4.1 INTRODUCTION

In this chapter, we focus on the second stage of the chirped pulse fiber amplifier which is essentially a high power amplifier. The stretched pulses are usually sent to a multistage pre-amplifier system before being subject to high power amplification. The most noted fiber designs which are currently used in high power amplifiers for producing high energy pulses are leakage channel fiber and rod type PCF, Limpert, J. et al. (2006); Wong, W. S. et al. (2005). These fibers are also known as large pitch fibers since their pitch is greater by ten times the operating wavelength. In these fibers, single-modeness is achieved by two methods. The first one is by loss filtering that involves differential loss for fundamental and HOMs, Wong, W. S. et al. (2005). The second method deals with gain filtering i.e, the fundamental mode (FM) is promoted with both high gain and low loss compared to HOMs, Marcianite (2009). This is done by keeping the doped area lesser than the fiber core area and this results in high gain for the FM and very low gain for HOMs.

In very large mode area (VLMA) fibers, maintaining single mode behavior has always been a challenging task. Increasing the mode area in fibers leads to increase in higher order modes (HOMs), which, in turn, may result in highly multimode propagation. The popular method of removing HOMs has been by means of coiling of fiber, Koplow, J. P. et al. (2000). However, this method turns futile with the VLMA fibers owing to their larger diameter. Some of the techniques known for larger diameter fibers are gain guiding while index anti-guiding, Sudesh, V. et al. (2008), resonant coupling of higher order modes, Liu, C. et al. (2007) and modified spatial dopant profiles, Bhutta, T. et al. (2002). In conventional fiber, although VLMA is implemented successfully, the design flexibility becomes difficult for improving other properties like reducing bending loss, larger dispersion, extended single mode cutoff, etc, Marcianite (2009). VLMA in fibers has been achieved with the holey structures in the cladding known as the photonic crystal fiber (PCF), Limpert, J. et al. (2006). It has emerged as an alternative for the conventional fiber owing to its enhanced LMA properties, Mortensen, N.A. et al. (2003).
In this chapter, we propose a Yb-doped large pitch photonic quasi crystal fiber (PQF) with large mode area, minimum bending loss, low attenuation and high overlap factor. To the best of our knowledge, this is the first proposal for large pitch PQF which has the best features of both conventional fiber and PCF, namely, the circular core profile and holey cladding structure. Here we introduce both loss filtering and gain filtering onto the same fiber for the enhancement of amplifier properties. Further, we prove using a suitable analytical model that the proposed fiber has the capability of producing high average power. This fiber may turn out to be an appropriate choice for realizing a high energy or high average power amplifier for ultrashort pulses.

4.2 DESIGN OF THE LARGE PITCH PQF

The proposed fiber is designed to encompass the desired characteristics such as large mode area, good beam quality, minimum bending loss, high overlapping factor, low attenuation loss for FM and high loss for HOMs. The cross section of six fold symmetry PQF with large pitch is shown in Fig. 4.1. The core is formed by 7 missing holes i.e., removing the centre and the immediate hexagonal ring holes. Thus, this takes the diameter of the core as 100 $\mu$m. The doped diameter of the fiber is varied from 25 to 75 $\mu$m and it is optimized to provide high gain for the FM when compared to that of HOMs.
The cladding of the fiber is formed by the combination of square and triangular unit cells. It is known that the number of rings in the cladding decides the confinement loss of the fiber. Usually more number of rings are preferred for low confinement loss. But, this ultimately ends up in complicated fabrication process. To overcome this challenge, we propose a novel design with the circular shape core and three rings in the cladding. This new design offers low confinement loss in addition to the ease of fabrication process.

