Chapter 1

Introduction

1.1 HIGH ENERGY ULTRAFAST FIBER LASER SYSTEM

The name ultrafast is related to the characteristics of laser pulse which has duration in subpicosecond to femtosecond regime. These pulses have huge applications in industries, healthcare, energy, research laboratories, etc. The applications keep spreading into different domains every year due to the enormous implications of ultrafast laser technologies, Sibbett et al. (2012). The reason for the technological advancement is mainly due to the change in the gain medium of the laser and accordingly, many lasers have been in use, namely, dye, solid state (Ti-Sapphire), fiber, thin disc, etc. The ultrafast laser system includes an ultrafast oscillator providing ultrafast pulses of less power and a short pulse fiber amplifier, M.E. Fermann et al. (2003).

The first reported femtosecond laser used dye as the gain medium, Fork et al. (1981). Although dye solution could provide enough gain bandwidth for the amplification and produce 100fs pulses by colliding mode-locking, its low efficiency and less practicality have confined it to only laboratory research, Fork et al. (1981). Then comes color center crystal as the gain medium. It is less reliable and its efficiency also is not good enough for commercialization. However, the dye and color center lasers form as the background for developing successful femtosecond laser in 1990s. In 1986, the laser characteristics of Titanium doped sapphire crystals were studied and the same have given a thrust to develop a Ti-sapphire femtosecond lasers, Fork et al. (1986). It is to be noted that this laser has larger gain bandwidth than any other gain media at room temperature. Further, Ti-sapphire femtosecond lasers have the potential to generate high energy, high power and low duration pulses. Ultimately, they turn out to be highly reliable in high power applications. The Kerr-Lens mode locked Ti-Sapphire laser, developed in 1990, has been a proven femtosecond laser, all through the years, for its stability. This mode locking phenomenon helps increase the peak power of the laser pulse upto 5 MW as against the KW range with the conventional lasers. Thermo-optic problem which limits the power scaling capability in Ti-Sapphire laser has been overcome by introducing a thin disk or slab as the gain media, Eggleston et al. (1984). However, the single pass gain for this
gain media is very less. Therefore, to get a nominal output, regenerative amplification system is incorporated along with the thin disk laser system, Buenting et al. (2009).

The above discussed solid state laser systems become complex when we need to produce high energy, high average power and low pulse duration. This ultimately limits the degree of robustness, compactness, and long-term stability. Hence, the need for enhancing the desired properties of present state-of-art bulk solid state ultrafast lasers have triggered interest in fiber based gain media. These media could provide high single pass gain and nullify the thermo-optic problems due to their large surface to volume ratio. The next essential parameter of the laser called the beam quality is preserved owing to the fact that it depends only on core diameter and not on the power. On account of the hitherto mentioned properties, there has been a great interest towards the development of ultrafast fiber laser systems that are capable of providing robust high-power femtosecond pulses for applications outside the research laboratories, Limpert et al. (2006). Presently, Ultrafast fiber laser system has reached the solid state laser average power as high as 830 W, Eidam et al. (2010) with the corresponding energy of 7.6 µJ. Eidam, T. et al. (2011b) reported a peak power of 3.8 GW with pulse energy of 2.2 mJ which is equivalent to Ti-sapphire laser output. Recent applications of ultrafast fiber laser systems are in optical frequency metrology, Udem et al. (2002), nanosurgery, Vogel et al. (2005), precision micromachining, Gattass and Mazur (2008), cataract surgery, Mamalis (2011) and precision imaging, Barretto et al. (2011).

For high energy ultrafast fiber laser system, the first stage is the fiber oscillator, followed by a short pulse fiber amplifier, the details of which have been discussed in what follows.

