

A nonlinear dual core photonic crystal fiber with low confinement loss at 1.55 μ m wavelength

Mohammed Salim Jasim AL-Taie

`mohammed.altaie@uomisan.edu.iq`

University of Misan

Research Article

Keywords: Photonic Crystal Fibers, Finit Element Method, Nonlinearity, Confinement, Refractive Index

Posted Date: October 22nd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10279632/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

A nonlinear dual core photonic crystal fiber with low confinement loss at 1.55 μm wavelength

Mohammed Salim Jasim AL-Taie*¹

¹*Department of Physics, College of Education, University of Misan, Misan, Iraq*

Abstract: This paper provides an creative layout of a Dual-Core Photonic Crystal Fiber (DC-PCF) based on a silica-air structure, where the design is optimized to achieve outstanding performance in two main areas: high nonlinearity and low retention loss, at a wavelength of 1.55 μm , which is considered the standard wavelength in optical communication systems and nonlinear applications. The performance of the fiber was evaluated using the Finite Element Method (FV-FEM), an accurate numerical method used to simulate the optical properties of optical fibers. The results prove that the design successfully achieves the desired balance between high nonlinearity and low retention loss, making it suitable for advanced applications in optics and communications.

Keywords: Photonic Crystal Fibers, Finit Element Method, Nonlinearity, Confinement, Refractive Index.

INTRODUCTION

Photonic Crystal Fibers (PCFs) featuring Microscopic silica-air formations have garnered significant interest recently due to their special qualities that traditional optical fibers are unable to achieve (Tang et al., 2022; Muhammad, & Lim, 2022; Al-Taie, 2023; Butt et al., 2021; Zhang et al., 2012; Chen et al., 2021). The light-directing technique is used to discriminate between two types of PCFs. Index guiding PCF is the first kind, and it uses many air holes in the cladding region and a solid core for complete internal reflection to guide light. However When light is focused on a low index core region, a second-type photonic band gap (PBG) effect is visible. Numerous researchers have examined the nonlinearity, confinement, dispersion, and birefringence associated with different PCF types (Danlard, , & Akowuah, 2020; Li et al., 2022; Li, 2020; Rafi et al., 2020; Mohammad et al., 2022; Amin et al., 2021; Upadhyay et al 2021; Baul et al., 2024; Singh et al., 2024; Kumar, & Anbazhagan, 2020; Raja et al., 2020, Islam, & Islam, 2024). The light is led along a single flaw in the middle region of the typical index guiding PCF. By adding two cores or neighboring flaws to a PCF, it has been demonstrated that the PCF can be used as an optical fiber coupler. Dual-Core Photonic Crystal Fiber (DC PCF) is the name given to this kind of PCF. Many unique characteristics of DC-PCF include high nonlinearity, negative dispersion, low transmission loss, and high features of coupling (Hasan et al., 2014; Abdelaal et al ., 2020; Stajanca et al., 2014). Among all the attributes of DC-PCF, nonlinearity and confinement loss are crucial aspects. Russell et al. conducted an experimental study on DC-PCFs in 2000 (Gómez-Cardona et al., 2021). DC PCFs are mostly utilized in

nonlinear optics applications, couplers, multiplexers (MUX), demultiplexers (DEMUX), and various gas sensors (Fernandes, 2018; Yoosefi, 2021; Chen et al., 2024; Olaleye et al., 2023; Qian et al., 2022). Pitch Λ and air hole diameter (d) can be tuned to characterize DC-PCF's propagation characteristics. Because of its intricate architecture, Photonic Crystal Fiber's optical propagation parameters are calculated using a variety of mathematical methods.

COMPLETE VECTORIAL FINITE ELEMENT THEORY(CV-FET)

The complete vector solution includes propagation, leaking, and cavitation patterns in two dimensional transverse cross sections with cylindrical positions (Rahaman et al., 2020). Triangular elements have both first and second order interpolation functions. Perfectly matched layer boundary conditions are used in the computational domain to evaluate the effective mode area and birefringence of the proposed PCF (Halder et al., 2024; Monir et al., 2019; Anwar et al., 2017; Baul et al., 2024; Ribeiro, 2024). One begins with the source-free time harmonic version of the vector wave equation in any anisotropic lossy material (Mallick et al., 2017). The suggested PCF is evaluated in the computational domain using identical multilayer boundary circumstances to determine its effective mode area and birefringence. It can be started with the source-free time harmonic form of the vector wave equation for any anisotropic lossy material (Mishra, S. S., & Singh, 2011).

$$\nabla \times \left\{ \frac{1}{s} \nabla \times E \right\} - k_0^2 \epsilon_r E = 0 \quad (1)$$

Coordinate stretching and the constant of dielectric are represented by complicated diagonal tensors s and ϵ_r , respectively. The details of the mathematics are provided in another study [10].

