41.9 fs hybridly mode-locked Er-doped fiber laser at 212 MHz repetition rate

Xing Li, Weiwen Zou,* and Jianping Chen

State Key Lab of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

**Corresponding author: wzou@sjtu.edu.cn*

Received December 12, 2013; revised February 11, 2014; accepted February 11, 2014; posted February 12, 2014 (Doc. ID 203015); published March 12, 2014

We demonstrate a hybridly mode-locked erbium-doped fiber laser. It combines saturable absorption and nonlinear polarization evolution to produce stable and purified femtosecond pulses with a high repetition rate of 212 MHz. The average output power is larger than 65 mW, and the single-pulse energy is 0.31 nJ at a pump power of 750 mW. A wide spectrum with FWHM of 61.4 nm is obtained. The dechirped pulse duration is 41.9 fs, which is near the transform-limited range.

OCIS codes: (140.3500) Lasers, erbium; (140.4050) Mode-locked lasers; (320.7090) Ultrafast lasers.

http://dx.doi.org/10.1364/OL.39.001553

Femtosecond mode-locked fiber lasers with high-repetition rates are attractive for numerous applications, such as high-speed optical sampling for photonic analog-to-digital convertor [1–3], frequency comb generation for optical frequency metrology [4], and optical arbitrary waveform generation [5], etc. There are two basic passive mode-locking mechanisms based on a fast or slow saturable absorber. A fast saturable absorber, including nonlinear polarization evolution (NPE) [6–12] and nonlinear optical loop mirror (NOLM) [13], is a common method to generate a broad spectrum and therefore ultrashort pulses due to the large modulation depth and essentially instantaneous response. NPE mode-locked lasers are relatively unstable due to polarization drift caused by environmental disturbance. The NOLM and its variants are unable to obtain high fundamental repetition rates. In comparison, a slow saturable absorber such as saturable Bragg reflector [14] can easily achieve self-starting, and thus mode-locking is thereby stable. However, inevitable pulse shaping caused by slow saturable absorbers limits the pulse duration to an order of picosecond and the spectral bandwidth to a few nanometers. In recent years, the novel saturable absorber materials, such as carbon-nanotube [15] and graphene [16], which have both fast and slow saturable absorption properties, were widely adopted in mode-locked fiber lasers while the spectral bandwidths were still constrained to a few nanometers.

To alleviate this problem, simultaneous application of two mode-locking techniques in one hybrid laser cavity has been developed, which demonstrate the advantages of both a fast and slow saturable absorber. For instance, Byun *et al.* reported an erbium-doped (Er-doped) fiber laser mode-locked using the combination of NPE and an saturable absorber, which achieved a repetition rate of 234 MHz, pulse duration of 102 fs, and spectral bandwidth FWHM of 35.8 nm [17]. A similar schematic to realize a repetition rate of 301 MHz, spectral width of 21.5 nm, and pulse duration of 108 fs was presented [18], in which two diodes are combined by a polarization multiplexer to get a total pump power of 1.2 W, and a pair of silicon flats with large normal group velocity dispersion (GVD) is introduced to balance the gain fiber's anomalous GVD and operate the laser in the stretched pulse regime. However, in the aforementioned cavity configurations, the pump light was directly coupled into the cavity via free-space optics, thus resulting in low pump efficiency and instability of the fiber oscillator. Recently, Kim *et al.* adopted the fiber-based coupling to this hybrid technique so as to achieve 156 mW high output power but with quite low repetition rate of 49.9 MHz [19]. Besides, those achievable pulse durations [17–19] were much larger than those obtained from traditional NPE-based mode-locked lasers [20–23].

In this Letter, we demonstrate a hybrid scheme of Er-doped mode-locked fiber laser that incorporates the NPE and semiconductor saturable absorber mirror (SESAM). The NPE is intended to shape ultrashort pulses; the SESAM adopted here enables self-starting since the fiber length of the oscillator is too short for NPE alone to achieve it. The incorporation of these two mode-locking mechanisms results in 41.9 fs pulse duration with a fundamental repetition rate of 212 MHz. To the best of our knowledge, this is the shortest pulse duration directly generated from a hybridly mode-locked fiber laser. The pulse duration and repetition rate are even comparable to the best-reported values for Er-doped ring fiber lasers based on only NPE [21–26].