The pitch of the fiber is fixed as 30 µm based on the diameter of the fiber. The relative air hole size d/Λ is varied from 0.15 to 0.5 and it is optimized according to minimum attenuation and bending loss with high overlapping factor. The next important design parameter to be fixed is the refractive index of core as well as cladding. In this work, the material and waveguide dispersions have not been taken into account since the length of fiber used in the amplifier is only about a few metres. Therefore, the refractive index of the ytterbium doped core is assumed to be 1.45. Here, the change in refractive index of silica due to ytterbium doping is nullified by a reverse doping with fluorine, Eidam, T. et al. (2011a). Another designing criterion is the index depression which is defined as the refractive index difference between silica and the doped core i.e., Δn = n_{silica} − n_{doped}. This index depression is introduced for enhancing the mode field diameter and the preferential gain of the FM, Eidam, T. et al. (2011a). Further, the index depression increases the mode discrimination capability of the fiber which inturn results in mode filtering, Jansen, F. et al. (2010). The core of the proposed PQF is highly circular when compared to hexagonal shape of the conventional PCF and former one does improve the various properties of large pitch fiber.

4.3 CHARACTERISTICS OF THE LARGE PITCH PQF

4.3.1 MODAL CHARACTERISTICS

Having discussed the appropriate theoretical background and designing aspects of large pitch PQF, now, we delineate on the different characteristics of the same. The diameter of the doped region is chosen to be 50 µm. The electric field distribution of the fundamental mode and the first higher order mode is shown in Fig. 4.2. This analysis is carried out at 1.06 µm wavelength. The fundamental mode field in PQF is highly circular, like in the case of the standard single mode fiber, due to the circular cladding as depicted in Fig. 4.2(a). This circular field distribution is not possible in the conventional PCF since,
Figure 4.2: (a) Field distribution of LP_{01} mode and (b) First order field distribution with index depression of $4 \times 10^{-5}$

for larger values of $d/\Lambda$, the horizontal and vertically polarized light components do not exhibit rotational symmetry due to the deviation in circular shape of the mode by hexagonal structure, Koshiba, M. and Saitoh, K. (2006). The refractive index of the doped region is reduced by $4 \times 10^{-5}$. The index depression process shifts the first order mode which is shown in Fig. 4.2(b) and eventually, it is out of the doped region. Therefore, the gain that the mode acquires during propagation also drastically reduces. This results in only FM mode to take part in amplification process. Here, field distribution due to higher order modes need not be analyzed as their fields lie outside the doped core. The depressed index doping simultaneously enhances the mode area and reduces the confinement of light at the center of the core. This leads to decrease in nonlinearity of the fiber. The circular distribution of field in the core enhance the beam quality of the high energy laser pulse.

4.3.2 MODE LOSS ANALYSIS

The fundamental mode loss is an important parameter of an amplifier in deciding the efficiency. In this section, we compute the loss of the fundamental mode for various values of $d/\Lambda$ and then compare this with that of conventional PCF. Fig.4.3(a) represents the FM loss of PQF for various values of $d/\Lambda$. From this figure, it is seen that the loss is constant for wavelength ranging from 1.0 to 1.1 $\mu$m and for $d/\Lambda$ from 0.15 to 0.5. Here, the pitch value is roughly thirty times greater than the wavelength and hence, the loss remains constant for a desired range of input wavelength. In this case, the loss
has been computed only up to 1.1 µm and the loss is found to be constant for all the wavelengths. The lowest loss occurs, when $d/\Lambda = 0.5$, due to the increase of air hole size. Fig. 4.3(b) illustrates the confinement loss of LP$_{01}$ mode of the PQF as well as conventional PCF of triangular hole arrangement. The values of $\Lambda$ and $(d/\Lambda)$ are fixed as 30 µm and 0.3, respectively, for both the fibers. The confinement loss for the PQF is found to be ten times lesser than that of the conventional PCF. This is due to the highly circular nature of the cladding which eventually enhances the light confinement.

The confinement of light in the center of the core depends only on the parameters of the cladding, which, in turn, depends on the hole arrangement which are highly circular in the
Figure 4.4: Bending loss of the fundamental mode of PQF as a function of bending radius

![Bending Loss Graph](image)

Figure 4.5: Electric field intensity distribution of PCF and PQF for the bending radius of 50 cm

(a) PCF  
(b) PQF

Figure 4.5: Electric field intensity distribution of PCF and PQF for the bending radius of 50 cm

proposed structure, $d/\Lambda$ and the number of rings of air holes. Thus, these three parameters decide the confinement loss. It is obvious that the hole arrangement only differs in the case of PQF when compared to PCF. Therefore, we conclude that the symmetry of the hole arrangement plays a vital role in determining the confinement loss.