Ultimately, the matrix generalized eigenvalues equation will look like this:

$$(A - n_{eff}^2 B) \{ E_{Ti} \} = \{ 0 \} \quad (2)$$

E_{Ti} stands for crosswise electric field, while n_{eff} , which is equal to β/k_0 , is the modal effective refractive index. In this case, β represents the guiding mode transmission constant and $k_0 = 2\pi/\lambda$ represents the free space transmission constant, where λ represents the free space wavelength.

3. DESIGN OF PCFS

The suggested PCF is made up of a hexagonal structure with an irregular arrangement of rectangular air holes. The circular air holes have a diameter of 1.2 μm , a pitch of 2.5 μm , and silica as the foundation material. Silica has a refractive index of 1.45, while air has a refractive index of 1. The suggestion for DC-PCF's configuration is depicted in Figure 1.

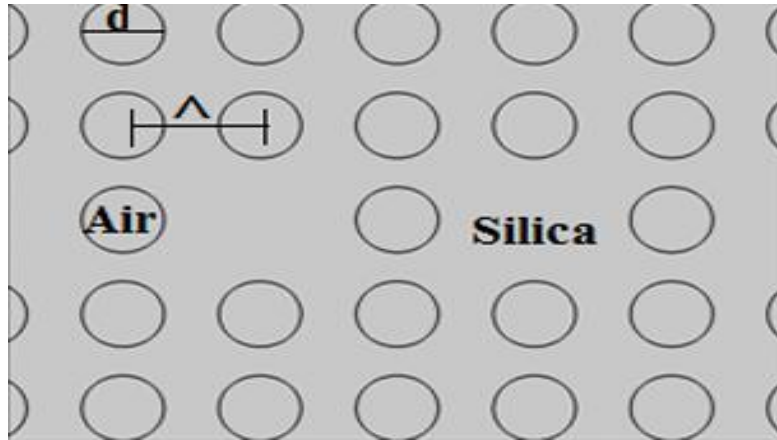


Figure 1: shows the suggested dual-core PCF's structure.

When a two-core photonic crystal fiber is visualized in three dimensions (as in Figure 2), the visual representation usually focuses on the internal structure of the fiber, which includes

1. Photonic crystal structure: Shows the periodic arrangement of holes or materials with different refractive indices around the cores. These holes can be arranged in geometric patterns such as hexagons, squares, or triangles
2. Dual cores: Shows the two cores in the center of the fiber, which can be spaced apart or close together depending on the design. The cores are usually represented as solid regions (without holes) or regions of different refractive indices.
3. Refractive index distribution: Shows how the refractive index changes in the fiber, emphasizing the difference between the cores and the surrounding regions.
4. Light propagation: Can show how light propagates in the cores and interacts between them, such as light coupling between the cores.

5. Three dimensions: The fiber is represented in three dimensions (length, width, height) to show the complete structure of holes and cores and how they are distributed in space.

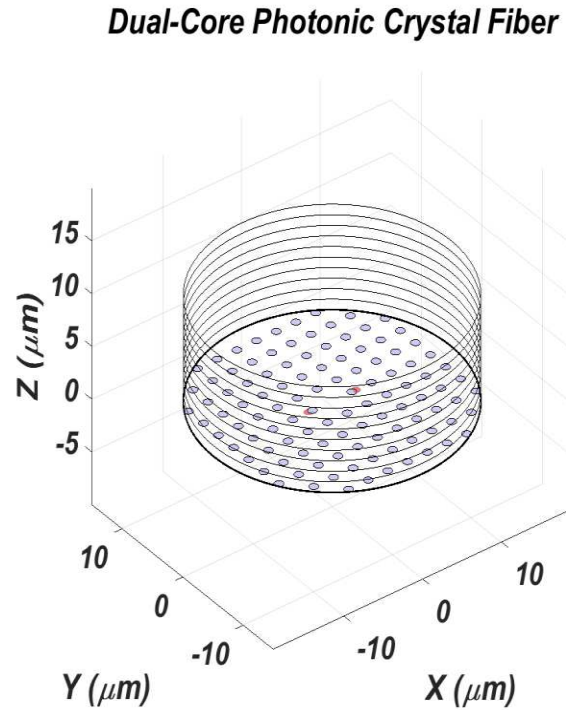


Figure 2: Shows the two-core photonic crystal fiber in three dimensions

DC-PCF coupling is attributed to four supermodes in x-y polarisation. The distinct cores enable the creation of four super-modes. Figure 3 depicts the distribution of electric fields for four super modes at 1.55 μm .

THE MODE FIELD DESIGN

In a photonic crystal fiber or optical fiber in general, the electric field distribution in modes can be described based on their symmetry and distribution in the xx and yy directions. The four modes I mentioned (two odd and two even in both xx and yy) refer to patterns arranged based on the symmetry of the electric field distribution. These modes are commonly known as LP (Linearly Polarized Modes), and are classified based on their mathematical behavior (even or odd) in the xx and yy directions.

