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Ultra-High Birefringence Property and Low Confinement Loss of Circular Photonic Crystal Fiber for Telecommunication Application

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Abstract: A redesigned PCF structure with minimal confinement loss and high birefringence is proposed in this research paper. It employs a circular lattice arrangement with one ring of identical air holes. High birefringence and low confinement loss are two of the properties that have been numerically studied using the finite element method with circular perfectly matched layer boundary conditions. By adjusting the hole size and spacing, it is possible to achieve both properties simultaneously. At an excitation wavelength of 1550 nm, a numerically obtained modal birefringence of 2.3179×10-2 is observed. Simultaneously, by methodically evaluating the cladding rings, the center-to-center distance between the air holes, and the number of cladding rings with equal diameters, a minimal confinement loss (<10-1) may be achieved. Additionally, the suggested PCF verifies that it is feasible to acquire. Our extremely birefringent fiber can be controllably created thanks to the development of birefringence with structural modifications. The suggested structure has better optical characteristics, making it a potential contender for sensing and broadband dispersion correction.
Keywords: Birefringence, Elliptical Core Hexagonal Photonic Crystal Fiber, Finite Element Mode, Photonic Crystal Fiber, Wavelength Division Multiplexed.

I. INTRODUCTION

In terms of geometric parameters like hole-to-hole distance/spacing [1,2,3], pitch, air hole radius/diameter, and air filling fraction, photonic crystal fibers (PCFs), hole-fibers (HFs), and microstructure optical fibers (HFs) display a spectrum of unique optical properties that cannot be achieved with traditional optical fibers (COFs) technology. PCFs provide more leeway in adjusting birefringence, confinement loss [4], and dispersion [5,6] for any combination of air channels in the vicinity, all without doping the silica core [7].

Optical fibers made on a silica-air microstructure type are known as PCFs. The reduced refractive index cladding and small air holes in the silica backdrop run the length of the fiber [8]. It is typical for air holes to be positioned in periodic patterns inside the cladding, although they may also be hexagonal, octagonal, circular, or square. The central component might be solid (like a silica core) or hollow (like an air core). Just like traditional optical fibers (COFs), the first core type PCF uses a modified Total Internal Reflection (TIR) mechanism to steer light.

The latter employs a novel pathway called the photonic band gap (PBG) to direct light [9]. So, it's not strictly required for PCFs that the core and cladding be constructed of materials with high refractive indices. Additionally, it is not required that all optical fibers use TIR mechanisms to restrict light to their cores.

By including small air passages into the cladding of PCFs, a greater range of design options is available, allowing for tremendous property customization [10]. One may create guiding qualities tailored to a particular application by adjusting the parameters of the silica-air hole microstructure.

PCFs exhibit a wide range of peculiar and unfathomable characteristics, such as permanently operating in a single mode [11], very high or low nonlinearities [12], extremely high or low birefringence [13], extremely flattening and extremely low chromatic dispersion [14], and many more. Due to their better and readily modifiable optical qualities, PCFs may quickly surpass traditional optical fibers in several technical and scientific domains.

II. BACKGROUND AND METHODS OF PCF

A. PCF

An important step forward in optical technology is the development of photonic crystal fibers, also known as holey fibers (HFs). These fibers have a cladding that resembles a two-dimensional (open periodic) array of densely packed glass capillaries, which is drawn at a high temperature. Much research on the extraordinary characteristics of holey fibers has been going on since the first publications detailing their production in 1996 [1]. As the range of possible uses for these fibers continues to develop, more and more academic institutions are beginning to use holey fibers in their investigations. Such fibers are of great interest in the context of numerous optical fiber problems [2–13], nonlinearities properties [14–19], atomic optics [14,20,21], the physics of photonic crystals and quantum electrodynamics [20–24], biomedical optics [26], data transmission [18], super-sensitive gas sensors, microwave sensors, and other practical application areas. The optical fibers that are often used to transmit messages via light are usually constructed from two glasses. A cylindrical core made of solid glass with a higher refractive index runs along the center of the fiber, making it a waveguide. In order to provide a uniform covering for the core, another solid glass with a lower refractive index is used [5]. Silica (SiOz) is a common substance that both glasses are formed of. For silica glass to have a higher or lower refractive index, the element germanium or fluorine is often doped into the material [6]. By creating an index difference between the core and cladding, light may be guided down the fiber's length using total internal reflection (TIR) [7]. This helps to confine the light within the core. Conventional optical fiber describes this kind of fiber. While its current state of the art indicates extensive use in telecom and non-telecom applications, there are certain things that it just cannot perform. For such common fibers, the characteristics of the glass used in their production are the limiting factor [8]. Because silica glass has rigid characteristics, regular fibers aren't going to cut it for certain new uses. Photonic crystal fibers, also known as holey optical fibers (HOFs) or microstructure optical fibers (MOFs), were invented as a possible solution to the problems caused by traditional fibers and are now a staple in fiber-optics technology [9].

B. Evolution of PCF

After the first holey optical fiber was shown in 1996 by Knight et al. [17], the area of PCF research got underway. Holey fibers with periodic air-holes organized in a hexagonal lattice have been practically realized by them [18]. The researchers' first goal was to find a way to guide light using the PBG principle, but they ended up finding that the new holey fiber is more like regular fibers in that it uses a modified TIR mechanism, much like the old ones [9]. It wasn't long before they noticed the new fiber's durability and light-guiding efficiency. Coupled light is also simple to achieve. When comparing the traditional fibers with the PCFs, we found that they differed significantly in both design space and optical characteristics. Figure 2 shows how the PCF research area has grown rapidly in recent years [35]. Since only the most prominent journals are taken into account, the real quantity of papers is more than what is shown in the chart.

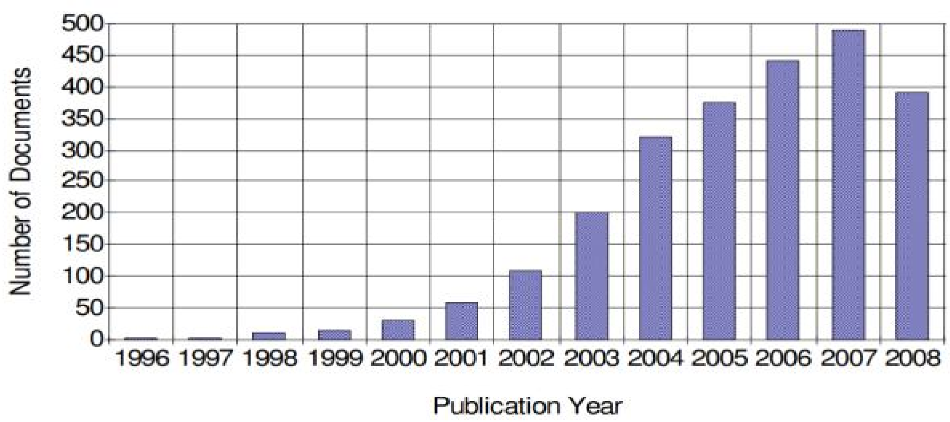

Figure 2 Growth of PCF work document [35]

Thus, index guiding PCF research is ongoing; however, hollow core fibers were not yet feasible owing to the difficulty in creating enough big air holes in the fiber core to meet the dimensions necessary for PBG guidance. A breakthrough in numerical computation—the development of fully vectorially numerical methods—led to the 1978 demonstration of the Bragg fiber[41]. Research on PCF has made significant strides since its discovery in 1978, as shown in Table I [36].

