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# Design of uncomplicated triangular core PCF for enhanced non-linearity applications

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ABSTRACT

An innovative design of Photonic Crystal Fibre (PCF) for enhanced non-linearity applications using simulation with the Finite Element Method (FEM) is presented. The PCF is a kind of fibre optic waveguide that has air-holes along the entire length of the optical fibre, which exploits its exclusive features of being continuously single-moded and having a modifiable spot-size and dispersion properties for various linear and non-linear applications. This proposed triangular core PCF is made of silica material with a refractive index of 1.445 and features three large air-holes placed 120° apart in the core, each with a refractive index of 1.00. The air-holes have a pitch length of 6.03 μm and a radius of 2.86 μm, and the wavelength of operation is 1.55 μm. The proposed PCF design has a large diameter to pitch ratio (d/Λ) of up to 0.95, resulting in a reduced spot-size of just above 1.00 $\mu m^2$. This indicates that the proposed triangular core PCF design could be used to enhance non-linearity applications. This study introduces a novel structure that simplifies construction by employing three strategically positioned large air-holes in the cladding, thus achieving the necessary properties for guiding light through the core. This streamlined approach overcomes complexities associated with previous designs from the literature, hence, offering a practical solution for effective light guidance while minimising construction difficulties. This inventive proposed PCF design can be fabricated using the Stack and Draw process or the slurry casting method.

## 1. Introduction

### 1.1. Non-linearities in photonic crystal fibers (PCFs)

PCFs are known for their distinctive characteristics, such as ceaselessly single-moded [1–3] behaviour and modifiable spot-size [4–6] and the properties of dispersion [7], which make them suitable for various linear and non-linear uses [8]. However, the non-linear properties of PCFs are also of great interest, as they can be used for various non-linear optical phenomena, such as supercontinuum generation [9], non-linear frequency conversion [10], and soliton formation [7] bidirectional terahertz graphene plasmonic switch [11], plasmonic-based nanosensor [12], optical couplers [13], and optical filters [14].

One of the key non-linear properties of PCFs is their large non-linear coefficient [8], which is quite a few orders of degrees greater than that of conventional single-mode fibres [15–18]. This large non-linear coefficient is due to the great light confinement in the small core of the PCF [19–22], as well as the high contrast of the refractive index in-between the core and the cladding [23–25]. The high contrast of the refractive index leads to also to high confinement of the light in the core of the PCF and also leads to a high intensity of the optical field [26–28], which is necessary for non-linear optical processes to occur [7].

Supercontinuum generation is a famous phenomenon in non-linear optics in PCFs [29–33]. It is the process in which a narrowband input beam is transformed into a broadband output beam through the interaction of light with the non-linearity of the fibre [34,35]. This process is extremely reliant on the dispersion properties of the PCF and can be tailored by engineering the dispersion properties of the fibre [36]. Agrawal et al. [37], have proposed and experimentally demonstrated the generation of a supercontinuum using an equiangular spiral PCF. Karim et al. [4], were able to produce a parametric study of the supercontinuum generation in a $Ge_{11.5}As_{24}Se_{64.5}$ nanowire PCF.

Non-linear frequency conversion [38] is another important non-linear process that can be achieved in PCFs. This process is the conversion of light from one wavelength to another wavelength through the interaction of light with the non-linearity of the fibre [39–41]. The efficacy of nonlinear conversion of frequency is highly dependent on the phase-matching conditions [42], which can be achieved by engineering

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the dispersion properties of the PCF [43].

Soliton formation [44] is another non-linear optical phenomenon that can be observed in PCFs. Solitons are special types of optical pulses that maintain their shape and amplitude while propagating through the fibre [45–47]. This is a consequence of the balance between the non-linearity and dispersion of the fibre. Soliton formation in PCFs has been studied in [2], where the authors have proposed and demonstrated the formation of solitons in a PCF that possesses a triangular lattice of air-holes within the cladding [2].

