Chapter 2

Modeling Photonic Quasi-crystal Fibers

In this chapter, we delineate the design aspects of MOFs. In sections 2.1 and 2.2, we demonstrate the structural arrangements of quasi-crystals and the light guidance in PQFs, respectively. Next, in section 2.3, we discuss the design of PQFs. Section 2.4 explains the analysis of PQFs and their properties. In sections 2.5 and 2.6, we bring out the design of PQFs with various folds of 6, 8 and 10. Of these, we optimize 10-fold PQF as it provides the desired optical properties. Further, we demonstrate that the chosen 10-fold PQF can be used for generating few cycle pulses and can also serve as a biosensor.

2.1 GEOMETRICAL ARRANGEMENTS OF QUASI-CRYSTALS

The photonic quasi-crystals are a new class of non-crystallographic rotational symmetry materials. Quasi-crystals are also called quasi-periodic crystals with repeated arrangement of unit cells in long range order. Mostly any crystal is composed of a three dimensional arrangement of atoms that repeat in an orderly pattern. Quasi-crystals also possess an orderly pattern, but unlike crystals, this pattern never repeats itself exactly. Quasi-crystals do not show three dimensional translation periodicity. Regarding physical characteristics, some physical characteristics resemble with periodic crystals and some with amorphus alloys.

The first quasi crystal was invented by (Shechtman et al., 1984). Shechtman and his coworkers mixed aluminium and manganese in a roughly six-to-one proportion and heated the mixture until it melted. They observed a metallic solid of Al with 14% Mn with long range orientational order, but with icosahedral point group symmetry. This symmetry is inconsistent with lattice translations. Their diffraction patterns were very sharp like those of crystals but could not be categorized to any kind of Bravais lattice, (Shechtman et al., 1984). Shechtman bagged nobel prize in chemistry in 2011 for the
invented of quasi-crystal. The mechanical and physical properties of a quasi-crystal are quite similar in the standard of common metals.

The unusual optical properties of quasi-crystals could pave way for a myriad of applications in photonics. Owing to the fact that some of these properties being surface related, there has been a motivation for surface scientists to explore them further. The first quasi-crystals invented in 1984 are well ordered but have aperiodic intermetallic (Shechtman et al., 1984). They are basically binary and ternary metallic alloys with 60% – 70% aluminium and they exhibit strange properties, such as low friction, low adhesion, high hardness, high wear resistance, etc.

It is known that quasi-crystals provide many unique features, of which, structure of quasi-crystals has attracted much attention of scientists. These crystals do not belong to either periodically ordered type or amorphous type. However, they have do possess a well defined discrete group symmetry and they are incompatible with three-dimensional periodic translation order (e.g. exhibiting 5, 8, 10, or 12-fold symmetry axes), (Goldman and Widom 1991; Samavat12).

It is obvious that the crystal lattices may be carried or mapped into themselves by imposing relevant symmetry operations. In general, symmetry operation is defined as a rotation about an axis that passes through a lattice point. Lattices can be identified with 1, 2, 3, 4 and 6-fold rotation axes that carry the lattice into itself. However, it is not possible to find a lattice that can go into itself under $2\pi/5$ radians. Hence, the lattices do not have 5-fold rotation axis as it is not possible to fill all space with a connected array of pentagons. However, it is to be noted that quasi-crystals do exhibit 5-fold symmetry.

2.1.1 FOLDS IN QUASI-CRYSTALS

Quasi-crystals are found with different kinds of symmetrical folds. Here, we discuss, in brief, the designs of different kinds of folds in quasi-crystals. There are certain basic movements also named as zipper which can be performed to rearrange a particular tiling (Oxborrow and Henley 1993). Fig. 2.1 refers some zipper updates for creating of different shapes from a basic square and triangle.

Fig. 2.1(a) shows the creation of a pair of thin rhombi by a zipper update move
Figure 2.1: Different kinds of zipper update moves for creation of (a) a pair of thin rhombi, (b) A-type flip, (c) B-type flip and (d) a bounce, (e) annihilation of a pair of rhombi. Figure courtesy: (Oxborrow and Henley 1993).
to triangle and square unit. Fig. 2.1(b) shows a type of flip ‘A’, which is a kind of arrangement through which obtuse corners of the thin rhombus are joined. Fig. 2.1(c) is another kind of flip named ‘B’-type and Fig. 2.1(d) is one bounce. Six types of bounces are possible in quasi-crystals. Bounces are related to the rotation of the active thin rhombus, whose arrow reverses the direction by $\pi/3$ radians clockwise and $\pi/6$ radians anticlockwise, respectively, about the point at which two thin rhombi touch. Fig. 2.1(e) represents the annihilation of a pair of thin rhombi.