TABLE I
IMPORTANT MILESTONES IN THE EVOLUTION OF HFS

Year	Milestones	References
1978	Idea of Bragg fiber	[37]
1992	Idea of the photonic crystal fibre with air core	[38]
1996	First index guiding (Solid core) PCF introduced	[39]
1997	Endlessly single-mode PCF	[40]
1998	Large mode area PCF	[41]
1999	Hollow core PCF, dispersion shifted PC	[42]
2000	Multicore PCF, PM PCF, Er-doped PCF laser, and SC	[43]
2001	Polymer PCF, nonlinear processes in PCFs, PCF lase	[44]
2002	SF glass PCF, Ultra-flat dispersion PCF	[45]
2003	Tellurite glass PCF	[46]
2004	FWM & Twin photon generation in PCFs, Ge-doped PCF	[47]
2005	PBGs at 1% index contrast, Bismuth PCF	[48]
2006	Hybrid PCF	[49]
2007	Silicon double inversion technique for manufacturing polymer templates for photonic crystals	[50]
2008	Chalcogenide highly nonlinear PCF	[51]
2009	Hollow-core photonic bandgap fiber	[52]
2013	Double cladding seven core photonic crystals	[53]
2014	PCF based nano-displacement sensors	[54]
2015	Design of equiangular PCF	[55]
2015	Integration of PCF fiber laser	[56]

In the time after, it underwent extensive study by academics and industry professionals alike, and it is today a prominent area of electro-optical research [9, 20].

C. Inclination

One of the most significant developments in the history of fiber was the creation of the PCF [9]. It has ushered in an era of boundless opportunity and possibility. Many industrial and scientific applications in linear and nonlinear regimes rely on its exceptional optical features, which include a larger design space, flexibility, and superiority [9, 35]. According to predictions, PCFs and our investigation of their light-control possibilities hold the key to optics's bright future. In the medical field, for instance, new-wavelength lasers or broadband light sources are needed for diagnosis; in the telecommunications industry, more adaptable amplifiers and inexpensive, easy-to-install fibers are sought after; and in the sensor business, sensitive gas detector systems for both on-site and off-site monitoring are sought after. PCFs, with their hollow or solid cores, may function as optical components in all of these new industries [36]. These fibers are ideal for delivering high-power beams for laser cutting and welding since they may display much greater damage thresholds compared to traditional fibers. They have the potential to greatly improve environmental sensing by facilitating a number of nonlinear optical processes. Nevertheless, for a number of new uses, including power supply with ultra-short pulses and pulse compression, design and refinement of additional features are necessary. These features should ideally have enhanced bandwidth, near-zero flat chromatic dispersion, and nonlinear response control [9, 35, 36].

Great technical hurdles persist in doing these vital jobs. The next parts will provide a quick overview of some of these challenges, while the following chapters will go into more depth on them. Taking into account the aforementioned technical challenges and the boundless potential of this emerging area, I have chosen to contribute to the continuing endeavours of developing smart PCFs for a range of technological uses.

D. Applications Based on Dispersion Managed

Even though PCFs provide a lot of leeway in terms of design, designers still have a tough time creating nearly-zero dispersion-flat PCFs (NZDF PCFs), which are necessary for practically all applications [16, 21]. The reason is, that in addition to dispersion-flat features, minimal confinement loss is needed for the majority of dispersion-managed applications [21]. To obtain a dispersion-flat curve and low confinement losses at the same time, designers employ either PCFs with non-uniform cladding [23] or PCFs with multiple rings of air-holes [12] to decrease confinement losses. In addition to being inappropriate for managing wideband dispersion [23], the previous design method significantly increases the holey cladding area and makes manufacturing more difficult [24]. The second method reportedly poses a significant manufacturing challenge due to non-uniform cladding, despite its widespread usage. Increasing the number of design factors has a multiplicative effect on fabrication and tolerance when the cladding is not uniform, as is the case with air-hole modulation. Novel design strategies are necessary to solve these obstacles, which still remain today.

E. Non-linear Applications of PCFs

In the field of nonlinear optics, highly nonlinear PCFs (HNL-PCFs) have found many uses, including optical parametric amplification, wavelength converters, super continuum production, and soliton creation [25, 26]. Choosing an appropriate zero-dispersion wavelength around the telecom window is the most difficult part of designing highly nonlinear PCFs. This is because, on one hand, a PCF with a small pitch and uniformly small air holes will cause the zero-dispersion wavelength to move towards shorter wavelengths [26]; on the other hand, a PCF with a large air hole relative to its pitch will limit the bandwidth available for single mode operation [27]. For this reason, maximizing the air-hole diameter while simultaneously retaining architectural simplicity is of the utmost importance. As the pitch value of HNL-PCFs decreases, controlling confinement loss and being sensitive to changes in the parameters become significant challenges. A greater sensitivity to changes in parameters and a greater confinement loss are outcomes of a narrower pitch [28]. Up until this point, the same difficulty has persisted and requires effective resolution.

F. Applications as Sensor

Sensor applications are well-suited to highly birefringent PCFs, or HB-PCFs. It is necessary to impart pressures to the cladding or to disrupt the symmetry of the fiber axis in order to design extremely birefringent PCFs [29]. Problems with manufacturing and other issues with designing for low confinement losses and almost nil dispersion are brought on by such modifications to PCF claddings. This is because, according to the literature, birefringent fibers should exhibit almost negligible dispersion at the desired wavelength [30]. Because of the need of careful design, this is also a continuous problem.

G. Telecom Application

Optical device applications were the only ones first thought of while PCF technology was being studied, rather than data transmission medium. This occurred because these fibers had very large optical losses [31]. The optical losses have been brought down to 0.28 dB/km recently by using precise and high-tech methods of design and manufacture [32]. As a result, there is a rising tide of enthusiasm for reconsidering PCFs as a medium for reconfigurable data transmission in the future [33]. For these kinds of tasks, PCFs with a big mode area work well. Even if there are papers that deal with this matter, there are additional problems associated with the design of large mode area PCFs (LMA-PCFs).

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III. PROPERTIES AND LOSS CALCULATION OF PHOTONIC CRYSTAL FIBER (PCF)

Achieving excellent properties in birefringence [61-69], dispersion [70-78], single polarization single mode [79-80], nonlinearity [81], and effective mode area [83-85], photonic crystal fibers (PCFs) [52-60] have been widely used in applications such as fiber sensors [86,87], fiber lasers [88,89], and nonlinear optics [42-45] for some time now. Ultrahigh birefringence and distinctive chromatic dispersion are two optical features of PCFs that have been the subject of several research articles; they are almost difficult for standard optical fibers to achieve. Optical fiber communications, filters, sensors, lasers, and more may all benefit from optical fibers having a high birefringence.