In this study, we introduce a novel structural design that offers distinct advantages over previously explored configurations from the literature. This innovative structure represents a significant departure from conventional approaches by addressing some of the limitations associated with prior designs. Our proposed configuration simplifies the construction process by utilising only three large air-holes within the cladding, strategically positioned 120° apart. This deliberate arrangement achieves the necessary diameter to pitch ratio required for the core to have non-linear properties, thus enabling effective light guidance. Therefore, unlike the more intricate and complex array of air-holes utilised in prior studies to achieve a similar effect, our approach minimises construction complexities by streamlining the structural elements, thereby overcoming the challenges associated with intricate designs and ensuring a more feasible and straightforward fabrication process. This simplified yet efficient configuration not only resolves the drawbacks of previous structures but also offers a practical and accessible solution for achieving desired non-linear properties in guiding light through the core.

## 2. Methods

The proposed PCF design was simulated using the Finite Element Method (FEM) [23]. The results of the simulation were analyzed for the effective index, the loss and the spot-size. The effective index and the loss were calculated for the TM (transverse magnetic) mode, while the spot-size was calculated for the TE (transverse electric) mode. The PCF was made of silica having a refractive index of 1.445 and featured three large air-holes placed 120° apart in the core, each with a refractive index of 1.00. The air-holes had a pitch length of 6.03 µm and a radius of 2.86 µm, and the wavelength of operation was set to 1.55 µm.

The simulation was performed under TM (transverse magnetic) and TE (transverse electric) modes of operation. The simulations were run to obtain the effective index, the loss and the spot-size of the proposed PCF design. The diameter to pitch (d/Λ) ratio was varied to see its effect on the effective index and the loss and the spot-size.

Using this approach to obtain a modal solution that is established through the Finite Element Method (FEM), implies the complex cross-section of the PCF and the microstructured core of the PCF can then be signified employing many different triangles that are of varying shapes and varying dimensions [48]. Hence, making this tractability of the FEM to be a more desirable method to employ when likened to other techniques such as the Finite Difference Method (FDM). FDM has difficulty representing dielectric interfaces that are slanted or curved if these were present in the structure and it also uses inefficient regularly spaced meshing [49]. Thus, the waveguide optical modes with index contrast that is high, such as with the PCF having a 2 Dimensional confinement as well as being hybrid in nature, at the same time with all the 6 components representing the **E** and **H** fields existing would be preferable with the FEM [50]. This hybridness of the mode is also boosted by the manifestation of a slanted interface and interfaces of the dielectric material that tend to be curved in the PCF. This suggests that what is needed is the vector type of formulation which is required for the accurate calculation of the solutions in the modal type and to properly represent the dielectric interfaces in the PCF as a waveguide. Therefore, a **H**-field centred laborious complete vectorial FEM has been used for the analysis of the procedure of PCFs that have air-holes organized in the triangular framework in the silica cladding of the PCF [48]. This **H**-field design was formerly used for the microwave frequencies and also for the optical frequencies for wave devices up to the intermediate Terahertz frequency region. Below is the H-field formula including the penalty function for augmentation:

$$\omega^2 = \frac{\left(\int \left(\nabla \times \vec{H}\right) * \cdot \hat{\varepsilon}^{-1} \left(\nabla \times \vec{H}\right) d\Omega\right) + \left(\int (\alpha/\varepsilon_o) \left(\nabla \cdot \vec{H}\right) * \left(\nabla \cdot \vec{H}\right) d\Omega\right.}{\int \vec{H} * \cdot \hat{\mu} \vec{H} d\Omega} \tag{1}$$

The full vectorial complex magnetic field is $\vec{\boldsymbol{H}}$. The symbols $\varepsilon$ and $\mu$ represent permittivity and the permeability of the PCF. The symbol $\varepsilon_0$ is used to denote the permittivity of the free space in a waveguide whereas $\omega^2$ denotes the eigenvalue. The symbol $\omega$ is used to denote the wave's angular frequency. This $\alpha$ is a factor that has no dimension that is used to enforce a condition in the magnetic field to make it free of divergence in the sense of least squares. Therefore, the symbol $\hat{\varepsilon}$ as well as the symbol $\hat{\mu}$ are factors that can be random complex tensors in this formulation with off-diagonal coefficients, thus making it suitable for the characterization of electro-optic devices and also acousto-optic devices and as well as elasto-optic devices. For the calculation of the bending and leakage losses in a PCF, the Perfectly Matched Layers (PMLs) would be integrated into the computation frame thus making this into a complex eigenvalue equation [48].