1.1.1 ULTRAFAST FIBER LASER OSCILLATOR

Ultrafast laser oscillator generates low power picosecond to femtosecond pulses. The passive or active mode-locking techniques are employed to produce pulses with desired pulse duration. There are a variety of laser oscillators in vogue, such as semiconductor, solid state and fiber based ones. These are differentiated by their gain media. There have been enormous efforts put in to realize fiber laser oscillators that could provide high energy and high peak power comparable to that of their solid state counterpart. In 2005, Buckley et.al, demonstrated the successful femtosecond fiber laser with a high peak power of 100 kW, energy, 14 nJ and pulse duration, 100fs. A relatively lower pulse
width of 8 fs has been reported by G.Sogon et al. The Fig.1.1 shows the details of peak powers achieved through different types of oscillators. From the figure, it can be understood that the fiber based oscillator is a close match for the conventional solid state oscillator in terms of performance. Fiber based laser offers better stability, compactness, low cost and freedom from misalignment as the gain medium as well as all other components in the laser cavity are all fiber based. Ultrafast fiber laser oscillator is centered on four regimes of operation based on the pulse evolution inside the cavity, Wise et al. (2008). They are soliton, stretched pulse, similariton and all-normal dispersion lasers. While the soliton regime pulse has energy less than 1 nJ, stretched pulse has more than 1 nJ. Similariton and all-normal dispersion regimes are considered as high energy fiber laser oscillators since they produce pulse energies of more than 10 nJ, Buckley et al. (2005). Presently, all-normal dispersion (AND) fiber laser oscillators are widely used for generating high energy laser pulses. AND fiber laser does not contain anomalous dispersion component inside the cavity. This turns the laser to be simple, compact and capable of obtaining all fiber formats. Generally, ultra short pulse generation in the mode-locking technique needs compensation of group velocity dispersion in the laser cavity and a saturable absorber to initiate and stabilize the pulse train. Another revolution in fiber laser oscillator is the development of various saturable absorbers for generating high energy pulses of very short duration. Until now, the saturable absorbers used in the fiber os-

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**Figure 1.1:** Peak power versus average power of various laser oscillators, Sibbett et al. (2012)
cillators have been SESAM, carbon nanotube, graphene and effective saturable absorber obtained by nonlinear polarization rotation (NPR). Of these, NPR based saturable absorbers are widely used in the laser for better stability. However it is envisioned that graphene will play a significant role in the generation of few cycle pulses, Bonaccorso et al. (2010). Fig.1.2 shows the future passive mode-locked fiber laser oscillator. The pulses which are generated from the oscillators discussed so far do not generally find applications as the pulse energy is often in the range of nJ. Hence, amplifiers are used in subsequent stages and the same have been discussed in the following sections.

1.1.2 SHORT PULSE FIBER AMPLIFIER

Short pulse fiber amplifier forms the second stage in a ultrafast fiber laser system. Ytterbium doped fibers are widely used as an amplification medium in the amplifier owing to their excellent thermo-optic properties, higher gain bandwidth, higher saturation fluence and high optical pumping efficiency, DeLoach et al. (1993). Although fiber based amplifiers have a lot of advantages over the conventional solid state amplifier, they suffer from the pulse distortion while scaling the peak power or energy of the pulse. This is due to the nonlinear effects in the fiber by its long interaction length and small core area.

The techniques for amplifying the ultrashort pulses in fibers are parabolic amplification, Finot et al. (2006), direct amplification, Zaouter et al. (2008) and chirped pulse amplification, Galvanauskas (2001). The parabolic pulse amplification uses the nonlinear effect for increasing the peak power of the pulse. In this technique, the pulse propagates
self-similarly inside the fiber which allows the high energy pulse to propagate without distortion even in high nonlinear conditions. These pulses are called similaritons. The amplitude and width of the similariton pulse depends not on its shape, but on the input energy of the pulse. By using this technique, MWs of peak power pulse are generated in Yb-doped fiber. However, further scaling of the pulse cannot be accomplished due to the gain bandwidth limitation of Ytterbium doped fiber.

The second method involves direct amplification using a very large mode area fiber like rod type PCF, Zaouter et al. (2008). The main limitation in this technique is the pulse distortion due to the interplay of gain and self phase modulation (SPM) induced spectral broadening. Also, due to the high order dispersion and SPM, side lobes may appear in the pulse after compression. The main advantage of this technique is the compactness of the fiber amplifier as there is no need for the stretcher module. But, the compressor should have the capability to compress very large spectrum of amplified pulse without distortion. The scaling of energy or peak power of pulse by the above two methods is quite often complex. So the well known technique called chirped pulse amplification can be used in the fiber amplifier for scaling the energy of the pulse. In order to achieve this, the mode area of the fiber is increased and pulse is stretched in the time domain. This technique is elaborated in the next section.