1- Even in X and even in Y pattern

- Pattern Description: This pattern is symmetrical in both directions X, Y .
 - Electric field distribution: The electric field is at its highest intensity at the center of the fiber (along the core). It gradually decreases with distance from the center in both directions.
- Mathematical representation: $E(x, y) = E_0 \cdot \cos(k_x) \cdot \cos(k_y)$
- Example: Basic pattern: LP_{01}

2- Odd in X , Even in Y

- Pattern Description: This pattern is odd in the X direction and even in the Y direction.
- Electric field distribution: The electric field zero at X (node at the center of X). It has two lobes in the x direction and one lobe in the y direction.
- Mathematical representation: $E(x, y) = E_0 \cdot \sin(k_x) \cdot \cos(k_y)$
- Example: Basic pattern: LP_{11}^{odd}

3- Even in X , Odd in Y

- Pattern Description: This pattern is even in the X direction and odd in the Y direction.
- Electric field distribution: The electric field zero at Y (node at the center of Y). It has one lobe in the x direction and two lobes in the y direction.
- Mathematical representation: $E(x, y) = E_0 \cdot \cos(k_x) \cdot \sin(k_y)$
- Example: Basic pattern: LP_{11}^{even}

4- Odd in This pattern is individual in both directions.

- Pattern Description: This pattern is individual in both directions X and Y .
- Electric field distribution: The electric field zero both direction (node in the center for both directions)
- Mathematical representation: $E(x, y) = E_0 \cdot \sin(k_x) \cdot \sin(k_y)$
- Example: Basic pattern: LP_{21}

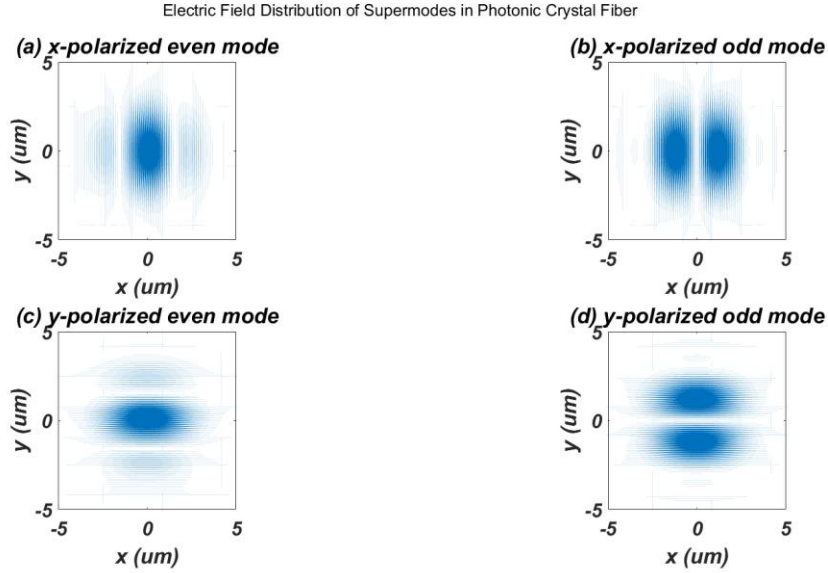


Figure 3: Arrangement of electric fields in the four major pattern

These modes are used in advanced applications such as multimode optical communications and sensing. And coupling in dual-core fibers, even and odd modes can be coupled, resulting in complex optical interactions.

DIFFERENCES IN THE EFFECTIVE REFRACTIVE INDEX

The effective refractive index varies with wavelength. For all three configurations, Figure 4 shows that the effective refractive index drops as wavelength increases. Buildings (i), (ii), and (iii) have effective refractive indices of 1.398, 1.402, and 1.406 at a wavelength of 1.55 μm , respectively. In contrast to the other two structures, the third structure has an extremely powerful and more limited mode field pattern because its effective refractive index reaches its highest point for shape (iii) at a wavelength of 1.55 μm . This indicates that the index guiding mechanism in the dual core area of the PCF is responsible for the guidance that light provides in this fiber.