## 3. Results and discussion

The simulation results for the proposed triangular core PCF design were analysed in terms of the effective index, the loss and the spot-size. Diameter to pitch ratio (d/Λ) was varied between 0.5 and 0.95 to evaluate the performance of the PCF.

As can be seen above, the cross-sectional area of the triangular-core PCF design is shown in Fig. 1. It illustrates the three air-holes and the triangular core, with a pitch of 6.03 µm, wavelength of 1.55 µm, and silica refractive index of 1.445.

The full structure field contour of the triangular core PCF in the TM mode for three air-holes and the triangular core PCF is shown in Fig. 2, with a pitch of 6.03 µm, a wavelength of 1.55 µm, and a silica refractive index of 1.445. It can be seen that the field contour matches the physical structure of the triangular core PCF under consideration. This structure enhances non-linearity in the PCF for applications such as sensing and supercontinuum generation. It should be noted that the field profile indicates a strong optical confinement in the core.

The half structure field contour of the triangular core PCF in the TM mode for three air-holes and the triangular core PCF is shown in Fig. 3, with a pitch of 6.03 µm, a wavelength of 1.55 µm, and a silica refractive

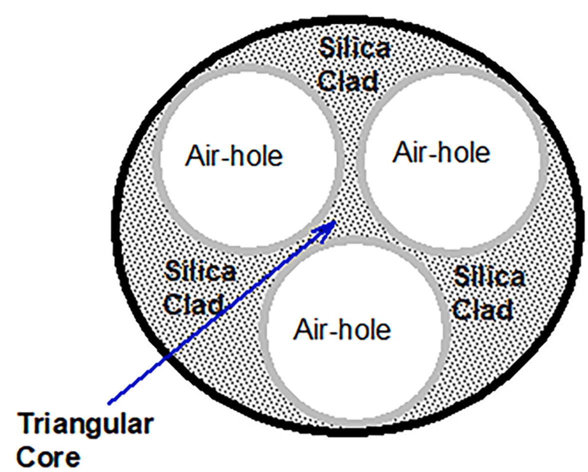


**Fig. 1.** Cross-section of triangular-core PCF showing the 3 air-holes and the triangular core Λ = 6.03µm, λ= 1.55µm, silica of $n$ = 1.445.