Figure 1 depicts the sigma configuration of the hybrid laser. The NPE mode-locking is carried out by a counter-clockwise cavity, which is composed of a highly Er-doped gain fiber (Liekki ER110-4/125), an OFS-980 fiber pigtail of a 980 nm/1550 nm wavelength division multiplexer (WDM), two leading fibers (SMF28) of the collimator1 and collimator2, and a set of free-space components (PBS, wave plates, and isolator). PBS acts as the polarizer for the NPE mode locking. The polarization-dependent isolator is inserted after the PBS to allow unidirectional operation of the cavity. The hybrid laser is counter-pumped by a 974 nm laser diode (Oclaro LC96U, a maximum power of 750 mW), and the OFS-980 fiber has a relatively larger nonlinear coefficient than SMF28. In consequence, the NPE action occurs dominantly in the OFS-980 and the SMF28 of the collimator2 while the SMF28 of the collimator 1 located after the output coupler has almost no contribution to the NPE effect

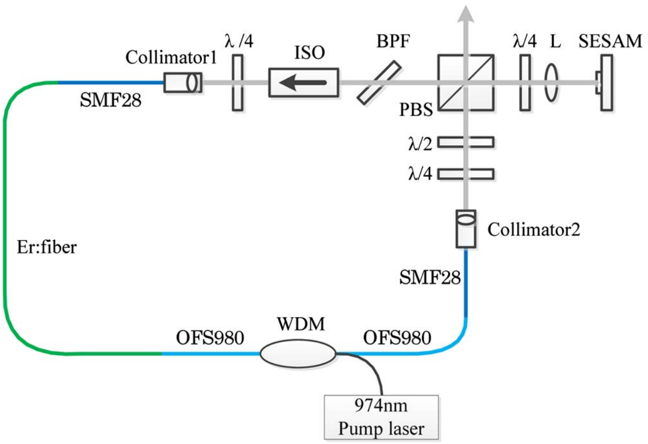

Fig. 1. Configuration of the hybrid laser. PBS, polarization beam splitter; BPF, bandpass filter; ISO, polarization-dependent isolator; $\lambda/2$, half-wave plate; $\lambda/4$, quarter-wave plate; L, aspheric lens; WDM, wavelength-division multiplexer.

due to weak optical power. It is noted that the NPE evolution in the cavity should be optimized by various wave plates.

The collimated beam of the collimator2 is divided into two linear polarization components by the PBS. The horizontal polarization component acts as the laser output. The vertical one enters the linear free-space arm and is then focused by an aspheric lens (focal length = 11 mm) onto the SESAM. The SESAM is a commercial unit (BATOP GmbH) with a 6% modulation depth, a 2 ps recovery time, and a 50 μJ/cm^2 saturation fluence. A quarter-wave plate in the linear arm is employed for the vertical-to-horizontal polarization rotation, which ensures a high-efficiency pass through the PBS. It is noted that a bandpass filter (BPF) with a bandwidth of 40 nm is sandwiched between the PBS and isolator to improve noise performance of the oscillator [27].

The length and GVD of all fibers are summarized in Table 1. Considering the GVD of SESAM and free-space bulk components, the net GVD of the whole cavity is estimated to be 1560 fs^2 at the central wavelength of 1550 nm. Therefore the output pulse is slightly upchirped, which will be dechirped with a certain length of SMF28 external to the ring cavity.

The laser output is characterized by a commercial frequency-resolved optical gating (FROG, Grenouille & Frog 15–40) and an optical spectrum analyzer (Yokogawa AQ6370C). The pulse train and RF spectrum are detected by a 16 GHz photodetector (Discovery Semiconductor DSC720), and then analyzed by a 2.5 GHz oscilloscope (Agilent DSO9254A) and a signal source analyzer (R&S FSUP50).

The dependence of the laser's output power on the pump power is shown in Fig. 2. At the maximum

Table 1. Parameters of all Fibers in the NPE Mode-Locking Cavity

	Er:fiber	OFS980	Collimator1	Collimator2
Length (mm)	380	180	80	100
GVD (fs^2/mm)	12	1.8	−22	−22

