Abstract

An Erbium doped fiber laser oscillator emitting at 1560nm is developed. The laser is mode-locked with saturable absorber based on nonlinear polarization rotation. The measured cw threshold power is about 70mW and the power scaling efficiency is 13%. The maximum output power obtained is 40mW. The mode-locking is self starting and the stability is verified in millisecond, microsecond and nanosecond time scale of an analogue oscilloscope. The repetition rate is measured to be 80MHz. The pulse spectra have the characteristic side lobes of soliton mode-locking with a central lobe of width 19nm. The temporal width of the pulse is measured by SHG intensity autocorrelation. The pulse width depends on the pump power. The width is about 130fs for the pump current of 800mA. The mode-locked pulse is not bandwidth limited, as is evident from the time bandwidth product. Extra-cavity second harmonic is generated in a BIBO crystal with efficiency of 1%. The intra-cavity second harmonic could not be generated as the SHG crystal disturbs mode-locking because of its birefringence properly.
1. Introduction

Bulk ultrafast lasers based on crystals like Ti:Sapphire and Nd:YAG are widely used. But their exorbitant cost, vulnerability to environmental perturbation, enormously bulky nature, high power requirement and expert maintenance limit their use within R & D laboratory only. For commercial application, the ultrafast laser has to overcome these limitations. Rare earth doped fiber lasers seem to be emerging as an alternative to the bulk solid state lasers due to their compact nature, ruggedness, low power consumption and order of magnitude low price. Erbium and Ytterbium doped fibers are proved to be efficient gain medium for ultrafast lasers because of their large single pass gain, broad gain bandwidth, good beam quality and compatibility to commercial diode laser pump sources. The fiber laser has got a big boost from the huge technological development in semiconductor diode lasers with fiber coupling. Furthermore, the development of double clad large mode area fibers for effective fiber amplifiers make it possible to up-convert the spectral brightness of the multi-mode diode lasers, and thus realize high average power laser outputs with excellent beam quality to complete with its bulk solid state counterpart. A large contribution to this development of large mode area fibers comes from the development of photonic crystal fibers. In spite of several advantages, much research is still needed to overcome the challenges like vulnerability of fiber to environmental changes, limitation to free space nonlinear polarization mode-locking and limitation to mode-locked pulse energy due to high optical nonlinearity.

The ultrashort pulse has numerous applications in areas of fundamental research, medical and industry. For example, ultrafast laser systems are used for time resolved studies in chemistry, optical frequency metrology, terahertz generation, two photon and CARS spectroscopy and microscopy, and optical coherence tomography. Other medical related applications are eye laser surgery and dentist drills. In the industry, ultrafast lasers are used for micro-machining and marking. Fiber based ultrafast lasers may be the most suitable ones for writing waveguides and photonic crystals.

The present report describes the investigation and development of Erbium doped fiber laser oscillator emitting radiation at 1560nm. The laser is mode-locked by nonlinear polarization rotation. The work is carried out at the facility of ELETTRA. The generation of second harmonic, both external and internal to the cavity, is investigated. Section 2 reviews the major developments in mode-locked fiber laser and the theory of soliton mode-locking is described in section 3. The description of the experimental development works on the fiber laser, its mode-locking, harmonic generation and results are provided in section 4. The scientific and commercial importance of fiber lasers are mentioned in section 5. Section 6 is dedicated to results and discussions, and section 7 concludes with some outlines for the future work.