A. Chromatic Dispersion

A wave's spectral components are separated by the optical phenomena known as dispersion. A wave's speed is proportional to its wavelength, which causes spectral component separations. To underline that it depends on wavelength, it is frequently referred to as the chromatic dispersion [74]. Fiber dispersion may originate from either the material, which is caused by a material's frequency-dependent reaction to waves, or the waveguide, which is caused by a wave's speed in a waveguide depending on its operating frequency. Signal quality drops due to fiber dispersion in the telecom industry. As seen in Figure 3.1, this is because the arrival timings of the various signal components might vary greatly. When a waveguide exhibits several modes with varying velocities at a single frequency, a phenomenon known as modal dispersion occurs. A particular example of this is the polarization mode dispersion (PMD), which arises from the coexistence of two modes with varying velocities as a result of random flaws that disrupt the waveguide's symmetry [46].

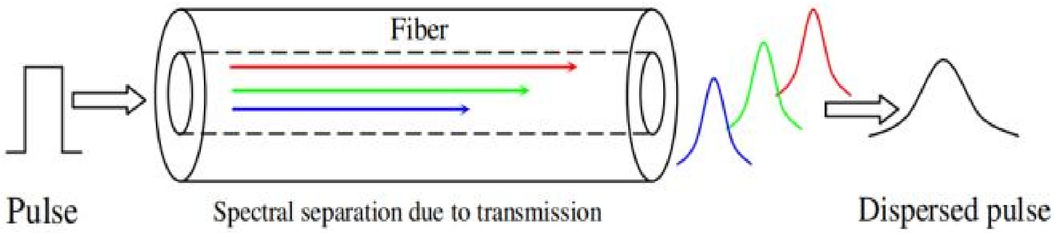

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Figure 3.1 Chromatic dispersion, Pulse Spreading in Optical fiber.

Chromatic dispersion, also known as total dispersion, is the product of material dispersion and waveguide dispersion. While fiber fabrication processes always include some degree of dispersion into the final product, the dispersion of a waveguide may be tuned by adjusting its design characteristics. Once tm(A) is constant and the actual component of the effective index of refraction ne, the material dispersion may be disregarded. Includes CD with dispersion data [11]

$$D = -\frac{\lambda d^2 (Re(neff))}{c d\lambda^2}\left(\frac{ps}{nm.km}\right) \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (1)$$

The operational wavelength is denoted by λ, while the speed of light in a vacuum is represented by 'c'. An effective refractive index, denoted as Re(neff), is the true value of the index.

B. Birefringence

Optical properties of materials whose refractive index changes depending on the polarization and direction of light transmission are known as birefringence.

The term "birefringent" describes these optically anisotropic substances. One common way to measure birefringence is by looking for the largest variation in the material's refractive indices. Plastics subjected to mechanical stress and crystals with asymmetrical structures both exhibit birefringence. Any anisotropic material will cause a light beam to divide or decompose into two components as it travels through it.

Core form may vary significantly over the length of a real optical fiber, including a PCF. In addition to this, a fiber's cylindrical symmetry may be broken by non-uniform tension. A periodic power exchange occurs between the two orthogonal components when the optical fibers become birefringent due to a breakdown in their homogeneity. This effect is responsible for the fact that the only variables in linearly polarized light are the primary axes.

Otherwise, polarization goes through a series of modifications throughout the length of the fiber, first becoming elliptical and then back to linear, all within the span of a single beat. A PM fiber is one in which the birefringence is not controlled by the haphazard size and shape of the core, but rather by stress-applying or symmetry-breaking components deliberately introduced to the fiber. The random polarization effect is reduced in this scenario by purposely produced birefringence. For standard PM fibers, the usual birefringence value is about 10^{-4}.

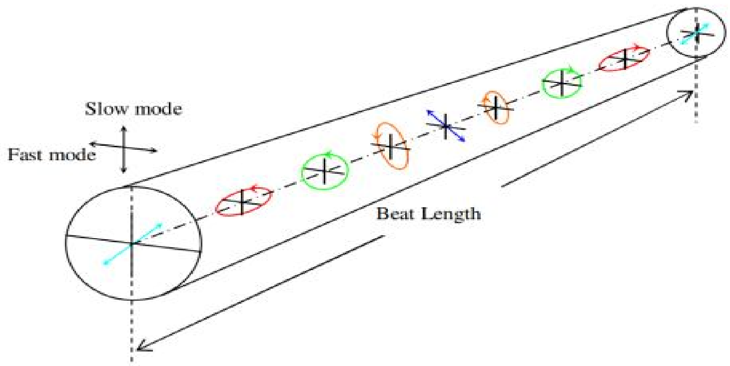

Figure 3.2 Polarization state over one beat length in a birefringent fibre.

The difference between the two effective refractive indices, called the birefringence magnitude, determines the non-standard angle at which the perpendicularity polarized component of light refracts when it enters a material at an acute angle to the optical axis, while the standard low of refraction determines the angle at which the unpolarized light beam enters the material [60–61].

$$\Delta n = n_e - n_0 \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (2)$$

For the prominent core Eigen modes along the x and y axes, LP01 x and LP01 y, the real part value of the effective indices is [60-61],

$$B = Re\left(n_{eff}x\right) \quad Re\left(n_{eff}y\right) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3)$$

C. Effective Mode Area

A quantity of paramount relevance is the effective area. Its primary use was as a metric for non-linearity; a large density of power is required for non-linear effects to be noticeable, and a small effective area provides that. In addition to its significance in numerical aperture, splicing loss, micro-bending loss, macro-bending loss, and confinement loss, the effective area may also be connected to the spot-size w via $A_{eff} = \pi w^2$. For $d<d^* \sim 0.45\Lambda$, PCFs can operate strictly in single mode, however for wavelengths over a particular cut-off λ^*, single mode operation is still achievable even for bigger air holes. For a certain hole size d, we show that the second-order mode's effective area is a helpful idea for calculating this cut-off. Furthermore, we show that, with λ*0, we may return to the eternally single mode regime. This is how the effective area, A_{eff}, was determined [98].

$$A_{eff} = \frac{\left(\iint |\vec{E}|^2 dxdy\right)^2}{\left(\iint |\vec{E}|^2 dxdy\right)\mu m^2} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4)$$

Whereas E is the electric field in the medium.

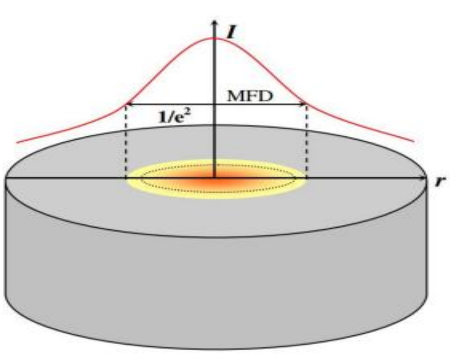

Figure 3.3 Effective mode field diameter with Gaussian Intensity profile.

D. Fiber loss

The IG-PCEs" loss spectrum is also similar to conventional fibers in that it is mostly | determined by the silica material. The intrinsic optical losses of IG-PCFs can be given as follows [91];

$$\alpha\left[\frac{dB}{km}\right] = \frac{A_{SC}}{\lambda^4} + B_{SC} + \alpha_{OH} + \alpha_{IR} \quad \ldots (5)$$

The following variables are defined: α total optical loss, Asc Rayleigh scattering coefficient, Bsc scattering loss due to defects, αOH OH absorption loss, and αIR infrared absorption loss.

