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# Generation of 47 fs Pulses from an Er:Fiber Amplifier *

Shang- Ming Ou(欧尚明)[1], Guan-Yu Liu(刘关玉)[2**], Hui Lei(雷卉)[3],
Zhi-Gang Zhang(张志刚)[2], Qing-Mao Zhang(张庆茂)[1**]

[1]*School of Information Optoelectronics Science and Technology, South China Normal University, Guangzhou 510006*
[2]*State Key Laboratory of Advanced Optical Communication System and Networks, School of Electronics Engineering and Computer Science, Peking University, Beijing 100871*
[3]*Guangzhou Research Institute Of O-M-E Technology, Guangzhou 510663*

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*We demonstrate a self-starting erbium fiber oscillator-amplifier system based on the nonlinear polarization rotation mode-locked mechanism. The direct output pulse from the amplifier is 47 fs with an average power of 1.22 W and a repetition rate of 50 MHz, corresponding to a pulse energy of 24 nJ. The full width at half-maximum of the spectrum of the output pulses is approximately 93 nm at a central wavelength of 1572 nm so that the transform-limited pulse duration is as short as 39 fs. Due to the imperfect dispersion compensation, we compress the pulses to 47 fs in this experiment.*

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High pulse energy femtosecond lasers have many applications in metrology, such as frequency-stabilized octave-spanning comb using Er- and Yb-doped fiber lasers,[1,2] micromachining fabrication,[3] arbitrary optical waveform generation,[4] and high-speed optical sampling.[5,6] Despite the popular use of solid-state lasers, optical-fiber-based ultra-short laser systems[7–9] have emerged as attractive alternatives due to their nature of being compact, low-cost, stable and maintenance-free.

Sub-50 fs pulses with energy range of 1–10 nJ have been achieved from an Er:fiber oscillator based on the nonlinear polarization rotation (NPR) mode-locked mechanism by intra-cavity dispersion managing.[10,11] All fiber integrated ultrashort-pulse amplifiers have been extensively studied in the past years.[12] The difficulty in reducing the time domain width of pulses output from Er-doped fiber amplifiers is that the spectrum gain narrowing in the negative dispersion fiber limits the spectrum width of pulses. On the other hand, the pulses commonly need to be extra-cavity compressed to sub-50 fs by prism pair or gratings.[13,14]

Considering the fact that the self-phase modulation (SPM) phenomenon occurs when pulses propagate in the fiber amplifier, for negatively chirped seed pulses propagating in the normal dispersion fiber, they will undergo spectral compression due to the opposite phase modulation induced by SPM, which have been investigated theoretically and experimentally.[15,16] On the contrary, the spectral width broadens after amplifying when the initial pulses are positively chirped. Moreover, as a well-known process, spectral broadening of transform-limited laser pulses through self-phase modulation in fiber has been widely applied to obtain short pulse duration.[17] The shortest optical pulse duration generated by this effect is 6 fs.[18]

In this Letter, we report an Er:fiber master-oscillator power amplifier system which generates 47 fs, 24.4 nJ pulses at a repetition rate of 50 MHz without a compressor. To the best of our knowledge, this is the shortest pulse from an amplifier with an erbium-doped fiber laser with a pulse energy above 24 nJ.

The system configuration is shown in Fig. 1, which includes an oscillator and a two-stage amplifier. A mode-locked erbium fiber oscillator was used as the seed source. The oscillator was operating in the anomalous dispersion regime with the use of NPR as the saturable absorption mechanism.[8] The optical fiber section of the oscillator cavity contains a 250-mm-long OFS980 fiber for 980/1550-nm wavelength-division multiplexer (WDM) with the group velocity dispersion (GVD) of $D_2 = -1.3\,\mathrm{fs}^2/\mathrm{mm}$, a 500-mm-long erbium-doped fiber (Liekki110-4/125) with the dispersion of $D_2 = +12\,\mathrm{fs}^2/\mathrm{mm}$ and the 1200-mm-long pigtail of the collimators (single mode fiber SMF-28), which have anomalous dispersion of $D_2 = -22\,\mathrm{fs}^2/\mathrm{mm}$. The 2000 mm long dispersion compensation fiber (DCF) with the dispersion of $D_2 = +3.8\,\mathrm{fs}^2/\mathrm{mm}$ is employed to compensate for net cavity dispersion to obtain a wider spectrum. The net cavity dispersion is approximately estimated to be $-13100\,\mathrm{fs}^2$ at the central wavelength of 1550 nm. The oscillator is pumped by a 980 nm laser diode.