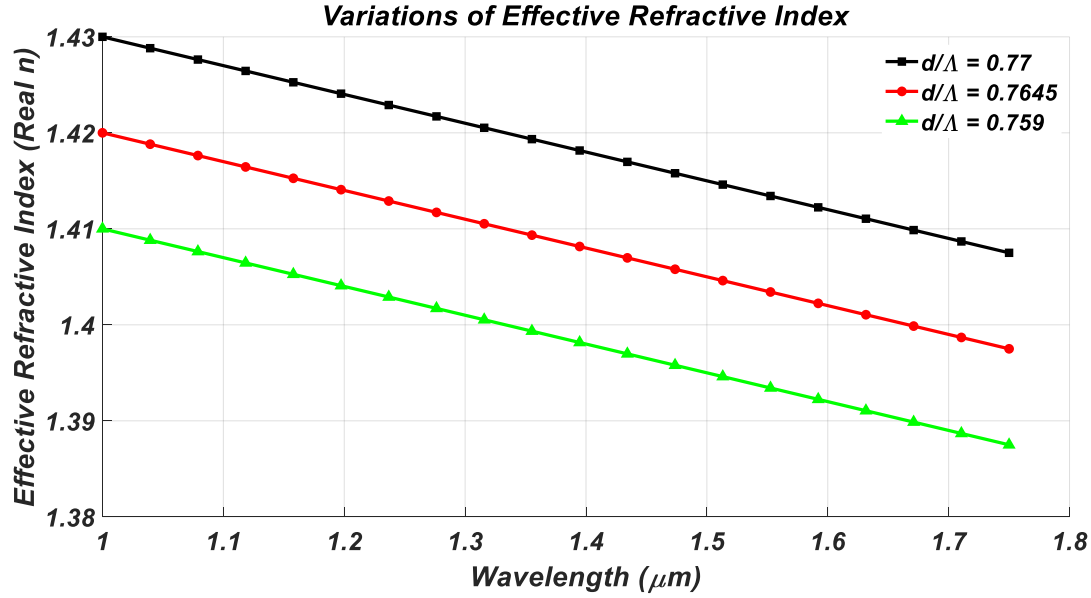


Figure 4: Three different structures with varying d/Λ have various effective refractive index spectra

The graph displays the variations in the effective refractive index for three distinct structures with differing d/Λ ratios (0.71, 0.7645, and 0.759).

1. Effective refractive index: For all three configurations, the refractive index falls as wavelength increases.
2. Wavelength range: 1.1 μm to 1.8 μm is the range of wavelengths.
3. Trends: The graph indicates that the refractive index decreases linearly as wavelength increases. At shorter wavelengths, the initial refractive index increases with the d/Λ ratio.

Applications in photonic crystal research and optical design require an understanding of these distinctions. The way light is reflected or transmitted through structures is influenced by the effective refractive index.

NONLINEARITY AND THE EFFECTIVE MODE AREA

An essential metric for determining nonlinearity is the DC-PCF's effective mode area factor. nonlinear coefficient, γ and Effective mode area, A_{eff} , for DC-PCF, can alternatively be computed using CV-FEM and using the following equation [10]:

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \times 10^3 \text{ W}^{-1} \text{ Km}^{-1} \quad (3)$$

$$A_{eff} = \frac{(\int_{-\infty}^{+\infty} |E|^2 dx dy)^2}{\int_{-\infty}^{+\infty} |E|^4 dx dy} \quad (4)$$

where n_2 is the nonlinear refractive index, λ is the wavelength, and E is the electric field.

With the use of Eq. (3), the nonlinear coefficient of DC-PCF may be readily determined. The nonlinear coefficient's wavelength change in the near-infrared region is depicted in Figure 5. Figure 5 makes it evident that for all three architectures, the nonlinear coefficient diminishes as wavelength increases. For structure (iii), the nonlinearity reaches a maximum of $60 \text{ W}^{-1}\text{km}^{-1}$ at a wavelength of $1.55 \mu\text{m}$.

Figure 6 displays the effective mode area variation with wavelength after the effective mode area is determined using Equation (4). For all three configurations, it is evident that the effective mode area grows as the wavelength increases. Structure (iii) has the smallest effective mode area when compared to other structures, measuring $2.34 \mu\text{m}^2$ at a wavelength of $1.55 \mu\text{m}$.

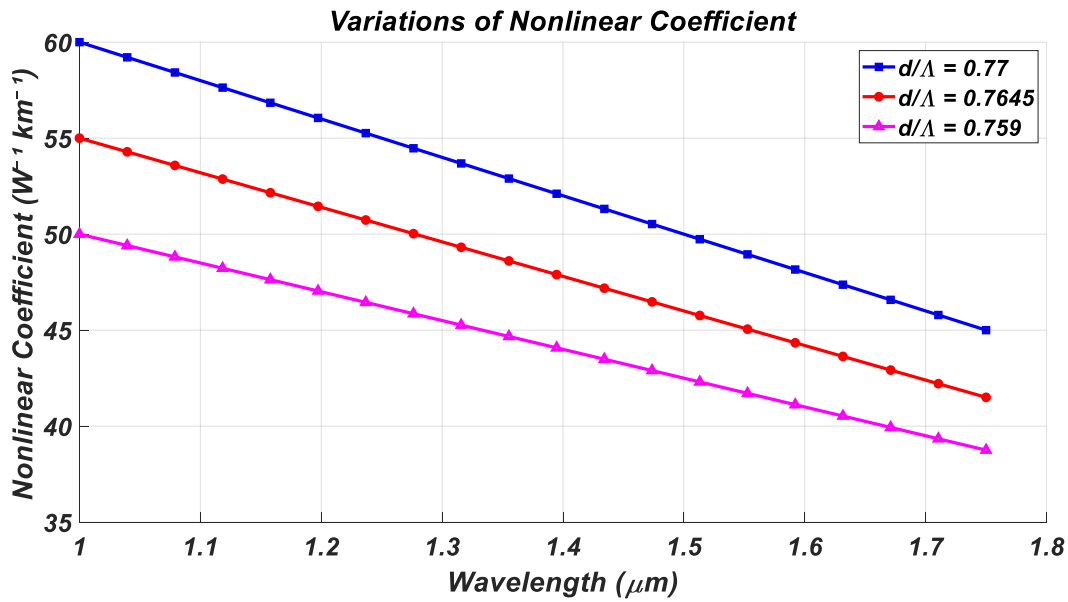


Figure 5: The nonlinear coefficient spectra of three structures with varying d/Λ exhibit variations.