2. Review on mode-locked fiber laser

In the last decade, the main research effort in fiber lasers has been to overcome the limitation in pulse energy and width due to the effect of Kerr nonlinearity experienced by the optical pulse during the propagation through the fiber cavity. Tamura et al [1] first reported the dispersion managed mode-locking to reduce peak power inside the fiber alleviating by part the detrimental effect of Kerr nonlinearity as compared to the conventional soliton regime. This
concept is implemented in operation regimes such as stretched-pulse [2] and self-similar [3], where the pulse width experiences large variations per cavity round trip. The development of mode-locked fiber lasers, made of purely normal dispersion fibers to achieve higher pulse energies, has attracted much attention in the recent few years [4-8]. In particular, it has been demonstrated that a spectral filter could stabilize high-energy pulses in an Yb-fiber laser leading to the achievement of more than 20 nJ energy with femto-second pulses [8]. However, pulse energy scaling capabilities of these fiber lasers is limited because of the small fiber core size and hence the strong accumulated nonlinearity. As known from ultra-fast fiber amplifier systems a reduction of nonlinearity and consequently potential performance enhancement can be obtained by the enlargement of the fiber mode area. Mode-locked fiber lasers employing low-numerical aperture large-mode-area (LMA) step-index fibers, forced to operate in single-transverse mode have been reported. However, the pulse quality and stability of operation was not satisfying due to mode-coupling in the high-order transverse modes. More recently, significant energy scaling in mode-locked fiber lasers have been demonstrated using LMA photonic crystal fibers [9-11]. Indeed, passively mode-locked fiber lasers operating in the anomalous dispersion regime [9] as well as in the purely normal dispersion regime [10-11] have been reported with exceptional performances in terms of pulse energy and peak power. Additionally, these lasers use only a semiconductor saturable absorber mirror as the mode-locking mechanism leading to very compact designs. However, in spite of the short typical lengths (about a meter) used in these experiments, the linear birefringence seems to play a key role and polarization effects on pulse shaping have been observed [10]. It is well known, that the linear birefringence is sensitive to the thermal and mechanical perturbations which could induce random birefringence changes in the fiber which are sources of environmental instabilities in mode-locked fiber lasers. One approach to compensate for linear polarization drifts in the fiber is the use of a Faraday rotator mirror [12, 13]. The most common approach consists of using polarization-maintaining (PM) fibers with the light polarized only along the slow axis. Environmentally-stable, partly in an all-fiber configuration, mode-locked PM core-pumped single-mode fiber lasers have been reported at various operation wavelengths [14-18]. The other environmentally-stable fiber laser configuration, so-called sigma cavity design, consists in a PM fiber inserted in the ring segment of a sigma cavity and a non-PM fiber introduced in the linear section with Faraday mirror rotator [19-20]. Recently, polarization maintaining LMA photonic crystal fibers have been demonstrated using the well-known technique of stress-applying parts (SAP) inside the fiber [21, 22]. In addition, it has been shown that using a particular design that comprises the stress-applying elements as part of the photonic cladding could result in single-polarization propagation over a large spectral range [22].

3. Theory of soliton mode-locked fiber laser

Starting from Maxwell’s well-known electro magnetic equations and appropriate induced nonlinear polarization, one can derive coupled partial differential equations for the light field amplitudes propagating through the optical fiber. These equations are called nonlinear Schrödinger equations. In frequency domain and time domain these equations, including the gain and loss, are respectively given by

$$\frac{\partial}{\partial z} A(z,\omega) = i\beta'(\omega) A(z,\omega) - \frac{\alpha(\omega)}{2} A(z,\omega) + \frac{g(\omega)}{2} A(z,\omega) + i\gamma FT\left|\int A(z,t)\right|^2 A(z,t)$$
Numerical modeling of mode-locked fiber laser can be made using the above equation, where $\beta_2$ is the group velocity dispersion, $\alpha_0$ is the small signal loss and $g_0$ is the small signal gain. The nonlinear coefficient, $\gamma$ can be calculated, when the radial field distribution is known. For most step-index fibers a Gaussian radial dependence with a mode-field diameter, $w$, set equal to the core diameter of the fiber, is a very good approximation for the field distribution.

For unpolarized light inside the fiber, the field can be written as

$$E(r,t) = \frac{1}{2}[(\tilde{x}E_x + \tilde{y}E_y)\exp(-i\omega_0 t) + c.c.]$$

And the induced polarizations are given by

$$\begin{align}
P_{NL,x}(r,t) &= -\varepsilon_0 2n_2 n(\omega_0) \left[ \left| E_x \right|^2 + \frac{2}{3} \left| E_y \right|^2 \right] E_x + \frac{1}{3} (E_x^* E_y) E_y \\

P_{NL,y}(r,t) &= -\varepsilon_0 2n_2 n(\omega_0) \left[ \left| E_y \right|^2 + \frac{2}{3} \left| E_x \right|^2 \right] E_y + \frac{1}{3} (E_y^* E_x) E_x 
\end{align}$$