There are several types of arrangement of basic unit cells as shown above which can form a quasi-crystal structure. There are several geometrical schemes adopted for constructing the structure of quasi-crystals. The most popular schemes for lattice arrangement of quasi-crystals are Stampfli, Penrose, Amman-Beenkar, etc. Fig. 2.2 portrays a 6-fold Stampfli tiling, (Zhao 2009). The square and triangular unit cells are generally used for Stampfli type of tiling.

**Figure 2.2:** Schematic of Stampfli tiling. Figure courtesy: (Zhao 2009).

Fig. 2.3 represents the example of a Penrose tiling, (Zhao 2009). The structure formed here consists of thin and fat rhombi unit cells.
Even though both Stampfli and Penrose can give rise to a particular fold of quasi-crystal, the basic unit cells and their arrangement will be always different. The Amman-Beenkar tiling scheme has been proposed as an extension of Pensrose scheme of tiling. In general, 8-fold quasi-crystals arrangements are explained with Amman-Beenkar tiling. Here the arrangement consists of thin rhombi and square unit cells.

Fig. 2.4 illustrates the arrangement of square and rhombus unit cells for a 8-fold quasi-crystal, (Ricciardi et al., 2009).

In the case of quasi-crystals, there are several arrangements followed for building the structure. Currently, the famous pattern of quasi-crystal arrangements are Penrose, Stampfli, Amman-Beenkar, etc. At this juncture, it is to be noted that the PQFs designed with these arrangements exhibit several unique optical properties over PCF, (Kim et al., 2007). It is known that, the PQFs have overcome the limitations of the PCFs in enhancing the single mode condition regime from $d/\Lambda = 0.45$ to 0.55. Further, they promise for a wide zero dispersion regime. Table 2.1 depicts the milestone in the development of PQFs.
2.2 DESIGN AND GUIDING MECHANISM IN PQFs

For the first time, Kim proposed the 6-fold PQF with index guidance and analyzed its optical properties, (Kim et al., 2007). In the case of PQF, the introduction of the quasi-structured periodic lattice of microstructured air holes in the cladding region enhances unique optical properties. Being an emerging field, the literature relating to the analysis of PQF properties is very much limited. The geometrical structure of the first proposed 6-fold PQF is illustrated in Fig. 2.5. Here, the diameter of the air holes is denoted as ‘d’ and the lattice constant is represented as ‘Λ’. The geometrical arrangement in the cladding region of the reported PQF was constructed as a combination of square and triangular lattice air holes. In solid-core PQF, the light is guided by the modified total internal reflection. A novel dual core PQF has been reported in 2009 (Kim et al., 2009). Later, PQFs with different folds have been investigated and their corresponding optical properties have also been analyzed (Zhao et al., 2010). Fig. 2.6 depicts the PQFs with Penrose, Stampfli, Amman-Beenkar tilings. Fig. 2.6 (a) shows a 6-fold Stampfli type of tiling with a combination of square and triangular unit cells.
Table 2.1: Milestone in the development of PQFs.