4.3.3 BENDING LOSS CHARACTERISTICS

Next, we study the important parameter called bending loss which, indeed, decides the compactness of the amplifier system. Here, we determine the bending loss for the PQF by replacing the refractive index profiles of the fiber with an equivalent refractive index
Figure 4.6: Index depression vs effective area and overlap factor for the doping diameter of 50 \( \mu m \)

profile of a bent fiber obtained by an equivalent straight waveguide formulation, Chen, X. et al. (2007). In this case, we assign, \( \Lambda = 30 \mu m \) and \( d = 9 \mu m \) and keep the doped diameter as 50 \( \mu m \). We study the bending along the x-direction. Fig. 4.4 shows the bending loss characteristics of PQF for various values of bending radii. Here, it can be noted that the loss is almost constant up to 30 cm and increases exponentially for lesser bending radius. Further, we emphasize that the loss for the PQF is less when compared to other large pitch fibers with more inner cladding rings. The reason for the low bending loss is that the circular cladding structure of PQF prevents the leakage of field into the cladding. In addition, it should be noted that the bending loss of PQF is better in comparison to that of PCF. In order to highlight this important point, we supplement with the Figs. 4.5(a) and 4.5(b) which illustrate the change in field distribution of FM mode for PQF and PCF, respectively. From the Fig. 4.5(a), it is very explicit that the circular cladding structure of PQF prevents the leakage of field into the cladding.

4.3.4 INFLUENCE OF INDEX DEPRESSION OVER EFFECTIVE AREA AND OVERLAP FACTOR

The index depression is an important technique for enhancing mode area. Further, this increases the loss for higher order modes. However, the increase of index depression reduces the overlap factor due to the less confinement of FM at the center of the core.
Therefore, an optimum value of index depression has to be determined by optimizing the effective area and overlap factor for achieving efficient amplification in the system. Fig. 4.6 depicts the variations of effective area and overlap factor for various values of index depression. In order to get a maximum amplification factor (overlap factor), the index depression should be as minimum as possible. Here, for a minimum value of depression of $10^{-5}$, the effective area is $4600 \, \mu m^2$ and the overlap factor is 0.55. It should be noted that it is practically a challenging task to obtain a minimum value of index depression in a repeatable fashion, Eidam, T. et al. (2011a). Thus we optimize the overlap factor to be 0.5 and the corresponding effective area turns out to be $4660 \, \mu m^2$ for best amplification with a minimum nonlinearity. It is to be noted that an index depression of $2 \times 10^{-5}$ ensures the hither-to mentioned optimized values for effective area and overlap factor.

**4.3.5 ROLE OF DOPING DIAMETER OVER EFFECTIVE AREA AND OVERLAP FACTOR**

The doping diameter decides the effective area and the gain of the fiber amplifier. In this section, we analyze the effect of doping diameter over the effective area and signal overlap factor of the fiber. It is necessary to optimize the doping diameter in order to achieve the higher effective area and to get a considerable gain with the amplifier. Fig. 4.7 shows the signal overlap factor for various doping diameters at 1.06 $\mu m$ wavelength.
Table 4.1: Physical parameters used in the simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{tot}$</td>
<td>$8.5 \times 10^{25} \text{m}^{-3}$</td>
</tr>
<tr>
<td>$\sigma_a(\lambda_p)$</td>
<td>$25 \times 10^{-13} \mu\text{m}^2$</td>
</tr>
<tr>
<td>$\sigma_e(\lambda_p)$</td>
<td>$21.7 \times 10^{-13} \mu\text{m}^2$</td>
</tr>
<tr>
<td>$\sigma_a(\lambda_s)$</td>
<td>$0.448 \times 10^{-13} \mu\text{m}^2$</td>
</tr>
<tr>
<td>$\sigma_e(\lambda_s)$</td>
<td>$21.7 \times 10^{-13} \mu\text{m}^2$</td>
</tr>
<tr>
<td>$\lambda_p$</td>
<td>976 nm</td>
</tr>
<tr>
<td>$\lambda_s$</td>
<td>1060 nm</td>
</tr>
<tr>
<td>cladding diameter</td>
<td>240 $\mu$m</td>
</tr>
<tr>
<td>core diameter</td>
<td>100 $\mu$m</td>
</tr>
</tbody>
</table>