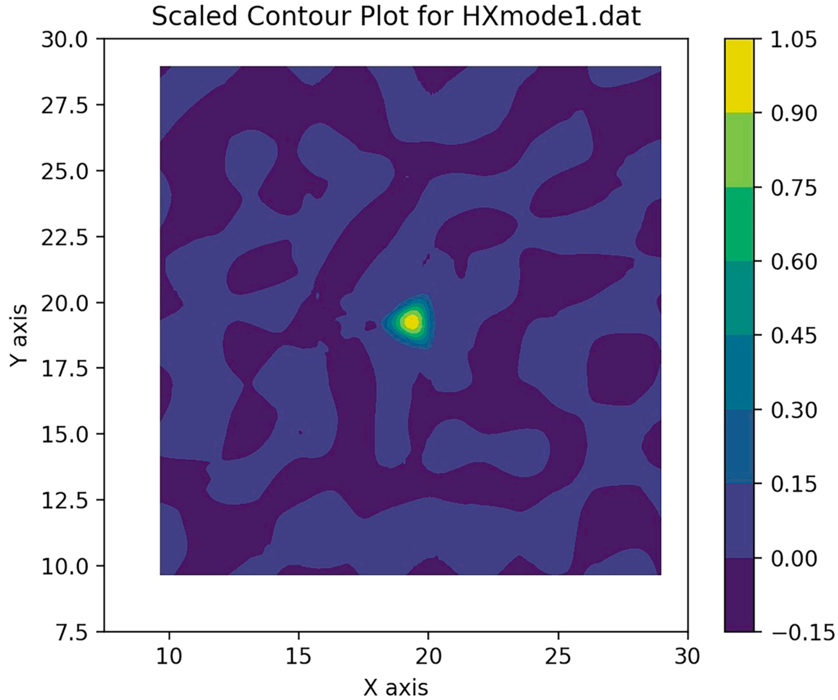


**Fig. 2.** The full structure field profile of the triangular core PCF (Magnified) in the TM mode for 3 air-holes and the triangular core PCF, pitch = 6.03 µm, λ = 1.55 µm, silica of $n$ = 1.445.

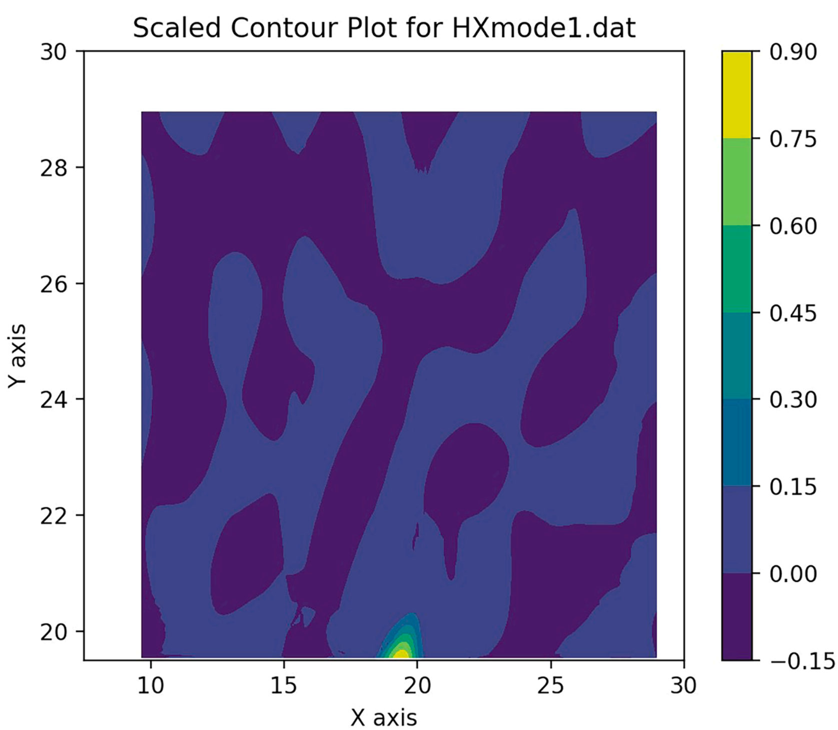


**Fig. 3.** The half structure field contour of the triangular core PCF in the TM mode for 3 air-holes and the triangular core PCF, pitch = 6.03 µm, λ = 1.55 µm, silica of $n$ = 1.445.

index of 1.445. It can also be seen here that the field contour matches the physical half structure of the triangular core PCF under consideration.

The half structure field contour of the triangular core PCF in the TE mode for three air-holes and the triangular core PCF is shown in Fig. 4, with a pitch of 6.03 µm, a wavelength of 1.55 µm, and a silica refractive index of 1.445. It can also be seen here that the field contour matches the physical half structure of the triangular core PCF under consideration. Similar strong optical confinement is observed for both the TM and the TE modes.