1.2 CHIRPED PULSE FIBER AMPLIFIER SYSTEM

One of the well known techniques to produce high peak-power laser pulses is chirped pulse amplification (CPA). This technique which has its roots from the radar technology wherein it was used to increase the peak power of the radar signal to enhance the range of operation, Cook (1960). In 1985, the technique was first used for amplifying the chirped optical signal from solid state bulk mode-locked laser, Strickland and Mourou (1985). A ps pulse amplification with 1mJ energy after compression was reported. The stages in this technique include stretching, amplification, and compression. This process ultimately circumvents the possible damage to laser amplifier and further, this technique could scale power of the short pulse to extreme peak power, Jovanovic (2010). The Fig.1.3 illustrates the various stages in chirped pulse amplification. The short pulse that enters into the stretching stage undergoes chirping and hence gets lowered in its peak-power which reduces cumulative nonlinear effects during amplification and also increases the damage threshold of the amplifier. This stretched pulse is sent to
the laser amplifier section wherein the chirped pulse undergoes amplification and it is scaled to higher values depending upon the pump power. To restore the original pulse-duration at the output of the CPA system, the amplified pulse is sent to the compression stage where linear or nonlinear compression takes place to result in good quality output pulses.

There has been a wide interest towards developing a robust, high power and simple CPA fiber laser system. Fiber based CPA possesses high beam quality independent of high average power. On downside, CPA suffers from nonlinear effects arising out of its increase of peak power. There have been various approaches tried to increase peak power inside the fiber with minimum disturbance to the pulse. The first as well as a simple approach has been to make use of large core fibers, Eidam, T. et al. (2011b). The other techniques are by the compensation of nonlinear effect by spectral preshaping, Prawiharjo et al. (2008) and third order dispersion compensation, Zhou et al. (2005). The direct compensation of third order dispersion is also named as nonlinear chirped pulse amplification, Wang et al. (2011). The main drawback of the nonlinear CPA is that the pulse quality may get degraded for high power. Recently, fiber based CPA has reported a high average power of 830 W with a peak power 12 MW, Eidam et al. (2010). It has the capability of scaling the power to a higher value which may be more than that of
the conventional solid state laser. The various modules of fiber based CPA systems are discussed in the following sub sections.

1.2.1 PULSE STRETCHING

Pulse stretching is the technique which reduces the peak power and broadens the width of the pulse. In general, prism or grating pairs are used to construct a pulse stretcher. Offner-type Martinez (1987), Martinez-type Lemoff and Barty (1993) and Barty-type Cheriaux et al. (1996) diffraction bulk gratings are used frequently in stretching the ultrashort pulses in CPA. However, these setups are not efficient, especially, at higher stretching ratios in the free space optics since several undesirable effects such as higher order dispersion, aberration etc. come into play Galvanauskas (2001). Normally the gratings are used to generate required amount of dispersion (normal or anomalous) into the input pulse. Here the Fig.1.4 shows the stretcher and compressor realized using bulk gratings. In the figure, the thick lines indicate the lenses. Both the lenses are kept within in the grating structures, each at a distance of (f-g) from each of the gratings. Further, the distance of separation between the lenses is 2f. It is to be noted that if (f-g) is less than f, the setup behaves as a positive dispersion stretcher, and if (f-g) greater than f, it would behave as a negative dispersion stretcher. Pulse stretching with bulk gratings needs large air space for higher dispersion requirement which is needed to obtain higher stretching ratio. But, the design of schemes as well as manufacturing of the required optical components pose considerable technical difficulties. Further, the optics in the schemes may result in intrinsic aberration and eventually, pulse distortion. Therefore, the diffraction gratings turn out to be a limiting entity for scaling the energy in fiber based CPA system. Also, the all fiber configuration of CPA is not possible with the above mentioned grating schemes.

In the recent past, fiber based components are highly preferred to conventional free space setup owing to higher efficiency, compactness and stability. Fiber based chirped Bragg gratings are introduced for stretching the laser pulse, Sumimura et al. (2007). Although this setup is good enough for low energy applications, it is very inefficient in scaling the energy of the laser system. So far, only the conventional single mode fibers have been employed widely for stretching an optical pulse in the Chirped pulse fiber amplifier (CPFA) system, Mukhopadhyay, P.K. et al. (2009). In the existing fiber stretcher, the available dispersion is very less and hence, it is necessary to have lengthy fiber for
achieving higher stretching ratio. Therefore, many linear and nonlinear higher order effects appear in the system. As a result, the distortion of the pulse takes place and thus affects the next amplification stage. Current mode-locked fiber lasers can generate pulses of energy more than 100 nJ. However, these high energy pulses need to be amplified further by a power amplifier. For stretching these higher energy pulses, the mode area of the fiber should be more and length of the fiber should be less in order to avoid the nonlinear effects that would arise during the stretching process.