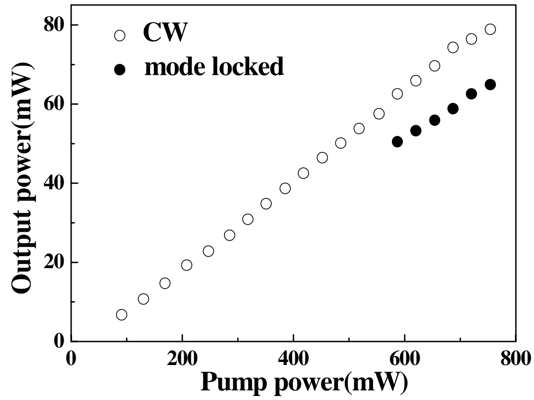

Fig. 2. Laser output power (CW or mode-locked) as a function of the pump power.

available pump power of 750 mW, the output power of continuous wave and mode-locking pulse are 78.9 and 65 mW, respectively. It indicates an overall pumping efficiency of 10.5%. It is noted that mode-locking is easily achieved by adjusting the wave plates at a pump power beyond 720 mW. Once set, the self-starting single pulse operation is maintained even when the pump power is weakened to 580 mW. The laser is highly stable due to fiber-based pumping and the hybrid mode-locking scheme, and it works normally with no change under 30 h continuous monitoring. Figure 3 illustrates equally spaced pulses emitted from the laser with the repetition rate of 212 MHz, suggesting no signs of dual-pulsing or Q-switched mode-locking operation of laser oscillator. A single-pulse energy is evaluated to be 0.31 nJ at 750 mW pump power. The slight fluctuation in pulse amplitude (see Fig. 3) can be attributed to the insufficient bandwidth and resolution of the oscilloscope.

Figure 4 depicts a typical optical spectrum and the corresponding FROG trace of this hybridly mode-locked fiber laser at a repetition rate of 212 MHz. The optical spectrum is centered at 1552 nm with a FWHM of about 61.4 nm [see Fig. 4(a)]. The broad spectral envelope as well as the smooth optical spectrum again confirms the stable single-pulse operation in the fiber laser. Figure 4(b) shows the FROG trace of the dechirped pulse by the SMF28 external to the cavity, which has the minimum pulse duration of 41.9 fs. For comparison, the direct laser output with a pulse duration of 133.8 fs is included

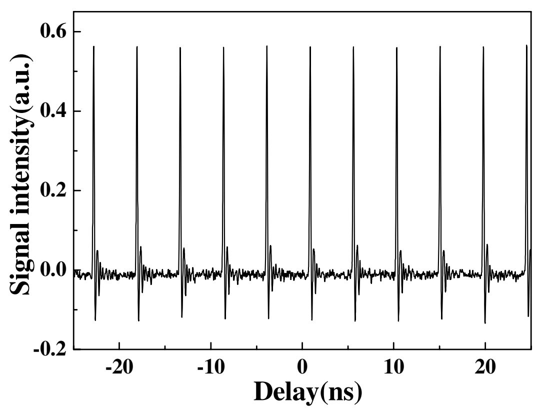

Fig. 3. Output pulse trains measured by an oscilloscope.

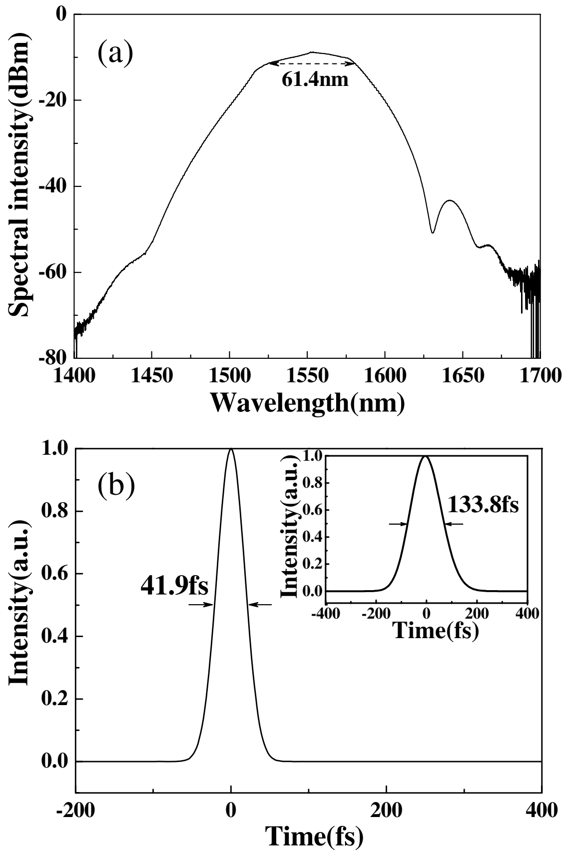

Fig. 4. Experimental results at a repetition rate of 212 MHz. (a) Optical spectrum. (b) FROG trace of the dechirped pulse by a certain length of SMF28. The FROG trace of the direct laser output is shown in the inset.