Two coupled equations for the slowly varying parts of $E_x$ and $E_y$ can now be written in a similar manner as:

$$\begin{align}
\frac{\partial}{\partial z} A_z(\omega) &= i\beta'(\omega) A_z(\omega) + i \frac{\Delta\beta}{2} (\omega - \omega_0) A_z(\omega) - \frac{\alpha(\omega)}{2} A_z(z,\omega) + \frac{g(\omega)}{2} A_z(\omega) \\
&+ i\gamma FT \left\{ \left[ A_x(t) \right|^2 + \frac{2}{3} \left| A_y(t) \right|^2 \right] A_x(t) + \frac{i}{3} A_x(t) A_y(t)^2 \exp(-2i\Delta\beta_0 z) \right\} \\

\frac{\partial}{\partial z} A_y(\omega) &= i\beta'(\omega) A_y(\omega) + i \frac{\Delta\beta}{2} (\omega - \omega_0) A_y(\omega) - \frac{\alpha(\omega)}{2} A_y(\omega) + \frac{g(\omega)}{2} A_y(\omega) \\
&+ i\gamma FT \left\{ \left[ A_y(t) \right|^2 + \frac{2}{3} \left| A_x(t) \right|^2 \right] A_y(t) + \frac{i}{3} A_y(t) A_x(t)^2 \exp(2i\Delta\beta_0 z) \right\} 
\end{align}$$

where $\Delta\beta_0 = \beta_{0,x} - \beta_{0,y} = \omega\Delta n/c$, $\Delta\beta_1 = \beta_{1,x} - \beta_{1,y} = \Delta n_0/c$, and $\Delta n$ is the (phase) birefringence of the fiber, $\Delta\omega$ is the group birefringence. The above equations can be applied to two limits: highly birefringent fibers and nonbirefringent fibers. For the non-birefringent case, $\Delta\beta_1 = 0$ and $\Delta\beta_0 = 0$. To eliminate the $A_x^* A_x^2$ and $A_y^* A_y^2$ terms in the above equation, the polarization representation can be changed from linear to circular, by introducing $A_z = (A_x + iA_y)/\sqrt{2}$, $A_y = (A_x - iA_y)/\sqrt{2}$, the nonlinear Schrödinger equations for the clockwise and anti-clockwise circularly polarized lights are given by
To observe the effect of only group velocity dispersion on an incident pulse, the terms like loss, gain and nonlinear polarization may be neglected.

\[
\frac{\partial}{\partial z} A_z(\omega) = i \beta'(\omega) A_z(\omega) - \frac{\alpha(\omega)}{2} A_z(\omega) + \frac{g(\omega)}{2} A_z(\omega)
\]
\[
+i \frac{2\gamma}{3} \text{FT} \left\{ \left[ |A_z(t)|^2 + 2 |A_z(t)| \right] A_z(t) \right\}
\]

\[
\frac{\partial}{\partial z} A_t(\omega) = i \beta'(\omega) A_t(\omega) - \frac{\alpha(\omega)}{2} A_t(\omega) + \frac{g(\omega)}{2} A_t(\omega)
\]
\[
+i \frac{2\gamma}{3} \text{FT} \left\{ \left[ |A_t(t)|^2 + 2 |A_t(t)| \right] A_t(t) \right\}
\]

(5)

To observe the effect of only group velocity dispersion on an incident pulse, the terms like loss, gain and nonlinear polarization may be neglected.

\[
\frac{\partial}{\partial z} A(z,\omega) = i \beta_z(\omega - \omega_0)^2 A(z,\omega)
\]

(6)

For an initial Gaussian pulse without chirp of duration \(t_0\), the field amplitude is given by

\[
A(0,t) = A_0 \exp \left( -2 \ln(2) \left( \frac{t}{t_0} \right)^2 \right)
\]

(7)

After propagation through a fiber of length, \(L\), and with group velocity dispersion \(\beta_z\), the output can analytically be calculated to be a chirped Gaussian pulse:

\[
A(L,t) = A_0 \exp \left( -2 \ln(2) \left( \frac{1 + iC}{1 + Ct_0^2} \right)^2 \right)
\]

(8)

where the \(C\) is given by: \(C = 4 \ln(2) \beta_z L / t_0^2\). The chirp of the pulse, \(c(t) = -\partial \phi / \partial t\), where \(\phi\) is the phase, is then given by \(c(t) = 4 \ln(2) Ct / t_0^2\) and is linear in \(t\). The FWHM temporal pulse duration has now increased to: \(\sqrt{1 + C^2} t_0\). Spectrally nothing has happened (to the power spectrum), as only a quadratic phase has been added:

\[
A(L,\omega) = \exp \left( i \beta_z L \left( \omega - \omega_0 \right)^2 \right) A(0,\omega)
\]