Figure 5 shows the nonlinear effects in a two-core photonic crystal fiber. These effects are represented by different values of the ratio d/Λ (the distance between the cores divided by the distance between the holes in the photonic crystal). Show how the optical and nonlinear properties of the fiber change as this ratio changes. The nonlinearity coefficient indicates how light interacts with the fiber material, and the nonlinear relationship shows how small changes in the fiber geometry (such as the distance between the cores) can affect the propagation of light and its optical properties. In short, the figure shows how changes in the geometry of a two-core photonic crystal fiber affect its nonlinear behavior, which could be important in applications such as optical communications and optical signal processing.

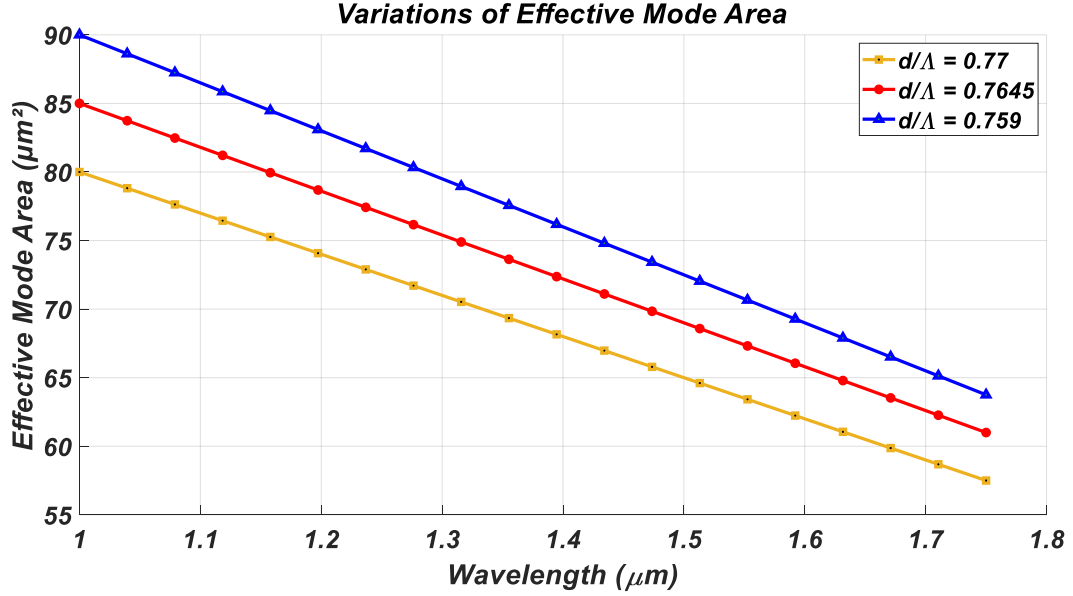


Figure 6: Different Effective Modes Three structures with varying d/Λ have various area spectra.

The interaction between the holes is reduced when the air hole diameter to distance ratio is greater. This could result in less noticeable nonlinear effects but more stable optical characteristics.

when the value denotes a state in which there is a moderate interaction between the holes. This could offer a compromise between nonlinear effects and stability.

On the other hand, the interaction between the holes is larger when the air hole diameter to distance ratio is smaller. In some situations where strong optical interactions are necessary, this can improve nonlinear effects.

LOSS OF CONFINEMENT

The PCF's confinement loss is one of its key characteristics. The following formula makes it simple to determine the confinement loss (dB/km) after the imaginary component of the effective refractive index has been determined using the CV-FET:

$$\text{Confinement loss} = 8.686k_0 \text{Im}[n_{eff}] \quad (5)$$

$$k_0 = 2 \frac{\pi}{\lambda}, \lambda \text{ the wavelength of light that propagates through the fiber}$$

Figure 7 demonstrates how the confinement losses grows as the wavelength rises. The structure (III) at 1.55 μm has the lowest confinement loss (0.001 dB/km) among suggested DC-PCF structures.