The oscillator starts mode locking with 440 mW pump power. The average power of the oscillator is 25 mW, at a central wavelength of 1560 nm and a repetition rate of 50 MHz for seeding the amplifier. The output spectrum of the oscillator is shown in Fig. 2,

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**Corresponding author. Email: zhangqm@scnu.edu.cn; liuguanyulh@163.com
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and the full width at half maximum (FWHM) of the spectrum is approximately 19 nm. The measured autocorrelation trace of the direct output pulse shows a pulse width of 117 fs with the Gaussian profile assumed (Fig. 3), which is close to the transform limit.

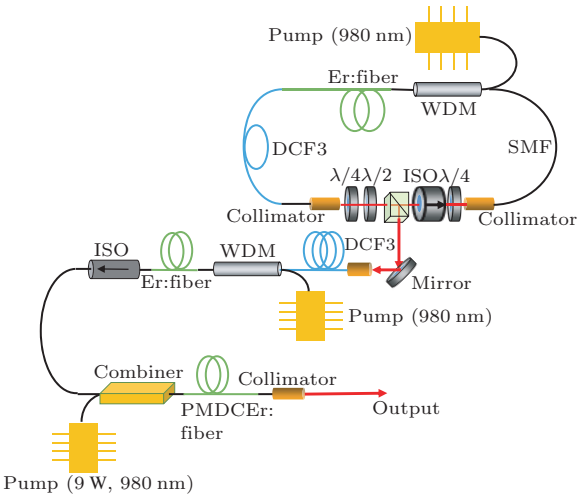


**Fig. 1.** (Color online) Schematic diagram of the laser. PBS, polarization beam splitter; SMF, single mode fiber; $\lambda/2$, half-wave plate; $\lambda/4$, quarter-wave plate; WDM, wavelength-division multiplexer; ISO, isolator; PMDC Er:fiber, polarization maintaining double cladding Er-doped fiber; and DCF, dispersion compensation fiber.

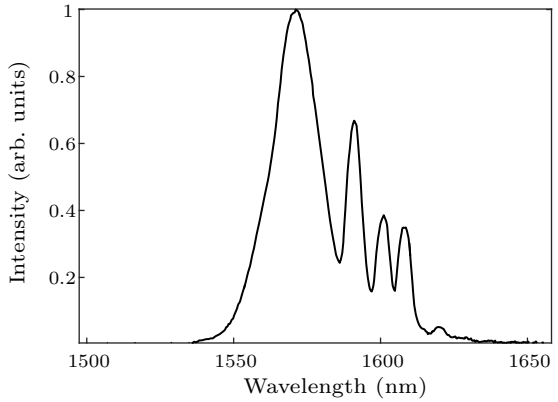


**Fig. 2.** The spectrum of the seed pulses measured in linear scale.

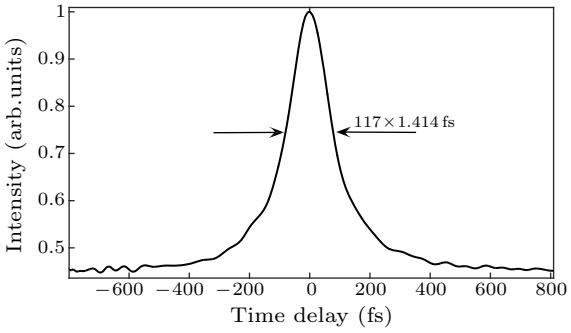


**Fig. 3.** Measured intensity autocorrelation trace of the seed pulses.

A two-stage amplifier is employed to obtain watt level average power. The all-fiber Er-doped femtosecond CPA amplifier is made up of a fiber stretcher, a single-mode fiber pre-amplifier, a second stage cascade energy amplifier, and a high-power collimator. Seed pulses leaving the oscillator first propagate in a 10-m-long dispersion compensation fiber (DCF3) with positive dispersion of $+3.8\text{fs}^2/\text{mm}$ before being injected into the first stage single mode erbium fiber amplifier. The preamplifier is pumped forward by a 980 nm diode laser with the max average power of 550 mW. A 450-mm-long erbium-doped fiber (Likkie80-4/125) is used as the amplification gain medium with normal dispersion to avoid pulse breaking caused by soliton formation and fusion under anomalous dispersion. The stretched pulses are amplified to 120 mW with 22% optical efficiency and the spectral bandwidth of the amplified pulse is 28 nm(Fig. 4). Spectral broadening is not observed due to the low peak power of pulses, which is extremely related to self-phase modulation and gain narrowing.