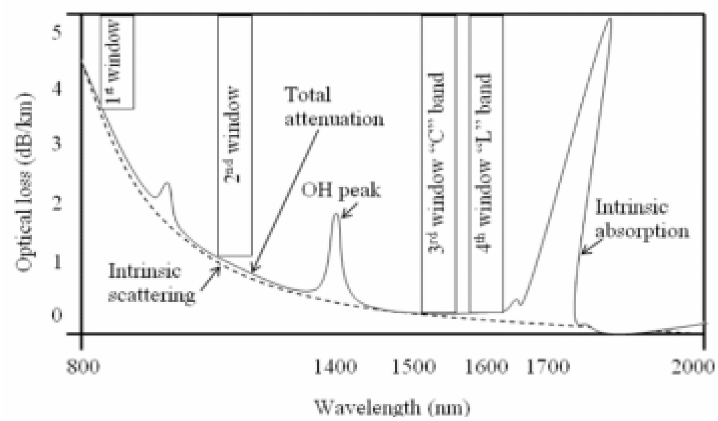

Figure 3.4 Optical Loss with different Optical window

E. Confinement Loss

Signal deterioration occurs as a result of confinement loss, which occurs when some of the directed light reaches the cladding zone. There are three modes that IG PCFs may support: guided, radiation, and leaky. They work similarly to traditional fibers in that they guide light via the TIR process. The loss of leaky modes is referred to as confinement loss among these modes. Except for a limited number of air-holes in the cladding, the effective refractive indices of the core and cladding in PCF are identical. In consequence, guided modes in PCFs are inherently leaky. The presence of an unlimited number of air-holes in the cladding is necessary for PCFs to avoid confinement losses. Theoretically, the small size of the cladding is the source of confinement losses in PCFs. There can be no confinement losses in a fiber with an infinite cladding. This loss is proportional to the core size, air-hole diameter, pitch, and cladding ring count. You may find the confinement losses, L, by using the formula [60-61].

Where, k_0 is the free space wave number and n_i is the imaginary part of n_{eff}.

$$L_c(\lambda) = -20\log_{10} e^{-k_0 n_i} = 5.45751E - 7 * \left(\frac{n_i}{\lambda}\right) = 8.686 * k_0 * n_i \frac{dB}{m} \quad \ldots (6)$$

F. Splice loss

An essential aspect of single mode fiber design is the splice loss. A mismatch, caused by geometrical misalignments or different MFD, causes losses known as splice loss when two comparable fibers or a PCF are coupled with a single mode fiber (SMF) via splicing procedures. Here is the formula to determine the splicing losses: [61]

$$L_s = -20\log_{10}\frac{2w_{SMF}w_{PCF}}{w^2{}_{SMF}w^2{}_{SMF}} \quad \ldots (7)$$

G. Single and Multimode response

1) Typically, the core size determines whether a conventional fiber operates in single-mode or multi-mode. The correct selection of air-hole dimensions and pitches, however, allows PCFs to be constructed for indefinitely single-mode operation. If the d/A ratio is less than 0.45 for a uniform cladding PCF, they will always respond in a single mode; going over this number may cause them to operate in either single or multimode modes. Finding the single mode response is easy with PCFs using the V parameter.

2) One-Only Mode Fiber can handle runs ranging from 2 meters to 10,000 meters, offering a wider distance potential.
3) The typical range of multimode is about 550 meters, but the range of single mode may go up to 10,000 meters (or 40,000 meters with extended range).
4) Light may travel further via single-mode fiber than multi-mode fiber due to the former's reduced power loss characteristic.
5) Optics for SMF are two times as expensive as optics for MMF.
6) However, when included into a project, the additional expense of SMF is insignificant in comparison to MMF.
7) When you don't need the distance that single mode can provide, you should choose multimode fiber since it is more cost-effective and less fragile than single mode.
8) You can achieve 10G speeds with either single-mode or current multi-mode fiber.
9) By contrast, multi-mode fiber (MMF) often employs a longer wavelength of light and a much larger core. The result is that MMF optics are more able to absorb laser light. This translates to less expensive optics in a practical sense.
10) The optics utilized with single-mode fiber (SMF) have much finer tolerances. A narrower laser wavelength and a smaller core make this possible. Because of this, SMF can support transmission over far longer distances and with a larger bandwidth. Compared to multimode fiber, which has a core size of 50 or 62.5 microns, single-mode fiber has a core size of 9 microns, so that light diffraction over distance is lower.

IV. THE PROPOSED DESIGN AND SIMULATION RESULTS

There has been a lot of interest in photonic crystal fibers (PCFs) [100,101] in the last ten years because of their exceptional and novel properties that are difficult, if not impossible, to achieve in traditional optical fibers. These properties include a large wavelength range of single-mode operation [102,103], a controllable effective modal area [104-106], tolerable dispersion [107], high birefringence [108,109], and controllable nonlinearity [110]. One of the most promising properties of PCFs is their strong birefringence, which has many possible uses in fields such fiber-optic sensing, single polarization transmission, and polarization maintaining fibers (PMFs) [114,115]. Typically, asymmetrical cladding or core regions of PCFs are used to create strong birefringence by disrupting the symmetry of PCF structures. Nonlinear applications rely on a small effective modal area [116], and several publications have detailed various PCF designs that achieve this goal. Conversely, optical parametric amplification, wavelength conversion, and super continuum generation (SCG) are just a few of the innovative uses that might benefit from highly nonlinear PCFs. To prevent pulse spreading, long-distance optical data transmission systems need to correct for dispersion. A big negative dispersion DCF may be used to compensate for this. We provide a revised framework for the high-birefringence index that directs PCF in light of this in this chapter. This PCF has an x- and y-axis-slotted variety of air-hole types crammed into a PC cladding around a solid silica core. The suggested construction has an oval central section, a rectangular core, and three varying-sized circular air-holes. Owing to the spaces between. Under external stresses, a fiber structure created with our suggested complex air-holes in a PCF cladding is stronger than that of a conventional design with a solitary size of air-holes. This is because the two air-holes are greater than the spaces between single holes. The design simplicity, wideband near birefringence, large negative dispersion, low effective area, low confinement loss, and high nonlinear coefficient are some of the appealing features of our proposed structure. These properties are highly desirable in sensing applications, nonlinear optics, and high bit-rate transmission networks. Based on the results of the simulations, the developed PCF displays a very high birefringence of 2.3179×10^{-2}. The chapter delves into the origins of birefringence and negative dispersion, exploring how they are affected by structural characteristics in PCFs with varying air-hole diameters in PCF cladding. Additionally, we go over how confinement loss and air-hole rings impact birefringence.