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Refs.</th>
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<tbody>
<tr>
<td>6-fold symmetric PQF</td>
<td>(Kim et al., 2007)</td>
</tr>
<tr>
<td>Dual-core PQF</td>
<td>(Kim et al., 2009)</td>
</tr>
<tr>
<td>Air guiding with PQF</td>
<td>(Sun et al., 2010)</td>
</tr>
<tr>
<td>Single-mode 12-fold PQF</td>
<td>(Zhao et al., 2010)</td>
</tr>
<tr>
<td>V parameter for PQFs</td>
<td>(Zhao et al., 2010)</td>
</tr>
<tr>
<td>PQF with large negative dispersion</td>
<td>(Yu-He et al., 2010)</td>
</tr>
<tr>
<td>PQF stretcher</td>
<td>(Sivabalan and Raina 2011)</td>
</tr>
<tr>
<td>PQF amplifier</td>
<td>(Sivabalan and Raina 2012)</td>
</tr>
<tr>
<td>Second harmonic generation in PQF</td>
<td>(Bhattacharjee et al., 2013)</td>
</tr>
<tr>
<td>Photonic quasi-crystal hollow core fibers</td>
<td>(Bahrampour et al., 2013)</td>
</tr>
<tr>
<td>Twin bow-tie polymer PQF</td>
<td>(Knight et al., 1996)</td>
</tr>
<tr>
<td>PQF design with various folds for SHM</td>
<td>(Bhattacharjee et al., 2014)</td>
</tr>
<tr>
<td>Zero birefringence 8-fold PQF</td>
<td>(Bahrampour et al., 2014)</td>
</tr>
<tr>
<td>ZBLAN PQF</td>
<td>(Su et al., 2014)</td>
</tr>
<tr>
<td>PQF based on the Thue-Morse sequence</td>
<td>(Ferrando et al., 2015)</td>
</tr>
<tr>
<td>PQF design for FCP generation (our work)</td>
<td>(Gandhi et al., 2015)</td>
</tr>
<tr>
<td>As\textsubscript{2}Se\textsubscript{3}-based PQF</td>
<td>(Zhao et al., 2016)</td>
</tr>
<tr>
<td>PQF based biosensor (our work)</td>
<td>(Gandhi et al., 2016)</td>
</tr>
</tbody>
</table>

Fig. 2.6 (b) represents an 8-fold Penrose tiling consisting of thin rhombi and square unit cells. Fig. 2.6 (c) shows the arrangement of square and rhombus unit cells which slightly follows the extension of the Penrose tilings.

In this thesis, a detailed analysis of geometrical structure of the PQF has been carried out by using FEM based software called COMSOL Multiphysics. In FEM, the geometrical structure of the PQF design is represented in $x−y$ plane in 2D. The full area of the PQF design is taken into account of several segments of triangular elements with
perfectly matched layer. Based on the refractive index profile, the size of area is chosen for meshing as shown in Fig. 2.7. It is used to estimate the mode field distribution of the light in two dimensional analysis of the PQF. Besides, the chosen meshing area in the core region is very less and hence the confinement is more at the center of the PQF. The next important step in the geometrical analysis is to solve the designed PQF using the FEM. This FEM technique, which solves the microstructured fibers analytically. It may be noted that the microstructured optical fibers of various designs have been reported
by the FEM analysis. In this thesis, we adopt this vital technique for the analysis of the proposed PQFs. This FEM technique is extremely flexible for calculating the different symmetries, (Kawano and Kitoh 2001).

The light propagation in PQFs is described using Maxwell’s equations. The basic equation for FEM analysis is given as:

\[
\nabla \times (\mu_r^{-1} \nabla \times E) - k_0^2 \varepsilon_r E = 0;
\]

(2.1)

where \(\mu_r\) is the relative magnetic permeability, \(E\) is the electric field intensity, \(k_0\) is the free space wavenumber, and \(\varepsilon_r\) is the relative permittivity of dielectric. By choosing the whole fiber area with several elements for meshing, the following equation is obtained,

\[
[K]\{E\} = k_0^2 n_{eff}^2 [M]\{E\},
\]

(2.2)

where \([K]\) and \([M]\) are the finite element matrices. \(\{E\}\) is the discretized electric field vector and \(n_{eff}\) is the effective refractive index. Using this \(n_{eff}\), the optical properties such as \(V\) parameter, dispersion, confinement loss, nonlinearity, etc, can be analyzed.
2.3 PQF: FABRICATION

It is known that the fabrication process is an essential part of design and development of new fibers. The quasi-periodic arrangement cannot be realized by conventional methods like stack and draw, extrusion and drilling, etc (Mrazek et al., 2004). However, PQFs can be fabricated by so called sol-gel method.

The sol-gel fabrication approach is complex casting technique which is independent of the arrangements of air hole, hole-to-hole spacing and shapes of the air holes. The various steps in a sol-gel process for fabricating microstructured optical fiber are presented in Fig. 2.8.

![Block diagram of various steps in fabrication processes](image)

**Figure 2.8:** Block diagram of various steps in fabrication processes, (Bise and Trevor 2005).

**Step 1:** In mixing and casting, the sol is mixed with the additives and kept under centrifugation for removing the impurities. Besides, gelling agent is added for solidification by freezing to make the molten state for casting.

**Step 2:** In this step, after aging in the molds, the mandrel is removed. Then tubes are launched under water directly onto carriers.
Step 3: In this step, the carrier or tube assemblies are placed into the drier where the tubes are made to slowly rotate and dry over several days in a carefully controlled atmosphere.