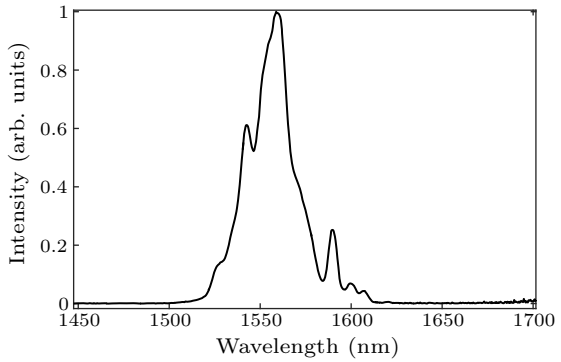


**Fig. 4.** Spectra of the pulses from the core-pumped energy preamplifier.

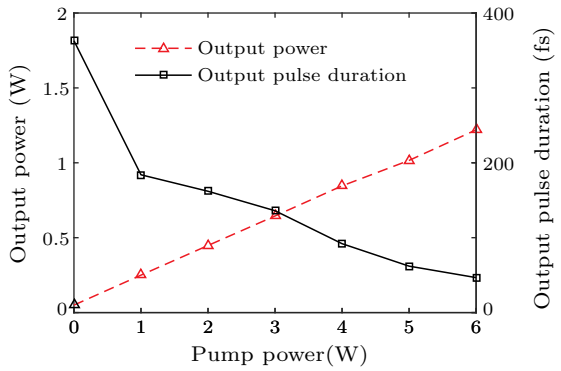


**Fig. 5.** Output power (dashed curve) and pulse duration (solid curve) of the amplifier as a function of the pump power.

The pre-amplified pulses are finally launched into the polarization maintaining cladding-pumped energy amplifier. The pigtail fibers of each component and the Er-doped PM gain fiber in the energy amplifier have anomalous dispersion. Figure 5 shows the change of the output power and direct output pulse durations with Gaussian profile assumed with respect to the increase of the pump power from zero to 6 W with 1 W increment. The average output power reaches 1.22 W

with 6 W pump power. The pulse energy is above 24 nJ.

The frequency spectrum shift at time $t$ after self-phase modulation is given by the time derivative of the phase perturbation,[19]

$$\delta\omega(t) = -\frac{\partial\Delta\phi}{\partial t} = -\frac{2\pi L_{\text{eff}}}{\lambda}\frac{\partial\delta n}{\partial t},$$

where $L_{\text{eff}}$ denotes the effective fiber length, $\lambda$ is the vacuum wavelength, and the intensity-dependent refractive index $\delta n$ is proportional to the intensity ($\delta n = \frac{1}{2}n_2|E|^2$, where $E$ is the electric field of the pulse and $n_2$ is the third-order nonlinear refractive index). Due to the SPM effect, new frequency components are added to the leading and the trailing edge of the pulses. To obtain pulse width shorter than the seed source after amplification, it is necessary to obtain a broader spectrum taking advantage of self-phase modulation. For the Gaussian-shape pulses, there is a simple relationship among the pulse width $\Delta\tau$, the maximum phase shift $\Delta\phi_{\max}$, and the width of the broadened spectrum $\Delta f$

$$\Delta\tau(\text{FWHM}) = 1.72\Delta\phi_{\max}/\pi\Delta f.$$

To avoid pulse shape distortions and self-focusing of propagating beams caused by excessive SPM, the nonlinear effect B-integral ($B = \frac{2\pi}{\lambda}\int_0^L n_2(z)I(z)dz$, where $I(z)$ is the intensity distribution of pulses along the $z$ axis), should not exceed three.