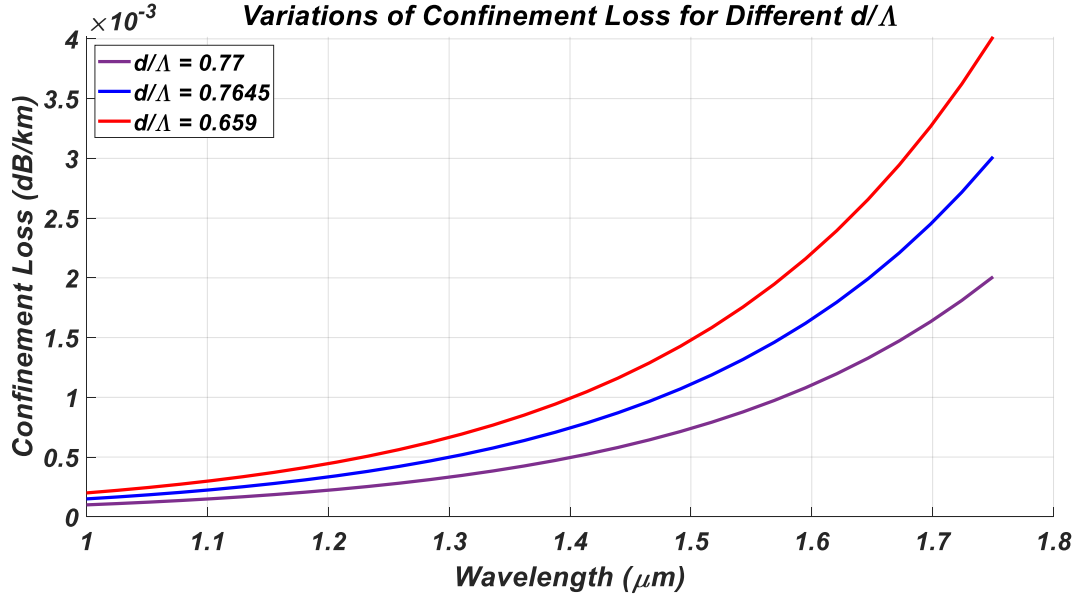


Figure 7: Three separate structures with distinct d/Λ have various effective refractive index spectra

The ratio (d/Λ) gives an idea of how the signal interacts with the medium through which it travels. When this ratio is large, it means that the wavelength is small compared to the distance, and vice versa. Signal loss can be the result of a change in signal loss (attenuation) based on the ratio (d/Λ). This relationship can be nonlinear and depends on the properties of the medium through which the signal is traveling. When signals travel through a given medium, they can interfere with each other. If the wavelengths and distances are compatible in a certain way, constructive interference (signal enhancement) or destructive interference (signal attenuation) can occur. This can create patterns or structures in the signal loss. The most important causes of attenuation in fibers are dispersion (Dispersion) In optical fibers, dispersion can occur because different wavelengths travel at different speeds. This can lead to certain patterns in signal loss, Reflections (Reflections) When a signal travels through a given medium, it can be partially reflected at junctions or changes in optical properties. These reflections can interfere with the original signal and create patterns. Resonance Sometimes, resonance phenomena can occur when the ratio (d/Λ) is close to certain values. This can lead to a sudden increase or decrease in signal loss. Understanding these structures helps in designing optical fibers with specific properties to minimize signal loss. This helps designers in improving communication systems by analyzing these patterns, and thus the performance of communication systems can be improved by choosing the appropriate wavelengths and distances.

CONCLUSION

An innovative design of a dual-core photonic crystal fiber based on a silica-air structure is presented. The design is optimized to achieve high performance in two key areas: high

nonlinearity and low containment loss at a wavelength of 1.55 μm , which is the standard wavelength in optical communication systems and nonlinear applications. In this study, a nonlinearity coefficient of up to 60 W/km/km is achieved at a wavelength of 1.55 μm , making the fiber suitable for applications requiring strong nonlinear optical interactions. An ultra-low containment loss of up to 0.001 dB/km is achieved, which reduces signal loss and improves data transmission efficiency. A small effective mode area (2.34 μm^2) is achieved, which enhances the nonlinear interactions. The complete finite element method (CV-FEM) is used to simulate the optical properties of the fiber, resulting in accurate and reliable results. This study shows that low-loss, high-nonlinearity fibers can improve the data transmission efficiency in optical communication systems, especially in high-speed networks. These fibers can also be used in nonlinear applications such as generating high harmonics, which are used in optical signal processing and improving signal quality. Due to their high sensitivity and low loss, they are also used in gas and chemical sensors, providing high detection accuracy. The innovative design and high performance of these fibers open up new horizons for research in the field of optical fibers and their advanced applications. This research paper presents an innovative design of dual-core photonic crystal fibers with high nonlinearity and low containment loss, making them suitable for advanced applications in optical communications, nonlinear applications, and sensors.

Declaration of Conflict of Interest: The authors declare that there are no known conflicts of financial interest or personal relationships that might appear to influence the work reported in this paper.

Authors' Contributions : **Mohammed Salim Jasim AL-Taie** (Conceptualization and design of the study, Data curation, formal analysis, and validation, Critical revision of the manuscript for intellectual content, Approval of the final version to be published) ; **Hayder Ahmed Hassan** (Methodology development and software implementation, Investigation, resources, and experimental work, Drafting and visualization of results, Approval of the final version to be published).