Step 4: In this process, the tubes are loaded into a silica ‘boat’ and heated in various gases to remove organic compounds, water, and refractory impurities.

Step 5: This is the last step of the process, in which the purified body is consolidated to clear glass in chlorine, helium, and oxygen.

This sol-gel technique is low cost and it has the ability of producing fibers with less bending loss. The main merit of the sol-gel technique is its design feasibility.

2.4 ANALYSIS OF STRUCTURAL PROPERTIES

Figs. 2.9 (a) illustrates the geometrical arrangement of the proposed fiber and field distribution at 1060 nm. The structure of the cladding region consists of air holes of diameter $d$ and pitch $\Lambda$, with five rings of air holes. In the center region, the air hole is removed and the solid silica core can be described as a defect and this gives rise to the propagation of guided modes. The refractive indices of air holes and silica are 1 and 1.45, respectively. Here, the pitch, $\Lambda$, is varied from 2 to 10 $\mu$m, in steps of 2 $\mu$m.

Fig. 2.9 (b) is the contour plot that represents the fundamental mode field distribution at 1060 nm. Fig. 2.9 (b) essentially represents a 6-fold SC-PQF as there are 6-folds in the first ring of SC-PQF. Further, it is also named as solid core photonic octagonal quasi-crystal fiber since it resembles the structure of octagonal quasi-crystal.

Fig 2.10. explains the variation of the effective index as a function of wavelength. For shorter wavelengths, the fields are tightly confined in the silica of core region and so the modal index is higher than the effective index of the cladding. For longer wavelengths, however, the fields overlap the holes and hence the modal index is lower. We observe that the slope of the effective index curve decreases for the higher values of the pitch.
Figure 2.9: (a) Geometric structure of the proposed SC-PQF, which is composed of square and triangular basic units. (b) The fundamental mode field distribution of a contour plot at 1060 nm.

Figure 2.10: Variation of effective index as a function of wavelength for various pitches ($\Lambda = 2, 4, 6, 8$ and $10 \mu$m).

2.4.1 DISPERSION

Controlling light propagation by tailoring the waveguide dispersion is widely practised, particularly in ultrafast nonlinear processes, dispersion and chirp compensation, and short pulse fiber lasers and amplifiers. The dispersion is an effect which
causes the different spectral components in a light pulse to travel with different speeds, ultimately resulting in spreading of pulses. This dispersion is known as chromatic dispersion. This chromatic dispersion coefficient can be derived from the frequency dependant propagation constant, $\beta = \frac{k}{\omega}$. The dispersion can be calculated by the following relation,

$$D(\lambda) = \frac{dk}{d\omega} = -\frac{\lambda}{c} \frac{d^2 n_{\text{eff}}}{d\lambda^2},$$  \hspace{1cm} (2.3)

where $n_{\text{eff}}$ is the effective refractive index of SC-PQFs. Index guiding SC-PQFs surrounded by five ring air holes can have a large waveguide contribution to the material dispersion. Therefore both normal and anomalous dispersion can be achieved as, in Fig. 2.11. This allows the dispersion management of the fibers even in the visible wavelength range with a suitable cladding design by changing the $\Lambda$ values (i.e., $\Lambda = 2, 4, 6, 8, 10 \mu m$). GVD is determined from the second derivative of the effective mode index as a function of the wavelength. We use the following expressions for determining the GVD and third order dispersion (TOD).

$$\beta_2 = \frac{d}{d\omega} \left[ \frac{dk}{d\omega} \right] = -\frac{\lambda^3}{2\pi c^2} \frac{d^3 n_{\text{eff}}}{d\lambda^3},$$ \hspace{1cm} (2.4)

and

$$\beta_3 = \frac{d}{d\omega} \left[ \frac{d^2 k}{d\omega^2} \right],$$ \hspace{1cm} (2.5)

where $k$ is the wavenumber, $\omega$ is the angular frequency. Figs. 2.12 and 2.13 represent the variation of GVD and TOD against wavelength for various values of pitch ($\Lambda = 2, 4, 6, 8$ and $10 \mu m$).