(9)

For the case of consideration of only nonlinearity, the other terms like loss, gain and GVD are disregarded.

\[
\frac{\partial}{\partial z} A(z,t) = i \gamma |A(z,t)|^2 A(z,t)
\]

(10)

This equation can also be integrated analytically to give:

\[
A(L,t) = \exp \left( i \gamma |A(0,t)|^2 \right) A(0,t)
\]

(11)

If the initial pulse is again assumed to be an un-chirped Gaussian pulse, then the chirp of the pulse has a nonlinear temporal dependence, and whereas nothing has happened to the temporal shape of the pulse, the spectrum is now no longer Gaussian, but has spectrally broadened.

When both GVD and nonlinearity is considered, the soliton mode of propagation can be obtained for a range of parameter values. The fundamental soliton is a solution of the simple nonlinear Schrödinger equation.
\[
\frac{\partial}{\partial z} A(z,t) = -i \frac{\beta_2}{2} \frac{\partial^2}{\partial t^2} A(z,t) + i \gamma |A(z,t)|^2 A(z,t)
\]

which preserves both its temporal and spectral shape, as it propagates in the fiber. The fundamental soliton is found in the anomalous dispersion regime ($\beta_2 < 0$), and is characterized by a very characteristic sech shape:

\[
A(z,t) = \left( \frac{|\beta_2|}{\gamma t_0^2} \right)^{1/2} \text{sec} h \left( \frac{t}{t_0} \right)
\]

and occurs when nonlinearities are exactly balanced by dispersion in the fiber.

4. Nonlinear polarization rotation

If a general elliptically polarized pulse is launched into a fiber where nonlinearities are present, it will experience a nonlinear polarization rotation (NPR). To illustrate this, only the nonlinear terms of the nonlinear Schrödinger equation for two polarization directions and in the non-birefringence approximation are maintained and all other terms neglected:

\[
\frac{\partial}{\partial z} A_+ = i \frac{2 \gamma}{3} \left( |A_+|^2 + 2 |A_-|^2 \right) A_+
\]

\[
\frac{\partial}{\partial z} A_- = i \frac{2 \gamma}{3} \left( |A_+|^2 + 2 |A_-|^2 \right) A_-
\]

These equations can also be integrated analytically to yield:

\[
\begin{bmatrix}
A_+(L) \\
A_-(L)
\end{bmatrix} = \exp \left( i \frac{1}{2} (\phi_+ + \phi_-) \right) \begin{bmatrix}
\cos \left( \frac{\phi_+ - \phi_-}{2} \right) & -\sin \left( \frac{\phi_+ - \phi_-}{2} \right) \\
\sin \left( \frac{\phi_+ - \phi_-}{2} \right) & \cos \left( \frac{\phi_+ - \phi_-}{2} \right)
\end{bmatrix} \begin{bmatrix}
A_+(0) \\
A_-(0)
\end{bmatrix}
\]

where,

\[
\phi_+ = \frac{2 \gamma}{3} \left( |A_+(0)|^2 + 2 |A_-(0)|^2 \right)
\]

\[
\phi_- = \frac{2 \gamma}{3} \left( |A_+(0)|^2 + 2 |A_-(0)|^2 \right)
\]

\[
\phi_+ - \phi_- = \frac{2 \gamma}{3} \left( |A_+(0)|^2 - |A_-(0)|^2 \right)
\]

and hence the polarization state rotates with an angle of $(\phi_+ - \phi_-)/2$. Notice that this angle is zero if the light is initially linearly polarized, as $|A_+(0)|^2 = |A_-(0)|^2$, and hence $(\phi_+ - \phi_-)/2 = 0$. Also if the light is circular polarized, the polarization state is maintained.
5. Experiment

5.1 Development of fiber laser

The experimental setup of the fiber oscillator assembled in the ring cavity configuration is shown in Fig. 1. The gain fiber (Liekki ER80-8/125, Thorlabs) is an Er-doped (doping concentration not known) step index single mode fiber of mode field diameter of 9.5µm and core numerical aperture of 0.13 at 1550nm. The pump light absorption at 980nm is quite large (value not known) resulting in requirement of short fiber length of just 53cm. The fiber laser is pumped by a fiber-coupled diode laser (BOOKHAM: LC96UD74 980 module 700mW, NEWPORT: Diode Laser controller : Model 6000) with the use of a WDM coupler (LIGHTEL WDM4-12-P-1-B-0, 980/1550, 1x2, OFS-980).