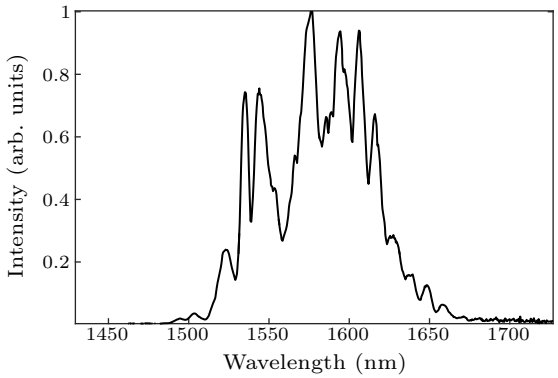


**Fig. 6.** Spectra of the pulses from cladding-pumped energy amplifier.

Spectral broadening in the amplified pulse is clearly observed as shown in the spectra plotted in Fig. 6 at a pump power of 6 W. The FWHM of the spectrum is approximately 93 nm at a central wavelength of 1572 nm so that the transform-limited pulse duration is as short as 39 fs with the Gaussian profile assumed. The FWHM of the spectrum is measured to be comparable with the working bandwidth of the passive components used in the amplifier. For positive pre-chirp pulses propagating in anomalous dispersion, the pulses can be compressed through the fiber. The temporal compression results in an increasing peak power, which includes significant nonlinear phase accumulation as exemplified by SPM for spectra broadening. Spectral broadening accompanying pulse duration compression is observed by measuring the intensity autocorrelation traces of the pulses immediately at amplifier output with pump power increased, as shown in Fig. 7. This process forms the positive feedback for pulse compression. On the other hand, at the high peak power level, a shorter compressed pulse duration can be obtained, which is to some extent resultant from the self-compensation of third-order dispersion (TOD) and nonlinear phase. The 47 fs pulse duration is obtained at the highest pump power of 6 W, as illustrated in Fig. 8. The pulse profile is not very clean due to the residual nonlinear phase, and the sidelobes are caused by high-order dispersion.

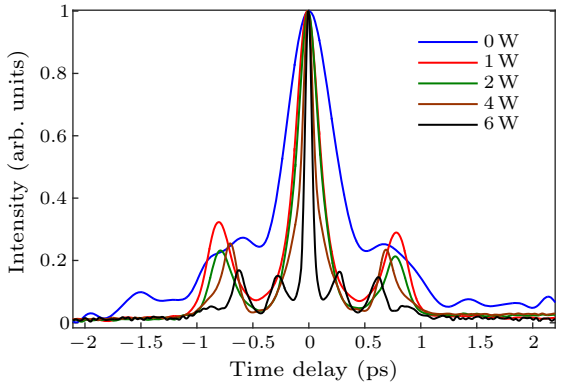


**Fig. 7.** (Color online) Measured intensity autocorrelation of the direct output pulse from the amplifier with different pump powers.

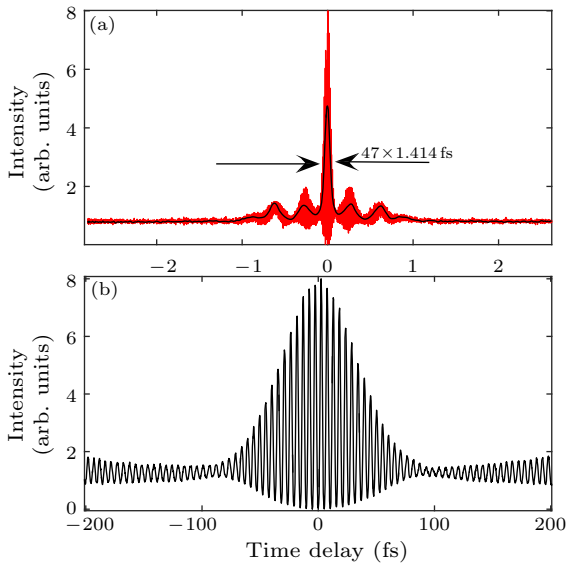


**Fig. 8.** (Color online) (a) Measured long-range interferometric autocorrelation (red curve) and intensity autocorrelation (black curve) of direct output pulse from the amplifier with 6 W pump power, the corresponding pulse width is 47 fs; and (b) short-range interferometric autocorrelation.

In conclusion, we have demonstrated an erbium fiber amplifier at a 50 MHz repetition rate. The mode locking is self-starting and stable against vibrations. The optimized direct output pulse width is 47 fs with

an average power of 1.22 W by taking advantage of spectra broadening effect induced by self-phase modulation. The single pulse energy of the system is above 24 nJ and the peak power is over 0.5 MW. This kind of fiber laser has potential in robust second harmonic generation for 780 nm pulses and other applications.

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