### 2.4.2 KERR NONLINEARITY

Before calculating the nonlinearity of the SC-PQF, it is essential to calculate the effective mode area, $A_{\text{eff}}$, of the fundamental mode. The following relations are used for calculating the effective mode area and effective nonlinearity,

$$A_{\text{eff}} = \frac{\left( \int \int_{-\infty}^{\infty} |E(x, y)|^2 dx dy \right)^2}{\int \int_{-\infty}^{\infty} |E(x, y)|^4 dx dy},$$ \hspace{1cm} (2.6)

$$\gamma(\lambda) = \frac{2\pi n_2}{\lambda A_{\text{eff}}},$$ \hspace{1cm} (2.7)
Figure 2.11: Variation of dispersion against wavelength for the different values of the pitch ($\Lambda = 2, 4, 6, 8$ and $10 \, \mu$m) with wavelength ranging from 200 to 3000 nm.
**Figure 2.12:** Variation of GVD against wavelength for the different values of the pitch ($\Lambda = 2$, 4, 6, 8 and 10 $\mu$m) with wavelength ranging from 200 to 3000 nm.

**Figure 2.13:** Variation of TOD against for the different values of the pitch ($\Lambda = 2$, 4, 6, 8 and 10 nm) with wavelength ranging from 200 to 3000 nm.
Figure 2.14: Wavelength dependence of nonlinearity for different values of the pitch ($\Lambda = 2, 4, 6, 8$ and 10 $\mu$m) with wavelength ranging from 200 to 3000 nm.

Here, $A_{e f f}$ is the effective area of the fundamental mode field distribution and $n_2$ is the nonlinear refractive index coefficient. In the proposed SC-PQFs, the optical properties have been computed for a wide wavelength range from 200 - 3000 nm. Fig. 2.14 describes the variation of nonlinearity as a function of wavelength.

Table 2.2. describes the obtained results of dispersion and nonlinearity for 1060 nm wavelength. From the results, we get very low anomalous dispersion ($\approx 0.015$ ps/km) and high nonlinearity ($\gamma = 1240.172$ W$^{-1}$km$^{-1}$) for $\Lambda = 2$ $\mu$m which would be optimum for the few cycle optical pulse generation.

Table 2.2: Optical properties the proposed fiber parameters at 1060 nm wavelength.

<table>
<thead>
<tr>
<th>Pitch($\mu$m)</th>
<th>Dispersion(ps/nm.km)</th>
<th>Nonlinearity (W$^{-1}$km$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.12</td>
<td>1240.172</td>
</tr>
<tr>
<td>4</td>
<td>0.4</td>
<td>108.284</td>
</tr>
<tr>
<td>6</td>
<td>0.35</td>
<td>50.726</td>
</tr>
<tr>
<td>8</td>
<td>0.02</td>
<td>30.148</td>
</tr>
<tr>
<td>10</td>
<td>0.015</td>
<td>3.279</td>
</tr>
</tbody>
</table>
Next, we extend the study of optical properties in different folds of the PQFs. In previous analysis of the SC-PQF, we have optimized the pitch, $\Lambda$, around 2 $\mu$m which shows better results compared to other values of pitch. We also conclude that for lesser values of pitch, the dispersion is minimum and hence the mode field confinement is larger which brings in high nonlinearity. Further, in the next analysis of SC-PQF for different folds, we have carefully chosen the value of pitch, $\Lambda$ to be 2.5 $\mu$m for the required optical properties and design feasibility of different folds.

2.5 MODELING SC-PQF WITH 6, 8 AND 10-FOLDS

Fig. 2.15 shows the geometrical cross section of 6, 8 and 10-folds of a proposed PQF. The arrangement conforms to the practice relating to the angular distribution of air holes from the center of the PQF by a scattering radius $r_s = \Lambda \times \sin(\pi/n)$, where $n$ is the number of folds and $\Lambda$ is pitch or lattice constant. It is to be noted that the term “fold”is a measure of rotational symmetry. Here, it should be emphasized that the various folds are designed by keeping the pitch as a constant. However, the air-hole diameter is varied to obtain the desired folds. First, we design a 6-fold PQF with the repetitions of square and equilateral triangles and the same is shown in Fig. 2.15 (a). Here, we keep the diameter of the air-hole, $d$, as 1 $\mu$m and the pitch, $\Lambda$, as 2.5 $\mu$m. Fig. 2.15 (b) illustrates a 8-fold PQF which is designed with the square and rhombus combinations. Here, airhole diameter is chosen to be 1.05 $\mu$m. Next, we design a 10-fold PQF with $d = 1.1$ $\mu$m and the resulting geometry is depicted in Fig. 2.15 (c). Here, we follow Penrose and Amman-Beenkar quasi-crystal tiling schemes for both 8 and 10-folds (Liu et al., 2011; Rechtsman et al., 2008). The inspiration for the structural arrangements of these folds stems from (Wang et al., 2003; Romero-Vivas et al., 2005). Further, we keep the $d/\Lambda$ ratio lesser than 0.525 to ensure that the PQF exhibits single mode condition. It is to be noted that with the increase in fold, the number of air holes in the first ring of cladding increases which eventually makes the confinement of the modes tighter and circular.
2.6 OPTICAL PROPERTIES OF THE 6, 8 AND 10-FOLDS PQF