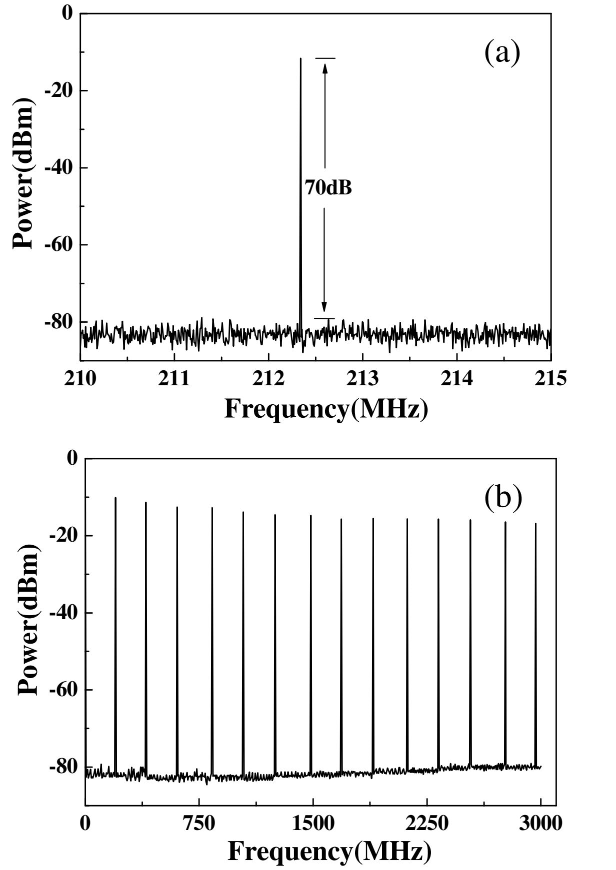

Fig. 5. RF spectrum of (a) fundamental mode beat (resolution bandwidth, 1 kHz) and (b) harmonics (resolution bandwidth, 10 kHz).

in the inset of Fig. 4(b). Assuming that the mode-locked pulses have a sech-function-like profile, the time-bandwidth product of the pulses is 0.322, suggesting that it is almost transform-limited. The tiny difference is attributed to some residual chirp induced by fiber nonlinearity in the laser cavity. No pedestal beats can be observed in both sides of the pulses, indicating that temporal beat pedestals are successfully suppressed by nonlinear amplitude modulation in the oscillator with the assistance of the SESAM.

The RF spectrum of the 212 MHz fundamental mode beat is illustrated in Fig. 5(a). The signal-to-background ratio of the fundamental frequency is up to 70 dB at a resolution bandwidth of 1 kHz, and no sideband is observed within a wide frequency range of 5 MHz. Figure 5(b) shows the RF spectrum of 14 harmonics (up to a frequency of about 3 GHz) at a resolution bandwidth of 10 kHz, which further verifies the high stability of our hybridly mode-locked Er-doped fiber laser.

In conclusion, we have demonstrated a hybridly mode-locked femtosecond fiber laser capable of generating 41.9 fs dechirped pulses at a repetition rate of 212 MHz. The laser delivers an average output power of 65 mW at a pump power of 750 mW, corresponding to pulse energy of 0.31 nJ. The FWHM of the optical spectrum is 61.4 nm, and no pedestal beat is observed in both sides of the time-domain pulse. Mode locking is self-starting and stable over 30 h. It is expectable to realize a repetition rate of >300 MHz based on this scheme if a compact free-space cavity configuration [28] could be substituted for the current 24.5 cm long free-space cavity. The high repetition rate and ultrashort-pulsed fiber laser could be excellent seed sources for the frequency comb generation and photonic analog-to-digital convertor.

This work was partially supported by the National "973" Program of China (no. 2011CB301700), National Natural Science Foundation of China (grant nos. 61007052 and 61127016), International Cooperation Project from the Ministry of Science and Technology of China (grant no. 2011FDA11780), SRFDP of MOE (grant no. 20130073130005), Shanghai Pujiang Program (grant no. 12PJ1405600), Shanghai Excellent Academic Leader Program (grant no. 12XD1406400), and "SMC Young Star" Scientist Program of Shanghai Jiao Tong University.