Fig. 5 shows how the effective index varies with the diameter to pitch ratio of the triangular core PCF in the TM mode. It can be seen from the figure that the effective index decreases as the d/Λ ratio increases. This

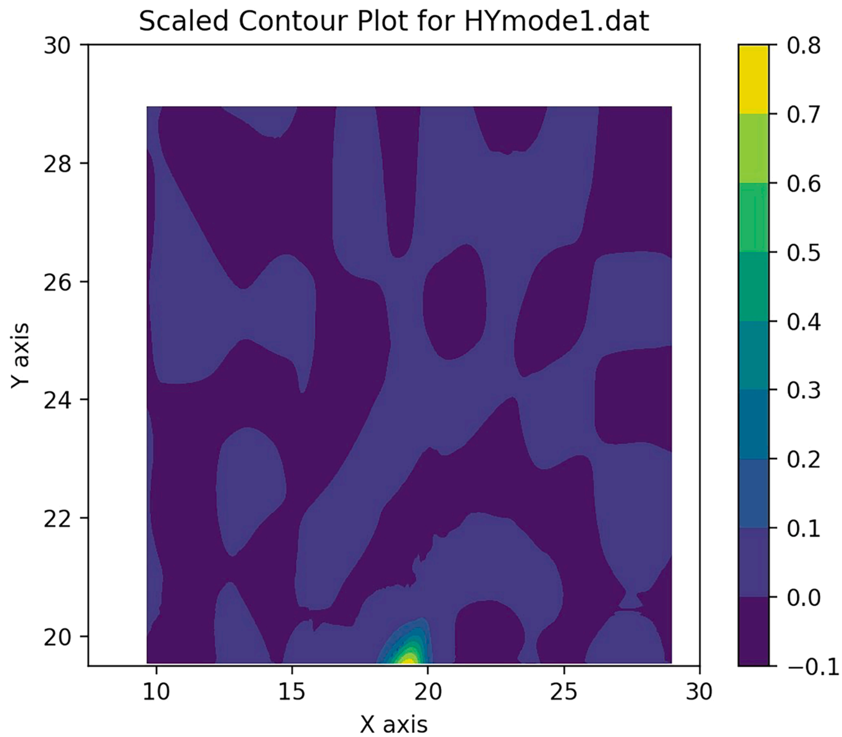


**Fig. 4.** The half structure field contour of the triangular core PCF in the TE mode for 3 air-holes and the triangular core PCF, pitch = 6.03 μm, λ = 1.55 μm, silica of $n$ = 1.445.

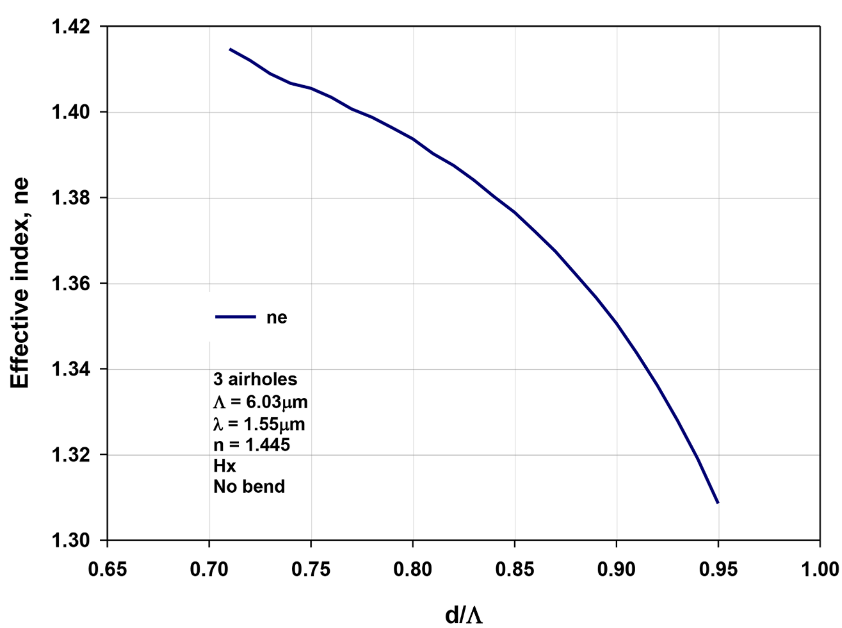


**Fig. 5.** Graph of the effective index varied with the d/Λ of the triangular core PCF in the TM mode for 3 air-holes and the triangular core PCF, Λ = 6.03 μm, λ = 1.55 μm, silica of $n$ = 1.445.

indicates that the proposed PCF design has a large diameter to pitch ratio, which is beneficial for enhanced non-linearity applications.