The dispersion, nonlinearity, effective cross section, gain and gain-bandwidth of the different types of fibers used in the ring cavity are shown in Table I. The length of OFS and SMF fibers are adjusted so that the repetition rate is around 80MHz and the phase due to GVD and Kerr nonlinearity are the same in magnitude but opposite in sign for soliton mode-locking. The fibers are spliced with splice loss as low as 0.01dB. Two collimators (Collimators: OZ OPTICS: LPC 04-1550-9/125-S-1.2-6.2AS-60-X-1-2) are used to pass the beam in free space through the quarter wave plates, half wave plate (MEADOWLARK OPTICS: NQ-050-1550, NH-050-1550), polarizing beam splitter and optical isolator for nonlinear polarization rotation mode-locking. The reflected polarization of the polarization beam splitter serves as the output. The optical isolator assures the unidirectional propagation of the laser light inside the resonator. First the cw lasing is observed by increasing the pump current to 800mA. The cavity is aligned by coinciding the two beam spots emitted from the two collimators at two places within the free cavity space. The output power is monitored (OPHIR 2A-SH detector & NOVA-II) after filtering the pump at 980nm when the alignment is done. The output power suddenly increases when the cavity is aligned. All optics within the free space are handled to optimize the output power. CW output power is recorded with the variation of pump power.

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>K₂(fs²/mm)</th>
<th>K₃(fs³/mm)</th>
<th>n₂(10⁻⁶cm²/W)</th>
<th>Aₑffective(µm²)</th>
<th>Gain BW (nm)</th>
<th>Gain (db/m)</th>
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</thead>
<tbody>
<tr>
<td>SMF28 @ 1550nm</td>
<td>-22.19</td>
<td>0.0869</td>
<td>2.3</td>
<td>84.95</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>OFS Lucent 980 @1550</td>
<td>4.51</td>
<td>0.109</td>
<td>2.3</td>
<td>44.18</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Liekki Er80-8/125</td>
<td>-16.91</td>
<td>0.0912</td>
<td>2.3</td>
<td>70.88</td>
<td>50.0</td>
<td>80</td>
</tr>
</tbody>
</table>

5.2 Mode-locking

The nonlinear polarization rotation mode-locking is realized by using the wave-plates, beam splitter and isolator. Initially, the cw output power is optimized by rotating all the optics. A part of the output beam is made to incident on a fast PIN Photodiode (Electro-Optics Technologies, Model ET3500) for tracing the pulses in a digital oscilloscope (Lecroy Wave runner 44X1 500MHz). Another part of the remaining beam is made to incident on a fiber coupled spectrum analyzer (Photon Control, SPM-002).
The rest of the beam is made to incident on an autocorrelator (APE Pulse Check) for measurement of the mode-locked optical pulse width by intensity auto-correlation. For the verification of cw mode-locking, the laser output is traced in an analogue oscilloscope (Tektronix 7104). For the measurement of the phase noise and pulse jitter, a signal analyzer (Agilent ****) is used. The output quarter-wave plate is rotated to see the modulation in the output. When the modulation is maximum, the half-wave plate is rotated a little to obtain stable mode-locking. If the mode-locking does not come, it is better to observe the spectra. The quarter wave plate and half wave plate is tilted to obtain broad spectra. The broad spectrum is an indication towards stable mode-locking. The tolerance of mode-locking can be increased by proper combination of the orientation of half-wave plate and quarter wave plate. If the stable mode-locking does not come after several tries, the pump power may be increased to the maximum to facilitate the mode-locking. Once a stable mode-locking is obtained, all optic orientations may be optimized for maximum mode-locked output power. The output power is measured in the mode-locked regime with the variation of input pump power. The oscilloscope trace, pulse spectra and auto-correlation traces are recorded for each pump power.