A. *Design Methodology of Proposed PCF*

A high birefringence PCF may be achieved by removing six central rows of air holes from the circular construction, replacing them with elliptical air holes, and then horizontally shifting the remaining rows towards the center. To complete the core area, elliptical air holes are used in lieu of the two vertically oriented center ones. Figure 4.1 shows a cross-section of our suggested PCF. It has an outside ring of one circular air hole with a radius of r_2, an inner ring of two elliptical air holes with dimensions of r_{15} and r_{16}, and a central elliptical air hole with semi-axes of r_{16} and r_{17}. In the horizontal and vertical directions, A_x and A_y represent the hole spacing, respectively. In this case, in Fig.5.1, we will pretend that $r_2 = 0.13\ bm$, $r_{15} = 0.7\ bm$, $f_{16} = 0.13\ bm$, $r_{17} = 0.6\ bm$, $f_{18} = 0.2\ bm$, A_3= 3.0 um, A_{16}= 1.4 um, A_{17}= 2 um, and A_{18}= 1 um. We minimized confinement loss by using six rings, omitting the core ring with the fault. In comparison to the air hole's refractive index of 1.55, the fiber silica's refractive index is 1.43.

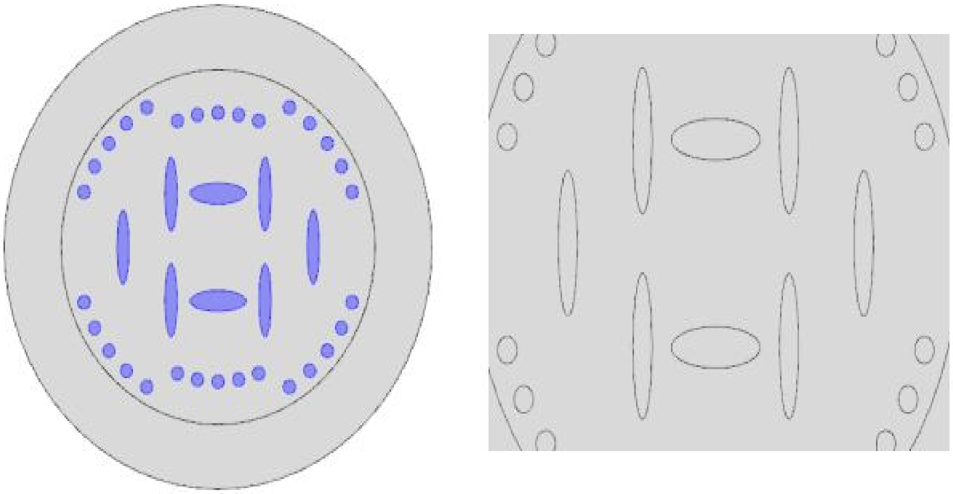

Fig 4.1 Air hole distribution of proposed PCF

There are nine factors in this structure that influence the behaviour of birefringence and confinement loss: r_2, r_{15}, r_{16}, r_{17}, r_{18}, A_3, A_{16}, A_{17}, and A_{18}. To obtain the best outcome, we maintained the pitch constant and altered the radius of the circle and the elliptical air hole.

B. Simulation Result

The fundamental optical field distribution optical field distribution for x & y polarized modes at operating wavelength 1550 nm shows in figure 4.2 according to simulation, it is seen that x and y polarized modes are strongly bounded in the high-index center region.

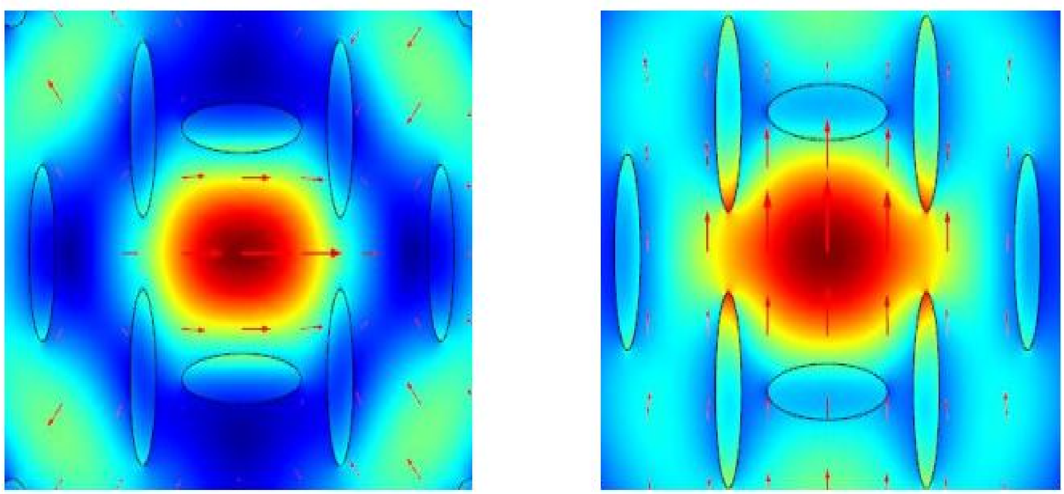

Fig 4.2 Optical field distribution for (a) X-polarized & (b) Y-polarized modes.

As shown in Fig 4.2, the blue parts denote the silica material, the white parts represent circular air holes, and the central-coloured red parts represent shows the intensities of modal fields which are well confined in the core region of the proposed PCF.

C. Birefringence

For the assumption parameters r_2= 0.13 um, r_{15}= 0.7 um, r_{16}= 0.13 um, r_{17}= 0.6 um, r_{18}= 0.2 um, A_3= 3 um, A_{16}= 1.4 um, A_{17}= 2 um, and A_{18}= 1 um, the effective refractive index curve of the suggested PCF is shown in Fig. 4.3. As seen in figure 4.3, the y-polarized first-order mode has a higher effective index compared to the x-polarized first-order mode. The disparity between the two modes results in a high birefringence of 2.3179×10^{-2} at 1550 nm, as shown in figure 4.4.

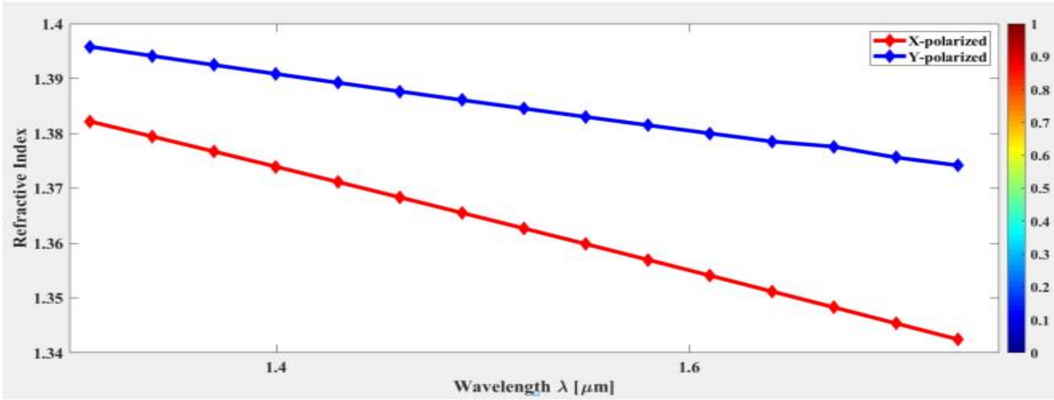

Fig 4.3 Effective refractive index as function of wavelength at r_2= 0.13 um, r_{15}= 0.7 um, r_{16}= 0.13 um, r_{17}= 0.6 um, r_{18}= 0.2 um, A_3= 3 um, A_{16}= 1.4 um, A_{17}= 2 um, A_{18}= 1 um.