We find that the overlap factor increases as the doping diameter increases. It is due to more confinement of FM within the core when the diameter of the doped core increases. The second parameter namely the effective area initially increases as doping diameter is increased and then it starts decreasing from 50 $\mu$m. The decrement in the effective area takes place because of index depression. As and when the index depression diameter increases, the field distribution spreads out of the doping region since the refractive index of the core eventually matches with that of the value of the cladding. Therefore, the optimum diameter of the doping is 50 $\mu$m at which the effective area is 4660 $\mu\text{m}^2$ and the corresponding overlap factor is 0.55.

4.4 MODELING OF PQF AMPLIFIER

In this section, we adopt the well known analytical model for the ytterbium doped fiber amplifier in order to study the effect of pump $\Gamma_p$ and signal $\Gamma_s$ overlap factors over the average signal output power. The spatio-temporal evolutions of the pump $P_p(z)$ and the signal $P_s(z)$ are given by, Paschotta, R. et al. (1997)-Hilaire, S. et al. (2006),

$$\frac{dP_p}{dz} = \Gamma_p[\sigma_e(\lambda_p)N_2 - \sigma_a(\lambda_p)N_1]N_{tot}P_p(z),$$  \hspace{1cm} (4.1)

$$\frac{dP_s}{dz} = \Gamma_s[\sigma_e(\lambda_s)N_2 - \sigma_a(\lambda_s)N_1]N_{tot}P_s(z),$$  \hspace{1cm} (4.2)

where the parameters $\sigma_a(\lambda_p)$ and $\sigma_e(\lambda_s)$ represent the absorption and emission cross sections of pump and signal, respectively. Here, $N_{tot}$ is the total population density and
N₁ and N₂ are the population density for lower and upper levels, respectively. The steady state values of N₁ and N₂ are given by Paschotta, R. et al. (1997),

\[ N₂ = \frac{R_{12} + W_{12}}{R_{12} + R_{21} + W_{12} + W_{21} + A_{21}}, N₁ = 1 - N₂, \]

where R₁₂, R₂₁, W₁₂, W₂₁ are the transition rates which, in turn, are given by

\[ R_{12} = \sigma_a(\lambda_p)I_p, R_{21} = \sigma_e(\lambda_p)I_p, W_{12} = \sigma_a(\lambda_s)I_s, W_{21} = \sigma_e(\lambda_s)I_s, \]

where \( I_i(h\nu_i)/\tau_i, \sigma_i \) for (i = 'p' or 's') represents the saturation intensity of pump / signal. \( \sigma_a \) and \( \sigma_e \) are the absorption and emission cross section of the doped material. Appendix B gives the detail of the absorption and emission cross section of Ytterbium for various wavelengths. Here, \( \nu_i \) is the corresponding frequency and \( \tau_f \) is the upper-state life time. The values of all the parameters mentioned above are listed in the Table 4.1.

4.5 PULSE AMPLIFICATION IN PQF

This section deals with the modeling of fiber amplifier based on the proposed PQF. Here, we calculate the average power generated from the fiber amplifier using the model mentioned in section 2.2. In order to study the amplification process, we solve the Equations (4.1) and (4.2) by the well known Runge-Kutta method. In the numerical simulation, we use the optimized value of the signal overlap factor which is 0.5. We calculated the pump overlap factor as 0.0434 which depends on the ratio of square of core radius to cladding radius. Here the length of the fiber is chosen to be 1.2 m. The optimization of the fiber length is done based on the doping concentration, pump power and desired output power. Table 4.1 provides the rest of the physical parameters used in the simulation, Mukhopadhyay, P.K. et al. (2009). Fig. 4.8. shows the input pump power against average output power generated by the amplifier. From the figure, it is evident that efficiency of the amplification is found to be 85% (amplification factor is 1.85) for the lower pump power while it is only about 55% (amplification factor is 1.55) for higher values of pump power. This variation in the amplification process takes place since the gain gets saturated in high power regime. Therefore, we find that the fiber amplifier performance depends mainly on the input average power, length of the fiber and overlap factors.