Very recently, pulse stretcher has also been proposed using photonic crystal fiber (PCF), Li, L.G. et al. (2010) as well as dual core conventional fiber (DCCF), Nielson, L.G. et al. (2010). For the first time, the idea of using the dispersion compensating fiber (DCF) for the stretching purpose has been proposed by Nielson, L.G. et al. (2010). The fiber has been fabricated and experimental results of its dispersion (111 ps$^2$) and effective area (6.4 µm$^2$) have also been reported. However, this fiber is not a good candidate for stretching high energy pulse due to its lower effective area. The ideas for enhancing the effective area with large second order dispersion and less third order dispersion have also been presented in this thesis.

1.2.2 HIGH POWER PULSE AMPLIFICATION

Pulse amplification is the next stage to the stretcher module in a CPA system. Since the pulse is stretched, the peak power of the pulse is lowered and this may reduce the nonlinear effect. By combining large mode area (LMA) and stretched pulse, the pulse amplification can be considerably increased without the pulse break up. As is seen in the Fig. 1.5, the pulse generated from the oscillator is fed to the grating stretcher wherein
stretching process takes place as has been discussed in the last section. The stretched pulse is sent to the amplification stage. The required amplification is achieved through many stages, involving preamplifiers and a main amplifier. Here, the preamplifiers are low power pumped Yb doped fiber amplifiers and the main amplifier is a high power Yb doped LMA or VLMA fiber amplifier. Finally amplified pulse is fed to the grating compressor for the final compression of the pulse. In this thesis, we discuss mainly the issues related to the fibers used in main amplification stage.

Main amplifier always uses large core fibers in order to accommodate high energy pulses. Most of the fiber configurations in this stage employ cladding pumping to improve the efficiency of the amplification. LMA of the fiber is the reason behind the high power handling capability in CPFA. It reduces the nonlinearity and increases the damage threshold of the fiber. For further scaling of power in CPFA system, the mode area of the doped fiber is increased with the single mode property being maintained. The single mode behavior in LMA fiber amplifier is one of the important topics of interest since it decides the beam properties namely beam stability and beam focusability in high power regime, Eidam, T. et al. (2011a).

Using photonic crystal in the cladding, a core diameter of more than 100 $\mu$m with single mode operation is reported by Limpert, J. et al. (2006). Figures 1.6 shows a conventional fiber, a rod type PCF of 85 $\mu$m and a large pitch fiber of 108 $\mu$m core used in the main amplifier. Large pitch fiber is a special type of large core PCF since the single mode behavior is obtained by providing higher loss to higher order modes. This type of fiber is also called leakage channel fiber, Wong, W. S. et al. (2005).

Above reported photonic crystal based large core fibers cannot be bent to smaller radius. Moreover, it has lower overlap gain factor and higher attenuation. These limitations...
1.2.3 PULSE COMPRESSION

Over a few decades, generation of high peak power pulses with short pulse duration has been a challenging topic of research. Pulse compression is a technique which makes the pulse duration shorter. The pulse compression techniques are basically of two types, namely, linear and nonlinear compression techniques. While the linear compression uses only lower order dispersions for compressing the chirped pulses, the nonlinear compression uses nonlinear effects like self phase modulation, stimulated Raman scattering and other higher order nonlinear effects. Martial et al. (2009); Sdmeyer et al. (2003); Kida et al. (2006).

Nakatsuka, H. et al. (1981) introduced a method for compressing the pulse based on the interplay between self-phase modulation (SPM) and group velocity dispersion (GVD). This method is widely used in compressing pulses to generate transform limited pulses. The compression of the amplified chirped pulses from CPA system was first reported by, Strickland and Mourou (1985). In general, for CPA system, mostly linear dispersive compression technique is being adopted, Mukhopadhyay, P.K. et al. (2009). However, a few nonlinear pulse compression techniques are also employed for compressing the amplified chirped pulses, Martial et al. (2009). In the case of linear compression, although bulk grating, prism pair, high dispersive optical fiber, fiber Bragg grating and hollow core fibers are all used, Galvanauskas et al. (1995), bulk gratings are preferred to others for compressing high energy pulses. Bulk gratings can provide compression even up to 1000 times. However, to catch up with such higher compression ratio, the grating
size and alignment tolerances turn out to be a limiting factor to be deployed in rugged and compact environment. High dispersive fiber and fiber Bragg gratings are not popular for compressing high energy pulses since the damage threshold is comparatively less, Smith et al. (2009). Turning to the hollow core fiber technology, one could envision a myriad of advantages in pulse compression such as large spectral broadening, monotonic spectral dispersion and excellent spatial beam quality, Suda et al. (2010).