In this section, we explore the various waveguiding properties of the proposed 6, 8 and 10-fold PQF. As a first step, we find the effective refractive index using FEM and the same is used to compute the linear birefringence and dispersion. Next, we compute the effective nonlinearity by calculating the fundamental mode field area. Finally, we calculate the quality factor of the fundamental mode.

Before embarking into the study of the linear properties, it is essential to compute the effective refractive index. Here, we compute the two effective refractive indices $n_{eff}^x$ and $n_{eff}^y$ of $x$ polarization and $y$ polarization components. Fig. 2.16 (a, c) represents the polarized mode field distributions of the $x$ and $y$ polarization components and Fig. 2.16 (b, d) describes the electric field profile along $x$ and $y$ polarization components for the three different folds of PQF. From Fig. 2.16 (a - d), it is known that when the number of folds increases, the confinement becomes more tight and circular and this property ultimately helps improve the quality factor of the fundamental mode field distribution.

2.6.1 BIREFRINGENCE

The main goal of this work is to explore the optical properties of a PQF for few cycle pulse generation. Therefore, it is highly important to check if the asymmetry introduced in the PQF structure induces birefringence. Thus, for ensuring the single mode condition in the proposed PQF, we design a PQF in such a way that it exhibits a less birefringence. Now, we proceed to quantify the amount of birefringence induced...
**Figure 2.16:** (a, c) Fundamental mode field confinement of the $x$ and $y$ polarization components at 1060 nm wavelength, (b, d) Fundamental mode field profile of $x$ and $y$ polarization components for the three different folds of PQF at 1060 nm wavelength.
Figure 2.17: Effective index as function of wavelength for 6, 8 and 10-fold PQF from 600 to 3000 nm wavelength.

Figure 2.18: Effective index as function of wavelength for 6, 8 and 10-fold PQF from 600 to 3000 nm wavelength.
owing to asymmetry introduced while designing the desired PQF structure. The birefringence of the PQF is calculated by considering the effective refractive indices of the two different polarization modes, i.e., \( n_{\text{eff}}^x \) and \( n_{\text{eff}}^y \) of \( x \) polarization and \( y \) polarization components. Figs. 2.18 (a) and (b) depict the effective refractive index as a function of the wavelength for both \( x \) polarization and \( y \) polarization components.

Eventually, all the single mode fibers exhibit two orthogonal polarization modes of the mode field distribution for each wavelength. Birefringence can be differentiated by linear and nonlinear birefringences. The linear birefringence occurs due to the unintentional asymmetry as a result of the fabrication method, (Agrawal 2012). These two different polarization modes are calculated by using the following relation, (Senior 2009),

\[
B = |n_{\text{eff}}^y - n_{\text{eff}}^x|.
\]

Here, \( \lambda \) is the wavelength of light, \( n_{\text{eff}}^x \) and \( n_{\text{eff}}^y \) are the effective refractive indices of \( x \) and \( y \) polarizations. These modes are calculated by using FEM. This linear birefringence can vary between \( 10^{-6} \) to \( 10^{-3} \) from low to high birefringent fibers, (Agrawal 2012; Ortigosa Blanch et al., 2000).

![Figure 2.19: Variation of birefringence as a function of wavelength for 6, 8 and 10-folds PQF](image)

Fig. 2.19 describes the variation of birefringence over wavelength for three folds.
of the proposed PQF. We observe that the birefringence increases as the wavelength increases. This is due to a relatively large effective refractive index difference between $x$ and $y$ polarization components for higher wavelengths. Further, we note that the birefringence also increases when the number of folds is increased since the asymmetry increases with the folds. Although the asymmetry is introduced in the proposed PQF, here, all the folds exhibit a very less birefringence. Of these folds, the 10-fold PQF exhibits a relatively high birefringence due to the more asymmetry in the cladding structure.