References

1. T. Hochrein, R. Wilk, M. Mei, R. Holzwarth, N. Krumbholz, and M. Koch, Opt. Express **18**, 1613 (2010).
2. G. C. Valley, Opt. Express **15**, 1955 (2007).
3. G. L. Wu, S. Q. Li, X. W. Li, and J. P. Chen, Opt. Express **18** 21162 (2010).
4. J. Rauschenberger, T. M. Fortier, D. J. Jones, J. Ye, and S. T. Cundiff, Opt. Lett. **10**, 1404 (2002).
5. S. T. Cundiff and A. M. Weiner, Nat. Photonics **4**, 760 (2010).
6. M. Hofer, M. E. Fermann, F. Harberl, M. H. Ober, and A. J. Schmidt, Opt. Lett. **16**, 502 (1991).

7. K. Tamura, H. A. Haus, and E. P. Ippen, Electron. Lett. **28**, 2226 (1992).
8. F. Ö. Ilday, J. Chen, and F. X. Kärtner, Opt. Express **13**, 2716 (2005).
9. J. R. Buckley, F. O. Ilday, T. Sosnowski, and F. W. Wise, Opt. Lett. **30**, 1888 (2005).
10. A. Chong, J. R. Buckley, W. H. Renninger, and F. W. Wise, Opt. Express **14**, 10095 (2006).
11. K. Kieu, W. H. Renninger, A. Chong, and F. W. Wise, Opt. Lett. **34**, 593 (2009).
12. F. O. Ilday, J. R. Buckley, W. G. Clark, and F. W. Wise, Phys. Rev. Lett. **92**, 213902 (2004).
13. N. J. Doran and D. Wood, Opt. Lett. **13**, 56 (1988).
14. J. J. McFerran, L. Nenadovic, W. C. Swann, J. B. Schlager, and N. R. Newbury, Opt. Express **15**, 13155 (2007).
15. A. Martinez, K. Fuse, B. Xu, and S. Yamashita, Opt. Express **18**, 23054 (2010).
16. A. Martinez and Z. Sun, Nat. Photonics **7**, 842 (2013).
17. H. Byun, J. Sickler, J. Morse, J. Chen, D. Pudo, E. P. Ippen, and F. X. Kärtner, Ultrafast Phenomena XVI **92**, 768 (2009).
18. J. L. Morse, J. W. Sickler, J. Chen, F. X. Kärtner, and E. P. Ippen, in *Conference on Laser and Electro-Optics (CLEO)* (Optical Society of America, 2009), paper CML1.
19. S. Kim, Y. Kim, J. Park, S. Han, S. Park, Y. J. Kim, and S. W. Kim, Opt. Express **20**, 15054 (2012).
20. K. Tamura, E. P. Ippen, H. A. Haus, and L. E. Nelson, Opt. Lett. **18**, 1080 (1993).
21. D. Y. Tang and L. M. Zhao, Opt. Lett. **32**, 41 (2007).
22. D. Ma, Y. Cai, C. Zhou, W. J. Zong, L. L. Chen, and Z. G. Zhang, Opt. Lett. **35**, 2858 (2010).
23. D. H. Deng, L. Zhan, Z. C. Gu, Y. Gu, and Y. X. Xia, Opt. Express **17**, 4284 (2009).
24. K. Krzempek, G. Sobon, P. Kaczmarek, and K. M. Abramski, Laser Phys. Lett. **10**, 105103 (2013).
25. L. M. Zhao, C. Lu, H. Y. Tam, P. K. A. Wai, and D. Y. Tang, IEEE Photon. Technol. Lett. **21**, 724 (2009).
26. T. Wilken, T. W. Hänsch, R. Holtzwarth, P. Adel, and M. Mei, in *Conference on Laser and Electro-Optics (CLEO)* (Optical Society of America, 2007), paper CMR3.
27. C. Ouyang, P. Shum, H. Wang, J. H. Wong, K. Wu, S. Fu, R. Li, E. J. R. Kelleher, A. I. Chernov, and E. D. Obraztsova, Opt. Lett. **35**, 2320 (2010).
28. H. Y. Yang, A. M. Wang, and Z. G. Zhang, Opt. Lett. **37**, 954 (2012).