Fig. 6 shows how the loss varies with the diameter to pitch ratio of the triangular core PCF in the TM mode. It can be seen from the figure that the loss decreases as the diameter to pitch ratio increases. This suggests that the proposed PCF design has low loss, which is also beneficial for enhanced non-linearity applications, as this is one of the challenges in the trade-off between non-linearity and confinement loss.

Fig. 7 shows how the spot-size varies with the d/Λ ratio of the triangular core PCF in the TE mode. It can be seen from the figure that the spot-size decreases as the d/Λ ratio increases. This indicates that the proposed PCF design has a small spot-size, which is beneficial for enhanced non-linearity applications. It is also noteworthy that the spot-size reduces from around 100 $\mu m^2$ to about 1 $\mu m^2$ as the diameter to pitch ratio increases from 0.70 to 0.95.

The simulation outcomes show that the envisaged triangular core PCF design has a large d/Λ ratio of up to 0.95, resulting in a reduced spot-size of just above 1.00 $\mu m^2$. This suggests that the proposed PCF

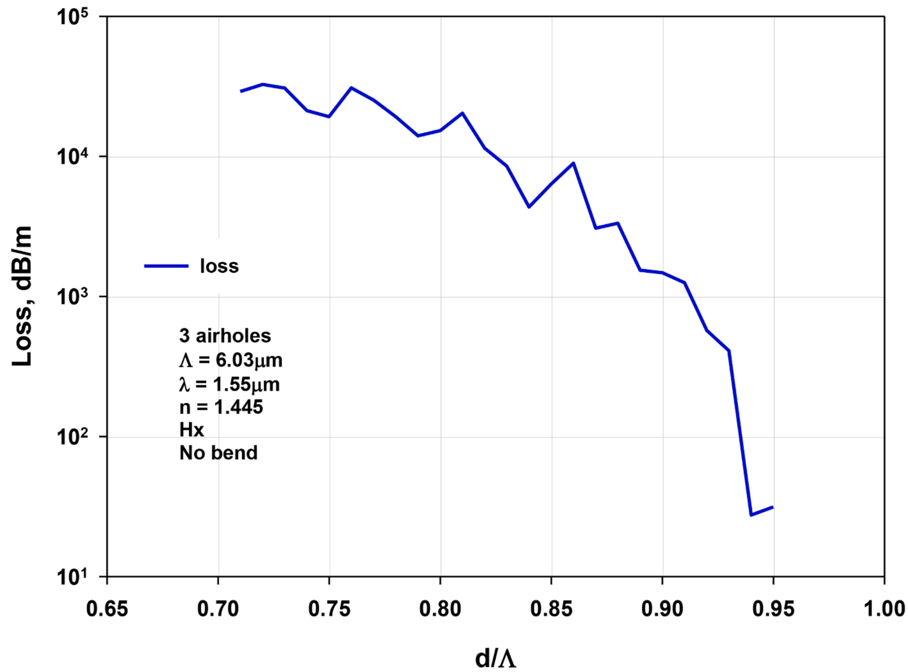


**Fig. 6.** The graph of loss with the variation of d/Λ of the triangular core PCF in the TM mode for 3 air-holes and the triangular core PCF, pitch = 6.03 μm, λ = 1.55 μm, silica of $n$ = 1.445.