2.6.2 DISPERSION

In this sub-section, we compute the next important linear property called dispersion. We take the second derivative of the effective refractive index, $n_{eff}$ to calculate the dispersion as a function of wavelength.

![Variation of dispersion against wavelength for three different folds of PQF](image)

**Figure 2.20:** Variations of group velocity dispersion as function of wavelength for three different folds of PQF

The variation of dispersion against wavelength for three different folds is shown in Fig. 2.20. We observe that the dispersion switches from normal to anomalous regime when wavelength is increased. It is due to the less confinement of the fundamental
mode up to a wavelength of 1040 nm approximately and beyond that, the confinement becomes much pronounced and hence this, results in anomalous dispersion. Further, we note that the 10-fold PQF provides a very less dispersion of -2.4765 ps$^2$/km at 1060 nm wavelength when compared to the other folds. Among all the folds, we are interested in calculating the zero dispersion wavelength for the ten-fold PQF and the same has been observed at 1040 nm wavelength as it provides a less dispersion which forms another crucial requirement for few cycle pulse generation.

### 2.6.3 CONFINEMENT LOSS

The absorption or attenuation of incident light in the conventional optical fibers occurs by several effects, namely, Rayleigh scattering, material absorption, and scattering or absorption by impurities of the material, (Gris-Sanchez et al., 2011). There are also other losses taken into consideration, say, bending loss and confinement loss. The confinement loss occurs due to the light leakage into the cladding region and bending loss is arises due to the bending of the optical fiber. We calculate this confinement loss by using the FEM. The fundamental mode of the incident light has high intensity at the center core region and fades with increase in radius. Thus, the light which is extended into the cladding region can be calculated as confinement loss of the fiber. This confinement loss can be calculated in the traditional PCF by using the FEM with perfectly matched layer as the boundary condition, (White et al., 2002). In such case, the effective refractive index has both real and imaginary parts. The calculated complex effective refractive index of the fundamental mode at different wavelengths in dB/m was computed using, (Ademgil and Haxha 2007)

$$L_c = 8.686 \times k_0 \times Im(n_{eff}).$$  \hspace{1cm} (2.9)

Here, $k$ is $\frac{2\pi}{\lambda}$ and $Im(n_{eff})$ stands for the imaginary part of the effective refractive index and $\lambda$ is the operating wavelength. Fig. 2.21 shows the variation of confinement loss for various wavelength ranges from 600 to 3000 nm. From Fig. 2.21, it is clear that the confinement loss increases when the wavelength is increased. Further, it increases abruptly beyond 1900 nm and it turns maximum at 3000 nm. This is due to the fact that the fundamental mode ceases to hold confinement in the core at these specific wavelengths. At this juncture, the imaginary part of the effective index becomes
larger for higher wavelengths. Besides, we find that the confinement loss increases with increase in number of folds. We compute the confinement loss as 0.00209 dB/cm, 0.00214 dB/cm and 0.30446 dB/cm at wavelength 1060 nm for 6, 8 and 10-fold PQF, respectively. Of these folds, the 10-fold PQF exhibits a relatively high confinement loss when compared to other folds. The reason for this is because of the number of air-holes available in the cladding region (White et al., 2001). Precisely, for 6-fold, the density of the air-holes in the cladding is higher than that of the 10-fold. Owing to this, 10-fold is more asymmetric in nature than that of 6-fold. Consequently, the confinement loss for 6-fold is lesser than these for the 10-fold. We provide the inset plot in Fig. 2.20 to appreciate the variation of loss for three different folds for a range of wavelengths from 600 to 1900 nm.

![Confinement Loss vs Wavelength](image)

**Figure 2.21:** Variations of confinement loss as function of wavelength for three different folds of PQF

### 2.6.4 EFFECTIVE AREA AND EFFECTIVE NONLINEARITY

Having studied the linear optical properties, namely, birefringence, dispersion and confinement loss, in this sub-section, we proceed to explore the nonlinear optical property based on Kerr effect. Before computing the nonlinear property, it is essential to determine the effective mode area of the fundamental mode.
Fig. 2.23 illustrates the variation of both effective area and nonlinearity against wavelength for three different folds. The effective area of the fundamental mode increases when the wavelength is increased. It is to be noted that the effective area is relatively less for the 10-fold when compared to rest of the folds. Consequently, the 10-fold PQF exhibits a high nonlinearity of 22 W\(^{-1}\)km\(^{-1}\) at 1060 nm wavelength for \(x\) polarization over 6 and 8-folds. From the detailed investigation on the optical properties for all the folds, we find that the 10-fold PQF provides the desired optical properties, namely, less dispersion and high nonlinearity for generating the few cycle laser pulses. Here, in order to gain the further understanding of these properties, we study the variations of dispersion and nonlinearity against wavelength for both \(x\) polarization and \(y\) polarization components as shown in the Fig. 2.23. At this juncture, we compare the hitherto computed optical properties with that of conventional PCF for appreciating the ultimate rationale behind migrating to PQF for the few cycle pulse generation.