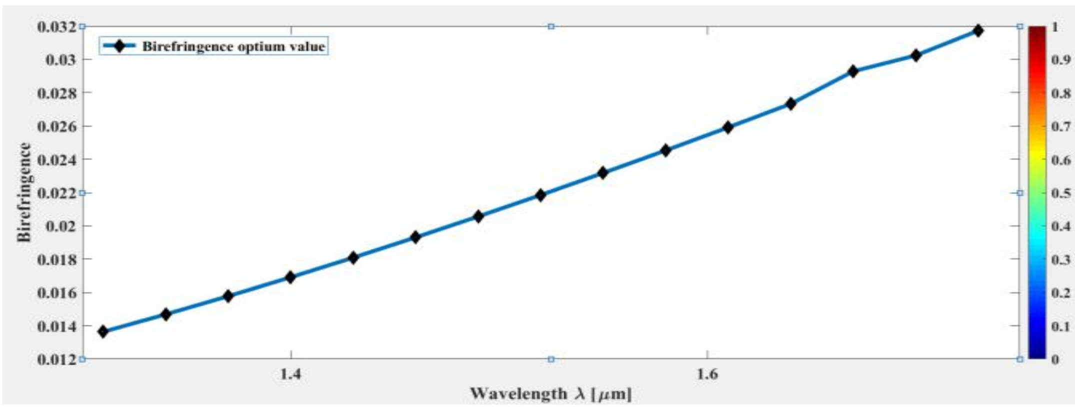

Fig 4.4 Birefringence as function of wavelength at r_2= 0.13 um, r_{15}= 0.7 um, r_{16}= 0.13 um, r_{17}= 0.6 um, r_{18}= 0.2 um, A_3= 3 um, A_{16}= 1.4 um, A_{17}= 2 um, A_{18}= 1 um.

D. Confinement loss

One of the most significant loss parameters in PCFs is the confinement loss. It is feasible to develop guiding qualities that are application specific by modifying the specifications of the holey cladding. For improved field confinement and to reduce confinement loss, the outer circular rings were maintained big. Following is Figure 4.5, which shows the confinement loss of our suggested design as a function of wavelength, using the assumption parameter for x-polarization.

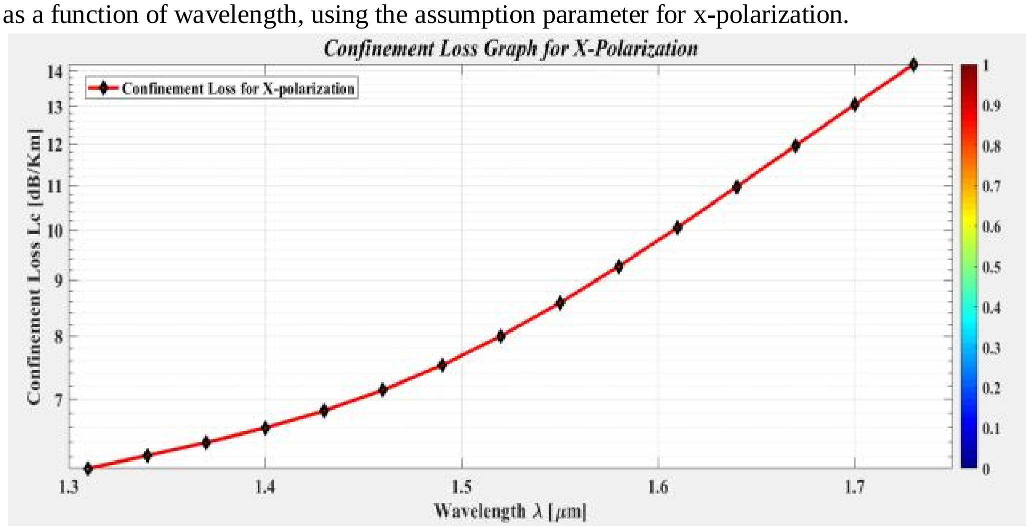

Fig 4.5 Confinement loss as function of wavelength at r_2= 0.13 um, r_{15}= 0.7 um, r_{16}= 0.13 um, r17= 0.6 um, r_{18}= 0.2 um, A_3= 3 um, A_{16}= 1.4 um, A_{17}= 2 um, A_{18}= 1 um.

The simulation results demonstrate that the assumed parameter of the suggested structure results in a very low confinement loss of around 0.1 [dB/km] for X-polarization at 1550 nm.

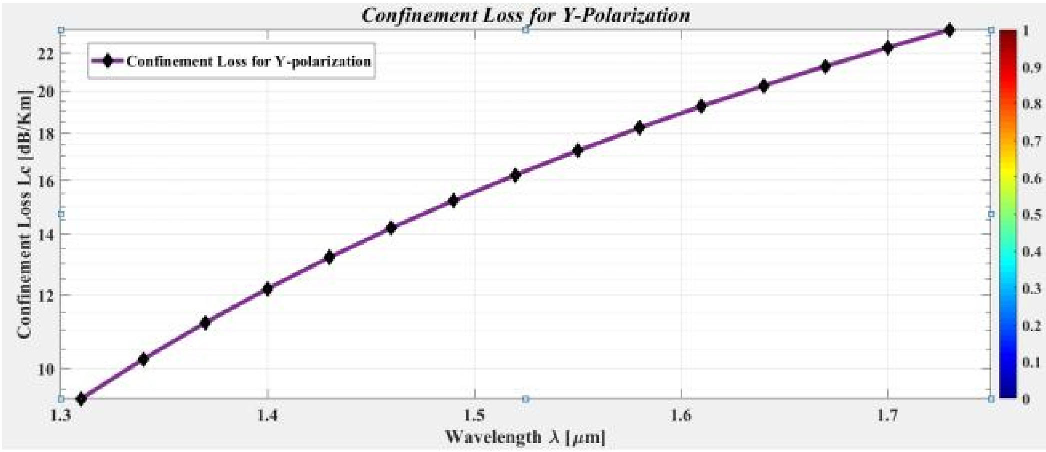

Fig 4.6 Confinement loss as function of wavelength at r_2= 0.13 um, r_{15}= 0.7 um, r_{16}= 0.13 um, r_{17}= 0.6 um, r_{18}= 0.2 um, A_3= 3 um, A_{16}= 1.4 um, A_{17}= 2 um, A_{18}= 1 um.

Assuming a value of 1550 nm for Y-polarization, the simulation results reveal that the suggested structure exhibits an extremely low confinement loss of around 0.1 [dB/km].

E. Optimum Parameter Design

Modifying the hole radius and spacing yielded the following simulation results, which allowed us to examine the effects of these parameters on birefringence and determine the best parameter for the proposed design. The birefringence is increased by reducing r_2, r_{15}, r_{16}, r_{17}, and r_{18} while maintaining the other parameters constant on the assumed value. This is due to the fact that a smaller air hole leads to a significant asymmetry, which in turn creates more birefringence. The birefringence is 2.3179×10^{-2} at 1.55 um for r_2=0.13 um, r_{15}=0.7 um, r_{16}=0.13 um, r_{17}=0.6 um, and r_{18}=0.2 um, which is a factor of one greater than that of traditional PMFs.