The damage of the fibre can be reduced by introducing an end cap which may expand the mode in the bulk region before striking the air glass interface. The damage threshold limits the peak intensities which are allowed in the fiber. For the Gaussian fundamental
mode, the maximum damage limited output power of any fiber laser or amplifier is given as

\[ P_{\text{out}} = \Gamma^2 I_{\text{damage}} \pi a^2 \]  

(4.3)

Where \( \Gamma \) is the ratio of mode field radius to the core radius \( a \) and \( I_{\text{damage}} \) is the upper limit of the intensity allowed in the fiber.

Without end caps, the \( I_{\text{damage}} \) is equal to the surface damage limit of the fiber i.e, 10 W/m² for silica Dawson et al. (2008). For the end cap fibers, the damage limit further increases, but for the margin of safety, one can consider \( I_{\text{damage}} \) equal to the surface damage limit. For the proposed PQF, the damage threshold power is calculated to be 24 KW.

### 4.6 COMPARISON AMONGST PREFERENTIAL GAIN FIBER AMPLIFIERS

In this section, we compare three types of preferential gain fiber amplifiers. These amplifiers use different types of fibers such as conventional fiber, photonic crystal fiber and the proposed large pitch PQF. The first one is a theoretical proposal of a conventional fiber, designed for 100 \( \mu \text{m} \) core diameter with a bending radius of 30 cm. It results in an amplification efficiency of 75 %, Marciante (2009). However, it doesn’t provide room for flexibility in terms of design to catch up with the desired optical properties. This can be overcome by the PCF which is discussed as follows, using the rod type PCF, Eidam, T.
Table 4.2: Comparison of various preferential gain fiber amplifiers

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Conventional fiber</th>
<th>Rod type PCF</th>
<th>Large pitch PQF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coredia (µm)</td>
<td>100</td>
<td>64</td>
<td>100</td>
</tr>
<tr>
<td>$A_{\text{eff}}$ (µm²)</td>
<td>not given</td>
<td>1750</td>
<td>4660</td>
</tr>
<tr>
<td>bending radius (cm)</td>
<td>30</td>
<td>bendingnotallowed</td>
<td>30</td>
</tr>
<tr>
<td>Amplifier efficiency (%)</td>
<td>75</td>
<td>60</td>
<td>85</td>
</tr>
</tbody>
</table>

et al. (2011a) with preferential gain implementation. The diameter of this fiber is 64 µm with no scope for bending. This fiber is largely used in high power pulse amplification for various applications. Table 4.2 compares the hitherto mentioned fibers with that of the large pitch PQF. From the comparison, one can understand that the PQF exhibits relatively a large mode area compared to the rest. In addition, the amplification efficiency is drastically improved by 10% . Therefore, the large pitch PQF amplifier turns out to be the ultimate choice for high average power amplification as well as compact package.

4.7 CONCLUSION

In order to investigate the amplification of high energy ultrashort pulses, we have designed a large pitch PQF with remarkable properties namely, very large mode area, lower attenuation, very low bending loss and high overlapping factor. The index depression has been optimized as $2 \times 10^{-5}$ and this results in large mode area with high overlap factor. From these properties, one could understand that the proposed PQF transforms into an improved version of rod type PCF wherein bending optimization is highly challenging. The numerical results pertaining to fiber amplifier corroborate that this fiber could be used in high power amplification process with an average slope efficiency of 65%. On account of the circular nature of the cladding, it is obvious that the beam quality may also be improved in high power regime.