journal **61**, 2799 (2022).
[24] J. Napari N-yorbe, E. K. Akowuah, I. Danlard, A. K. Amoah, International Journal of Optics **2023**, 612791 (2023).

*Corresponding author: gautamn.ph21.ec@nitp.ac.in