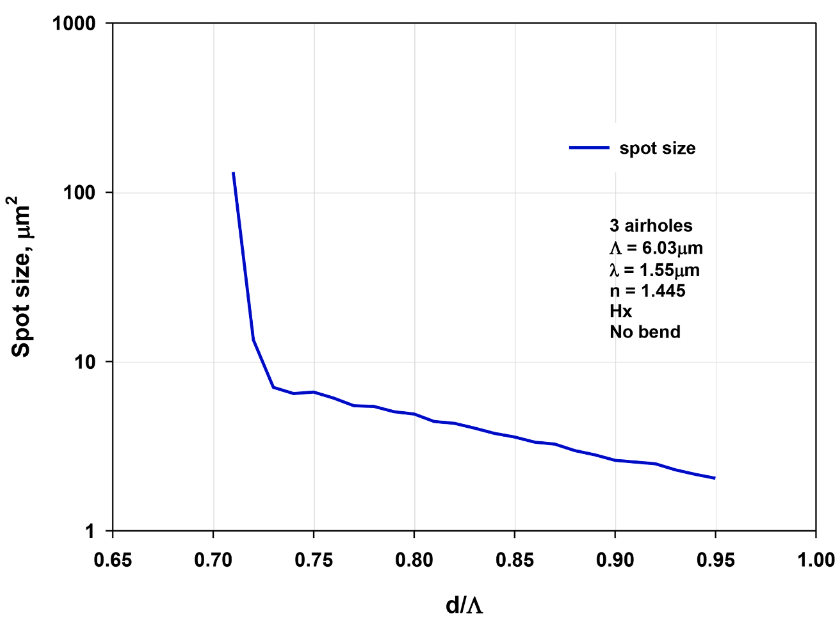


**Fig. 7.** Graph of spot-size being varied with the d/pitch of the triangular core PCF in the TM mode for 3 air-holes and the triangular core PCF, Λ = 6.03 μm, λ = 1.55 μm, silica of $n$ = 1.445.

design could offer the tight optical confinement required for enhanced non-linearity applications.

We believe that this triangular core PCF designed for enhanced non-linearity applications fabrication process can be achieved by utilizing the traditional Stack and Draw technique [31,51–54] or the slurry casting method [1,55–58]. Other fabrication techniques may be used in the fabrication of this design because of the simplistic nature of the structure, having just three large air-holes in the cladding.

## 4. Conclusion

A novel design of PCF for enhanced non-linearity applications is presented. Our study introduces a ground-breaking structural innovation that surmounts the limitations of conventional designs prevalent in the literature. The proposed triangular core PCF can be achieved in silica with a refractive index of 1.445 and also features three large air-holes positioned 120° apart in the core, each with a refractive index of 1.00. The air-holes have a pitch length of 6.03 μm and a radius of 2.86 μm, and the wavelength of operation is 1.55 μm. The design is simulated using the Finite Element Method (FEM) to evaluate its performance in terms of the effective index, the loss, and the spot-size. The promising results from the simulation show that the proposed PCF design has a large d/Λ ratio of up to 0.95, resulting in a reduced spot-size of just above 1.00 μm$^2$. This indicates that the proposed triangular core PCF design could be used to enhance non-linearity applications. The non-linear properties of PCFs are of great interest for various non-linear optical phenomena, such as supercontinuum generation, non-linear frequency conversion, and soliton formation. These phenomena can be tailored by engineering the dispersion properties of the fibre. Due to the simplistic nature of the structure, having just three large air-holes in the cladding of the PCF design achieves the crucial diameter to pitch ratio required for endowing the core with non-linear properties and facilitating effective light guidance. This streamlined approach not only mitigates complexities inherent in prior intricate designs from the literature but also presents a practical and feasible solution, thus addressing the shortcomings of previous structures and offering a straightforward avenue to attain desired non-linear light-guiding properties within the core. This design can be achieved using the traditional Stack and Draw techniques as well as other well-known fabrication methods for PCFs.

## CRediT authorship contribution statement

**Muhammad Uthman:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **B.M.A. Rahman:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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