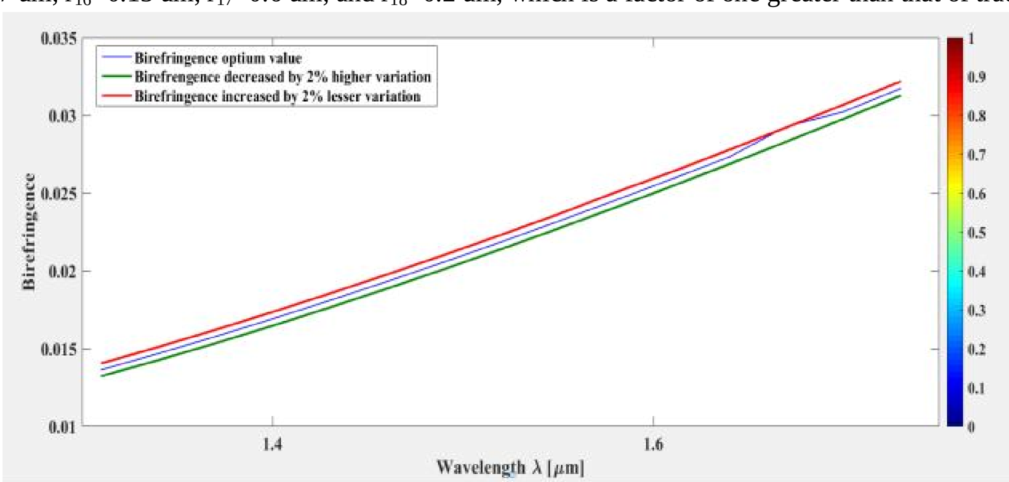

Fig 4.7 Birefringence as function of wavelength for 2% lesser variation (red line) of r_2= 0.1274 um, r_{15}= 0.686 um, r_{16}= 0.1274 um, r_{17}= 0.588 um, r_{18}= 0.196 um & for 2% higher variation (green line) r_2= 0.1326 um, r_{15}= 0.714 um, r_{16}= 0.1326 um, r_{17}= 0.612 um, r_{18}= 0.204 um & the optimum birefringence is for (blue line) r_2= 0.13 um, r_{15}= 0.7 um, r_{16}= 0.13 um, r_{17}= 0.6 um, r_{18}= 0.2 um

In order to delve deeper into the effects of higher variations in circle and ellipse radii (r_2, r_{15}, r_{16}, r_{17}, r_{18}), we find that the birefringence decreases for 2% higher variations and increases for 2% higher variations. This is due to the fact that a larger air hole increases the asymmetry, leading to a higher birefringence of 2.3179×10^{-2} at 1.55 um, which is one order of magnitude greater than in conventional PMFs.

F. Optimum Confinement loss

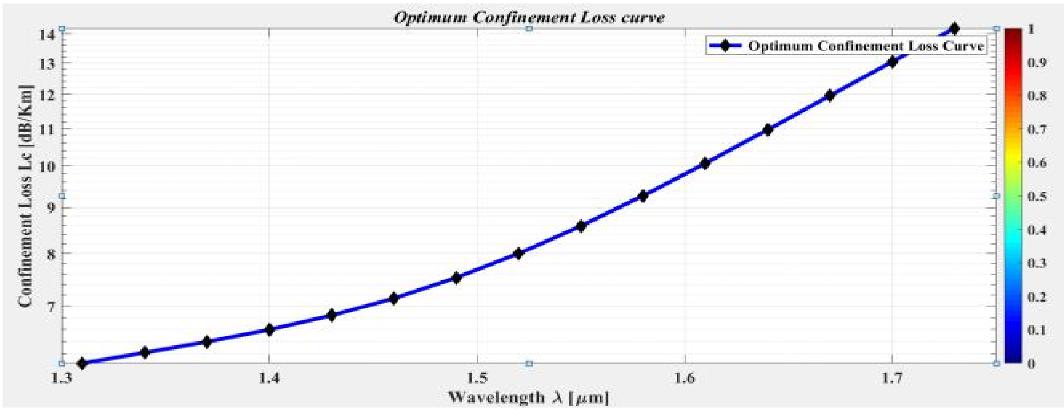

Fig 4.8 Confinement loss as function of wavelength at r_2= 0.13 um, r_{15}= 0.7 um, r_{16}= 0.13 um, r_{17}= 0.6 um, r_{18}= 0.2 um, A_3= 3 um, A_{16}= 1.4 um, A_{17}= 2 um, A_{18}= 1 um.

Examining the confinement loss accuracy of the suggested design was the next step after studying the confinement loss curve of the target wavelength (Fig. 4.9). Ensuring confinement loss flatness may be necessary for PCFs with a global diameter variation of 2% because a 1% difference in fiber global diameter may occur during manufacture.

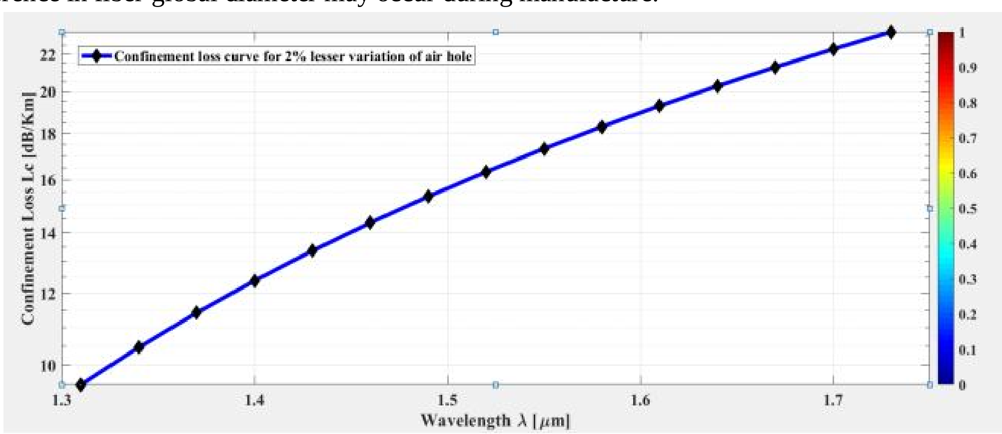

Fig. 4.9 Confinement loss for lesser variation of air hole radius at r_2= 0.1274 um, r_{15}= 0.686 um, r_{16}= 0.1274 um, r_{17}= 0.588 um, r_{18}= 0.196 um.