Funding statement: Not applicable

REFERENCES

- Abdelaal, S. M., Younis, B. M., Obayya, S. S. A., & Hameed, M. F. O. (2020). Highly negative dispersion dual-core liquid crystal photonic crystal fiber. *Optical fiber technology*, 60, 102330. <https://doi.org/10.1016/j.yofte.2020.102330>.
- Al-Taie, M. S. J. (2023). Supercontinuum generation by frequency chirp in photonic crystal fibers. *Indian Journal of Physics*, 97(10), 3097-3102.
- Amin, R., Khan, M. E., Abdulrazak, L. F., Al-Zahrani, F. A., & Ahmed, K. (2021). Design of novel models for optical communication with ultra-high non-linearity, birefringence and low loss profile. *Physica Scripta*, 96(12), 125107. DOI 10.1088/1402-4896/ac227c.

- Anwar, k., Nowsher, n., & Islam, b. n. (2017). *analysis of various pcf structures using finite element method* (doctoral dissertation, department of electrical, electronic and communication engineering).<http://hdl.handle.net/123456789/411>.
- Baul, A., Hossain, M. B., Sakib, M. N., Rana, M. M., Hossain, M. A., Hossain, M. S., ... & Amiri, I. S. (2024). High birefringence and negative dispersion based modified decagonal photonic crystal fibers: a numerical study. *Journal of Optical Communications*, 44(s1), s1839-s1849.<https://doi.org/10.1515/joc-2020-0015>.
- Butt, M. A., Khonina, S. N., & Kazanskiy, N. L. (2021). Recent advances in photonic crystal optical devices: A review. *Optics & Laser Technology*, 142, 107265.<https://doi.org/10.1016/j.optlastec.2021.107265>.
- Portosi, V., Laneve, D., Falconi, M. C., & Prudenzano, F. (2019). Advances on photonic crystal fiber sensors and applications. *Sensors*, 19(8), 1892.<https://doi.org/10.3390/s19081892>
- Chen, S., Ma, Y., Su, H., Fan, X., & Liu, Y. (2024). Few-Mode Fiber-Based Long-Period Fiber Gratings: A Review. *Journal of Optics and Photonics Research*, 1(1), 02-15.DOI: <https://doi.org/10.47852/bonviewJOPR42022414>.
- Danlard, I., & Akowuah, E. K. (2020). Assaying with PCF-based SPR refractive index biosensors: From recent configurations to outstanding detection limits. *Optical Fiber Technology*, 54, 102083.<https://doi.org/10.1016/j.yofte.2019.102083>.
- Fernandes, G. G. M. (2018). *Optical and Digital Signal Processing in Space-Division Multiplexing Transmission Systems* (Doctoral dissertation, Universidade de Aveiro (Portugal)).
- Gómez-Cardona, N., Jiménez-Durango, C., Usuga-Restrepo, J., Torres, P., & Reyes-Vera, E. (2021). Thermo-optically tunable polarization beam splitter based on selectively gold-filled dual-core photonic crystal fiber with integrated electrodes. *Optical and Quantum Electronics*, 53, 1-15.<https://doi.org/10.1364/OE.24.027225>
- Halder, A., Arafat, Y., Ahmed, I., Ahsan, M., Siddiquee, Z., Tanshen, R., & Anower, S. (2024). FEM analysis of a highly birefringent modified slotted core circular PCF for endlessly single mode operation across E to L telecom bands. *Journal of the European Optical Society-Rapid Publications*, 20(2), 35.<https://doi.org/10.1051/jeos/2024036>.