![Graph showing effective area and nonlinearity versus wavelength for 10-fold PQF.](image)

**Figure 2.22:** (a) Effective area and nonlinearity versus wavelength for 10-fold PQF.

When compared to conventional PCF, the proposed PQF exhibits the following desired optical properties, namely, a less birefringence, a low dispersion and a high nonlinearity which ultimately turn out to be the essential requirements for the generation of few—cycle pulses. We would like to record here that the proposed PQF can be fabri-
Figure 2.23: Dispersion and nonlinearity as a function of wavelength for 10-fold PQF.

dicated by any one of the following methods such as sol–gel, stack–draw, molding tech-
nique, extrusion technique, drilling and drawing method, etc. (van Eijkelenborg et al., 2001; Markos et al., 2013). Of these experimental techniques, we envisage that the most practical method to fabricate the proposed PQF is the drill and drawing technique as it provides a wide range of design flexibility and could minimize the deformation during the fabrication process (Shi et al., 2012).

### 2.6.5 QUALITY FACTOR

Next, we concentrate on the quality factor, $Q$, of the fundamental mode. It is defined as the ratio of the relative energy in the fundamental mode to the total energy of the pulse. It is necessary to calculate $Q$ factor for the analysis of nonlinear processes such as high harmonic generation, minimization of the higher order modes in the fundamental mode, etc. We calculate the $Q$-factor using the following relation (Granados et al., 2012),

$$Q = \frac{\int |E_1(r, \lambda)|^2 d\lambda}{\sum_{m=1}^{\infty} \int |E_m(r, \lambda)|^2 d\lambda}.$$  \hspace{1cm} (2.10)

where, $E_1(r, \lambda)$ is the intensity of the first order fundamental mode field distribution
Table 2.3: Q factor for 6, 8 and 10-fold PQFs for various wavelengths.

<table>
<thead>
<tr>
<th>$\lambda ,(nm)$</th>
<th>Q-factor for 6-fold</th>
<th>Q-factor for 8-fold</th>
<th>Q-factor for 10-fold</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>0.9905</td>
<td>0.9909</td>
<td>0.9979</td>
</tr>
<tr>
<td>1060</td>
<td>0.8167</td>
<td>0.9056</td>
<td>0.9961</td>
</tr>
<tr>
<td>2000</td>
<td>0.5497</td>
<td>0.7376</td>
<td>0.8535</td>
</tr>
<tr>
<td>3000</td>
<td>0.4818</td>
<td>0.6436</td>
<td>0.8465</td>
</tr>
</tbody>
</table>

and $E_m(r, \lambda)$ is the $m^{th}$ order of mode field distribution for the input wavelength. We present the $Q$ factor for different folds in Table 1. We note that $Q$-factor increases, when the number of folds of the PQF is increased. Among all the folds, the 10-fold PQF provides a maximum quality factor of $Q = 0.9961$ at 1060 nm wavelength which is due to the tight field confinement by circular nature of the cladding.

2.7 CONCLUSION

In summary, first we have analyzed 6-fold Stampfli structured quasi-crystal fiber. Later we have extended our study for different folds of the PQF. We have also analyzed the waveguiding properties of a photonic quasi-crystal fiber with a solid core surrounded by four large air holes and optimized the value of the pitch for the required optical properties. Further, we have presented the novel designs of a circular PQF of 6, 8 and 10-folds. The well established finite-element method has been used to explore the various optical properties of the designed circular PQF. By varying the number of folds and diameter of the air-holes, we have explored the various desired optical properties for generating few cycle pulses and supercontinuum. With the advancements in the fabrication technology, we are quite optimistic that the proposed PQF may be fabricated by drill and drawing technique. Thus the results obtained in this work corroborate that the proposed PQF have found unique waveguide optical properties for the applications of few cycle pulse and supercontinuum generation.