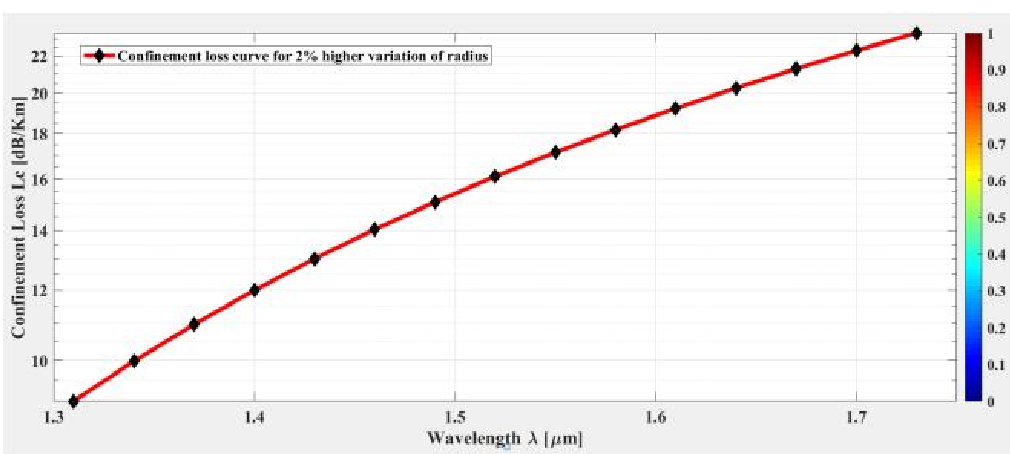

Fig. 4.10 Confinement loss for 2% higher variation (green line) r_2= 0.1326 um, r_{15}= 0.714 um, r_{16}= 0.1326 um, r_{17}= 0.612 um, r_{18}= 0.204 um.

The air-hole radiuses r_2, r_{15}, r_{16}, r_{17}, and r_{18} are adjusted by 2% in our design to assess the accuracy of confinement loss. The corresponding curves for r_2, r_{15}, r_{16}, r_{17}, and r_{18} may be shown in Figures 4.9 and 4.10, respectively. The paper concludes with a table comparing the selected PCF's attributes to those of other fiber designs used in dispersion compensation and sensing applications.

TABLE III
HFs COMPARISON BETWEEN THE PROPOSED DESIGN & OTHER DESIGNS

References	Birefringence B×10-2	Effective Area (µm2)	Confinement Loss (dB/Km)
[117]	2.2×10-2	2.44	<42.4
[120]	2.1×10-2	-	0.47
[122]	1.46×10-2	-	6.1×10-3
Proposed PCF	2.3179×10-2	2.17	<10-1

V. CONCLUSIONS

To summarize, a polarization-maintaining fiber and telecommunication band PCF with a circular form that has been intentionally adjusted to assure strong birefringence and low confinement loss has been presented. The numerical findings show that the suggested design has a strong birefringence of 2.3179×10^{-2} and a low confinement loss of roughly less than 10^{-1} (dB/km), making it a promising choice for use in the telecommunication window design's fiber optic communication connection. As a result of their wide wavelength range of single-mode operation, controllable effective modal area, tailorable dispersion, high birefringence, and controllable nonlinearity, this study can be expanded to design PCFs with circular cladding for octagonal and decagonal designs, as well as with artificially defected core PCFs. The suggested structure is difficult to fabricate due to the usage of several kinds of air holes, including elliptical air, in this thesis. Therefore, finding the best fabrication for sensing and broadband dispersion correction will be the next step. once again, the fiber's splice loss and bending loss, which are essential for certain applications, are not taken into account in this study. Thus, more research is necessary to quantify the splice loss and bending loss and find a way to compensate for these. once again, despite significant efforts to improve birefringence, the confinement loss remains rather high. the confinement loss should be minimized to the greatest extent feasible.

VI. ACKNOWLEDGMENT

This research can be extended to design PCF using circular cladding for octagonal and decagonal design and artificially defected core PCFs as they offer a wide wavelength range of single-mode operation, controllable effective modal area tailorable dispersion, high birefringence and controllable nonlinearity.

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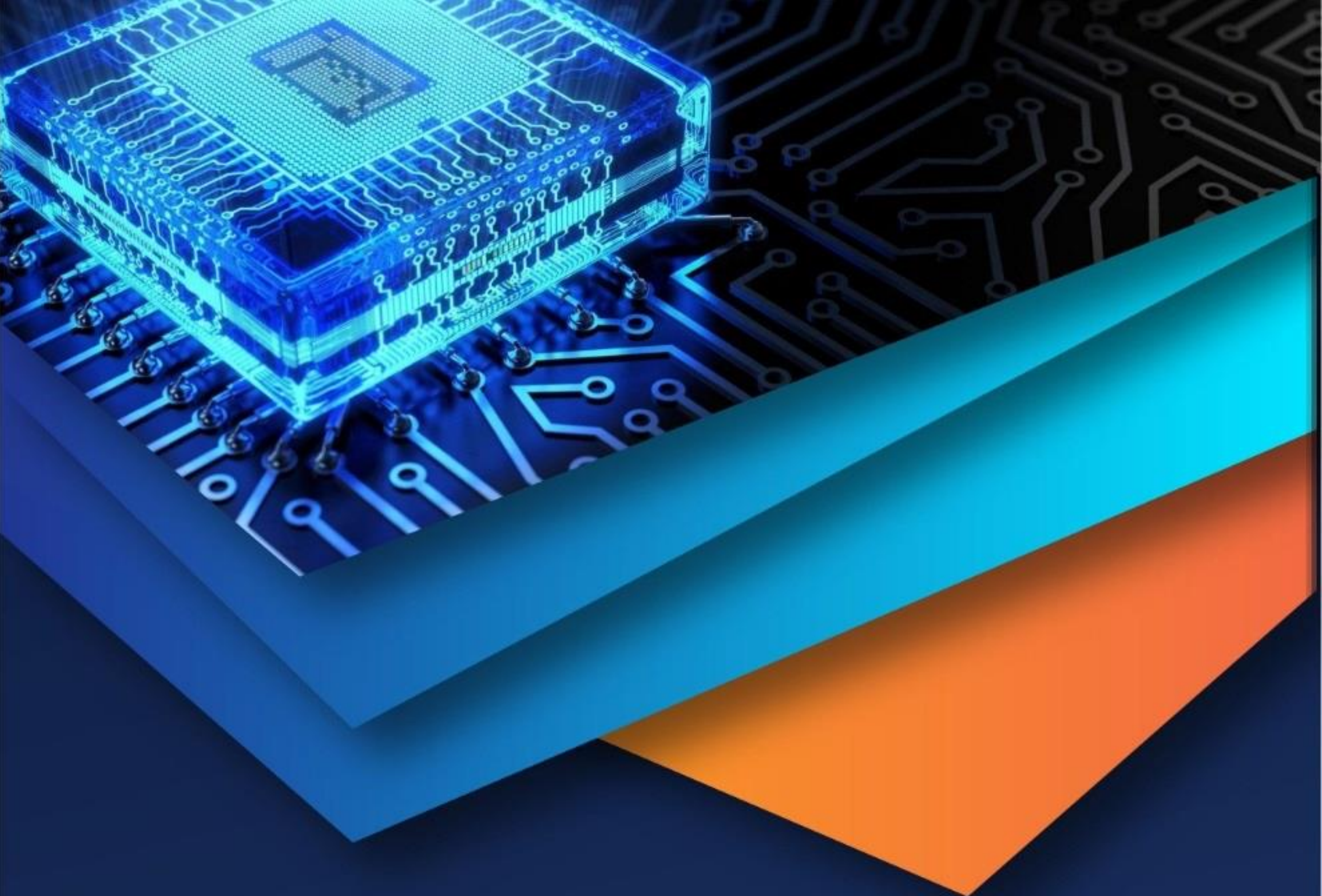

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