In recent times, the hollow core PCFs have turned out to be promising candidates for compressing high energy pulses, Ouzounov et al. (2003). The hollow core PCF works on the principle of photonic bandgap effect which could provide the required anomalous dispersion in the spectral region wherein conventional fibers would provide only normal dispersion, Cregan et al. (1999). As it exhibits relatively higher nonlinear threshold limit, it would be possible to propagate high power pulses without distortion. Further, the hollow core PCF can be filled with noble gases to control the nonlinearity to ease the compression process. High energy pulse compression technique was reported in 2003, based on the SPM-induced spectral broadening in a hollow core fiber filled with noble gases, Ouzounov et al. (2003). The disadvantages in gas filled fiber are complexity in filling gas in the fiber and maintaining the required pressure of the gas and this eventually makes the system a bulky.

In all fiber femtosecond fiber laser system, the pulse compression is carried out by hollow core photonic band gap fiber, De Matos et al. (2003); Limpert et al. (2003a). The reason behind this is that the fiber provides the required anomalous dispersion with low nonlinearity. In hollow core fiber, both dispersive and soliton pulse compressions are reported, Lægsgaard and Roberts (2009); Ouzounov et al. (2005); Gérôme et al. (2007). The main challenges in hollow core fiber dispersive pulse compression are that when scaling the peak power, the required anomalous dispersion is low and higher order dispersion (HOD) may distort the pulse, Lægsgaard and Roberts (2009). This can be avoided by using a hollow core fiber with high anomalous dispersion and less HOD but the reported hollow core PCF still suffers from HOD and lower anomalous dispersion, Heckl et al. (2011). This is taken as one of the challenging issues in this thesis and solution for the same has been proposed with the use of a hollow core PQF.
1.3 SCOPE OF THESIS

The aim of this dissertation is to design a stretcher, an amplifier and a compressor using photonic quasi-crystal fibers for high energy chirped pulse amplification. The proposed configuration may replace the existing one for enhancing the pulse energy. This thesis essentially encompasses three major segments.

In the first segment, Photonic Quasi-crystal fiber is used as the proposed stretcher fiber which possesses certain desired properties not seen with either conventional PCF or standard fiber. Due to the high normal dispersion and large mode area properties, the proposed fiber facilitates stretching of high energy pulse with negligible distortion. The middle segment deals with high energy power amplification wherein a very large mode area PQF is used to provide low confinement loss, low bending loss and high gain. The last segment is meant for dispersive pulse compression by using a hollow core PQF with high anomalous dispersion and less higher order dispersions. These properties of fiber help to compress the high energy pulses with best beam quality. Even though highly reliable stretcher, compressor and amplifier are available for the CPA system, they do have limitation when high energy pulses have to be amplified. The proposed fibers have been carefully configured to overcome these limitations.

1.4 ORGANISATION OF THESIS

In view of the objectives discussed above, the thesis is organized in the following way.

Chapter 2 reviews the linear and nonlinear properties of the microstructure fibers such as photonic crystal fibers and photonic quasi-crystal fibers. In addition, the designs of the stretcher, amplifier and compressor are discussed. Also the numerical methods such as finite element method, split step Fourier method and Runge Kutta method are elaborated, which are employed for modeling as well as analyzing the various characteristics of the proposed fibers.

In Chapter 3, we present the high energy ultrashort pulse stretcher which uses dual core PQF. The proposed PQF exhibits high normal dispersion and large mode area simultaneously at 1.06 µm. These properties are used for stretching high energy ultrashort pulse with good beam quality.

Next, in chapter 4, we propose a high energy short pulse amplifier with large pitch PQF. Using FEM, various properties of the proposed fiber are studied. The performance
of the amplifier with the proposed PQF is evaluated by using the well known amplifier model.

The last piece of work which is dispersive pulse compression using hollow core PQF has been presented in the chapter 5. The proposed PQF exhibits high anomalous dispersion around 1.06 µm which essentially does match with the stretcher characteristics. The high order dispersion is very low and thus, results in high quality pulse compression for high energy pulses.

Finally, the conclusion of the entire research contribution of this thesis and also possible future directions have been presented in the chapter 6.