5.3 Second harmonic generation

After obtaining the stable cw mode-locking, a 1mm thick BiB_3O_6 (BIBO) crystal cut for SHG of 1560nm is placed external to the cavity. But the second harmonic generation was not enough to measure. We use a 18mm focal length...
plano-concave lens to focus the beam on the second harmonic crystal. The red coloured second harmonic at 780nm was visible. The position of the crystal is adjusted in the focal plane of the crystal to optimize the second harmonic. The second harmonic power is measured after separating it out from the 980nm pump for laser and laser fundamental radiation at 1560nm. As the conversion was only 1-2% only, we put the crystal inside the cavity to increase the conversion efficiency by intra-cavity second harmonic generation. We use two lenses of focal lengths 18mm and 20mm for the telescopic arrangement within the cavity. We found that the crystal acts as an extra birefringent plate in the cavity affecting the mode-locking severely when it is rotated in its birefringent plane. The mode-locking is severely affected near the phase-matching position causing second harmonic generation to fail.

6. Results and discussion

The cw output power and cw mode-locked output power is plotted with input pump current in Fig.3. The lasing threshold is only 100mA corresponding to the optical pump power of 400mW. Whereas the threshold for cw mode-locking is 375mA and the corresponding optical pump power of 210mW. The slope efficiency with respect to the optical pump power is about 12%. The mode-locking was not stable with the tuning of the pump power. For a large change of pump power, the mode-locking is disturbed and it is restored by rotating the wave plates. The output power is not found to saturate within the range of pump power used in the experiment.

![Fiber Laser Power scaling](image.png)

Fig.2. Measured power scaling characteristics of the Fiber Laser

The mode-locked pulse train as recorded in the digitizing oscilloscope is shown in Fig.4. This data is recorded in nanosecond time scale. The stability of mode-locking is also checked in microsecond and millisecond time scale. The repetition rate is measured to be 80MHz. To assess the stability of cw mode locking, we trace the mode-locked
train as recorded in the analogue oscilloscope in Fig.5. It is evident from the figure that the long time stability of the cw mode-locking is very good.

Fig.3. Digital storage Oscilloscope trace of the mode-locked pulse train in nanosecond time scale

Fig.4. Analogue Oscilloscope trace of the mode-locked pulse train in nanosecond time scale
Fig. 5. Analogue Oscilloscope trace of the mode-locked pulse train in micro-second time scale

Fig. 6. Analogue Oscilloscope trace of the mode-locked pulse train in milli-second time scale

The pulse width is measured by noncollinear SHG intensity autocorrelation. The autocorrelation trace is shown in Fig. 7. The pulse width is found to increase as the pump current is decreased. The pulse width at pump current of 800mA is 129fs whereas its value at 350mA, i.e. near mode-locking threshold is as large as 230fs.
The spectrum of the pulse, as recorded in the spectrometer, is shown in Fig.8. The side lobes of the spectrum are the characteristics of the soliton mode-locking. The FWHM spectral width of the central lobe is 19nm for the pump power of 800 mA. The presence of chirping in the pulse is quite evident causing the deviation of the pulse width from bandwidth limitation. The time bandwidth product is 0.3.

![Noncollinear SHG Intensity autocorrelation Trace](image1)

Fig.7. Noncollinear SHG Intensity autocorrelation and its sech² fit

![Mode-locked Fiber laser spectra](image2)

Fig.8. Measured spectra of the mode-locked pulse

The variation of pulsewidth and spectral bandwidth with pump current is plotted in Fig.9.
Fig. 9. Variation of pulse width and spectral width of mode-locked pulse with pump power

7. Conclusion and future work

An Erbium doped fiber laser has been successfully developed. The laser provides femtosecond optical pulses at 1560nm with temporal width in the range 130fs, the repetition rate of 80 MHz, average power of 40mW. The laser is used to generate extra-cavity second harmonic in a BIBO crystal with conversion efficiency of 1%. The mode-locking is observed to be very stable. The pulse energy is quite low. In future, an amplifier may be incorporated to increase the pulse energy. To gain commercial success over the Ti:sapphire based femtosecond laser, the pulse energy of fiber laser has to be in microJoule range. Ytterbium based fiber lasers are advantageous for high power amplification. I therefore plan to submit a project proposal to one funding agency for the development of high power Yb fiber laser and amplifier for its application in pump-probe set-up, wave-guide writing and nonlinear optical study of nanomaterials.

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