- Hasan, M. I., Habib, M. S., Habib, M. S., & Razzak, S. A. (2014). Highly nonlinear and highly birefringent dispersion compensating photonic crystal fiber. *Optical Fiber Technology*, 20(1), 32-38.<https://doi.org/10.1016/j.yofte.2013.11.005>.
- Islam, M. I., & Islam, M. S. (2024, October). Designing of a PCF Based Ultra-High Negative Dispersion Compensation for Optical Transmission Link. In *2024 2nd International Conference on Information and Communication Technology (ICICT)* (pp. 284-288). IEEE. DOI: 10.1109/ICICT64387.2024.10839739.
- Kumar, C. S., & Anbazhagan, R. (2020). Highly Non-Linear PCF for Spectrum Broadening in Communication Systems: A Review. *Journal of Engineering Science & Technology Review*, 13(2).doi:10.25103/jestr.132.11.
- Li, J. (2020). A review: Development of novel fiber-optic platforms for bulk and surface refractive index sensing applications. *Sensors and Actuators Reports*, 2(1), 100018.<https://doi.org/10.1016/j.snr.2020.100018>.
- Li, Z., Hou, W., Hong, J., Fan, C., Wei, Y., Liu, Z., ... & Tu, B. (2022). The polarization crossfire (PCF) sensor suite focusing on satellite remote sensing of fine particulate matter PM_{2.5} from space. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 286, 108217.<https://doi.org/10.1016/j.jqsrt.2022.108217>
- Mallick, M. S., Siam, M. A., & Sakib, S. M. (2017). *highly birefringent, flattened dispersion, low loss pcfs for thz wave propagation* (doctoral dissertation, department of electrical, electronic and communication engineering). <http://hdl.handle.net/123456789/435>
- Mishra, S. S., & Singh, V. K. (2011). Highly Nonlinear Dual Core Photonic Crystal Fiber with Low Confinement Loss at 1.55 μm Wavelength. *International Journal of Optics and Photonics*, 5(2), 97-102.<http://ijop.ir/article-1-84-en.html>
- Mohammad, N., Abdulrazak, L. F., Tahhan, S. R., Amin, R., Ibrahim, S. M., Ahmed, K., & Bui, F. M. (2022). GaP-filled PCF with ultra-high birefringence and nonlinearity for distinctive optical applications. *Journal of Ovonic Research*, 18(2).DOI:10.15251/jor.2022.182.129.
- Monir, M. K., Hasan, M., Paul, B. K., Ahmed, K., El-Khozondar, H. J., & Amiri, I. S. (2019). High birefringent, low loss and flattened dispersion asymmetric slotted core-based photonic crystal fiber in THz regime. *International Journal of Modern Physics B*, 33(20), 1950218.<https://doi.org/10.1142/S0217979219502187>.
- Muhammad, & Lim, C. W. (2022). From photonic crystals to seismic metamaterials: A review via phononic crystals and acoustic metamaterials. *Archives of Computational Methods in Engineering*, 29(2), 1137-1198.<https://doi.org/10.1115/1.4026911>.

- Olaleye, T. M., Ribeiro, P. A., & Raposo, M. (2023, June). Generation of photon orbital angular momentum and its application in space division multiplexing. In *Photonics*, 10 (6), p. 664). MDPI.<https://doi.org/10.3390/photonics10060664>.
- Qian, Z., Wang, Z., Geng, C., & Luo, X. (2022). Vortex and cavity dynamics for the tip-leakage cavitation over a hydrofoil. *Physics of Fluids*, 34(9).<https://doi.org/10.1063/5.0099070>.
- Rafi, H. N., Kaysir, M. R., & Islam, M. J. (2020). Air-hole attributed performance of photonic crystal fiber-based SPR sensors. *Sensing and Bio-Sensing Research*, 29, 100364.<https://doi.org/10.1016/j.sbsr.2020.100364>.
- Rahaman, M. E., Mondal, H. S., Hossain, M. B., Hossain, M. M., Ahsan, M. S., & Saha, R. (2020). Simulation of a highly birefringent photonic crystal fiber in terahertz frequency region. *SN Applied Sciences*, 2, 1-7. DOI: 10.1109/JPHOT.2021.3057698.
- Raja, S. J., Rao, S. S., & Charlcedony, R. (2020). Design and analysis of dispersion-compensating chalcogenide photonic crystal fiber with high birefringence. *SN Applied Sciences*, 2, 1-10. DOI:<https://doi.org/10.1007/s42452-020-2308-0>.
- Ribeiro, R. O. (2024). Higher-Order Spectral Element Methods for Electromagnetic Modeling of Complex Anisotropic Waveguides. *arXiv preprint arXiv:2411.13573*.
<http://doi.org/10.48550/arXiv2411.13573>.
- Singh, S., Upadhyay, A., Sharma, D., & Taya, S. A. (2022). A comprehensive study of large negative dispersion and highly nonlinear perforated core PCF: theoretical insight. *Physica Scripta*, 97(6), 065504. DOI 10.1088/1402-4896/ac6d1a.
- Stajanca, P., Pysz, D., Michalka, M., Andriukaitis, G., Balciunas, T., Fan, G., ... & Bugar, I. (2014). Soliton-based ultrafast multi-wavelength nonlinear switching in dual-core photonic crystal fibre. *Laser Physics*, 24(6), 065103. DOI:10.1088/1054-660X/24/6/065103.
- Tang, G. J., He, X. T., Shi, F. L., Liu, J. W., Chen, X. D., & Dong, J. W. (2022). Topological photonic crystals: physics, designs, and applications. *Laser & Photonics Reviews*, 16(4), 2100300. <https://doi.org/10.1002/lpor.202100300>.
- Upadhyay, A., Singh, S., Sharma, D., & Taya, S. A. (2021). Analysis of proposed PCF with square air hole for revolutionary high birefringence and nonlinearity. *Photonics and*

Nanostructures-Fundamentals and Applications, **43**, 100896.
<https://doi.org/10.1016/j.photonics.2021.100896>.

Yoosefi, O. (2021). Simulation and design of all-optical logic gates based on photonic crystals. DOI10.5821/dissertation-2117-351130.

Zhang, Y., Sheng, Y., Zhu, S., Xiao, M., & Krolikowski, W. (2021). Nonlinear photonic crystals: from 2D to 3D. *Optica*, 8(3), 372-381.<https://doi.org/10.1364/OPTICA.416619>

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [GraphicalAbstract.docx](#)