325 MHz and near transform-limited pulse output directly from an Er:fiber ring laser

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A compact Er:fiber ring laser operated at a fundamental repetition rate of 325 MHz is reported. Two gain fibers with opposite dispersion are employed to shorten the fiber laser cavity for high repetition rate and soliton-like pulse generation without losing gain and compactness. The spectral bandwidth of the output pulse is 24 nm and the direct pulse duration is 123 fs without extra-cavity compression, which are values near the transform-limited range.

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Compact femtosecond fiber lasers with high repetition rates have numerous applications in areas such as high-speed optical sampling, optical frequency metrology, and frequency comb generation[1−6]. A larger frequency spacing than the resolution of a wavelength meter is required for the application of frequency comb metrology to determine the major wave numbers[7].

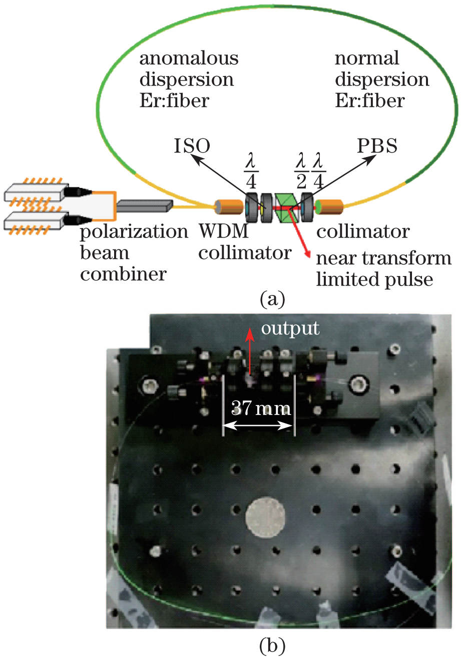
Fiber lasers with GHz-level[8,9] frequency spacing have been achieved in linear cavity fiber lasers through a fiber-tailed wavelength division multiplexer (WDM) placed outside the cavity. However, the saturable absorber (SA) pulse-shaping mechanism limits the spectral bandwidth and leads to a broader pulse. Nonlinear polarization evolution (NPE)[10] relies on a rapid saturation absorption mechanism and takes advantage of very short pulse generation. Unfortunately, NPE is only applicable to ring lasers[11], which limits the achievable frequency spacing.

Er:fiber ring lasers with repetition rate up to 300 MHz have been developed by several studies. For instance, a group of researchers from Massachusetts Institute of Technology reported a 301-MHz Er:fiber ring cavity laser pumped by spatially coupled 1.2 W[12]. Peng *et al.*[13] presented similar results. A Chinese group of researchers created a 325-MHz all-fiber ring cavity Er:fiber laser using a 5.7-cm-long high-gain Er^{3+}/Yb^{3+} co-doped phosphate glass fiber and a 55-cm-long anomalous dispersion single-mode fiber[14]. However, this kind of laser has an unsolved problem of splicing with single-mode fiber, and such a high normal dispersion causes dispersion compensation in the gain fiber. Furthermore, although they claimed a 105-fs output, they did not present solid evidence.

We have developed Yb:fiber lasers with high repetition rates up to 750 MHz with our innovative WDM collimator[15−17]. However, three obstacles limit the development of Er:fiber lasers with high repetition rate: low gain of the Er:fiber, dispersion compensation, and development of a compact WDM collimator for this wavelength. The low-gain fiber means that the fiber cannot be cut into a size as short as 10 cm, unlike the case in Yb:fiber laser. The relatively high-doped Er:fiber (e.g., Er110-4/125) is a normal dispersion fiber in the 1 550-nm wavelength. Mode locking is difficult to initiate in all normal-dispersion fiber lasers[18].

In this letter, we report a 325-MHz repetition rate, compact, and NPE mode-locked Er:fiber ring laser with two dispersion-inversed gain fibers that produce near transform-limited output pulse.

The schematic of the cavity is illustrated in Fig. 1. The free-space region includes a pair of innovative WDM collimators, a quarter wave plate, a 2-mm-thick pill-sized Faraday isolator (ISO), a polarization beam splitter (PBS), and a composite rotation stage that comprises



(a)

(b)

Fig. 1. (Color online) (a) Schematic of the Er:fiber laser. $\lambda/4$: quarter-wave plate; $\lambda/2$: half-wave plate. (b) Photo of the Er:fiber laser.

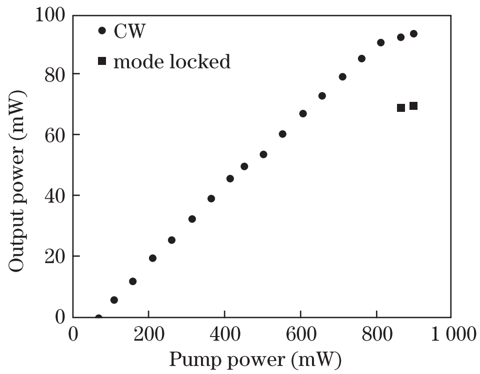


Fig. 2. CW and mode-locked output powers as a function of the pump power.

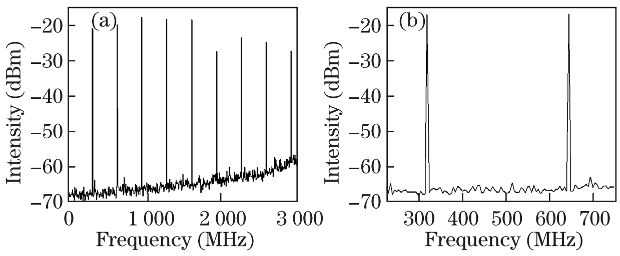


Fig. 3. (a) RF spectrum from 0 to 3 GHz with resolution bandwidth of 1 MHz; (b) zoom-in fundamental mode and second harmonic mode with resolution bandwidth of 30 kHz.

two wave plates on each side, The free-space region of the cavity is only 37 mm.

We selected two kinds of gain fibers, namely, Er110-4/125 and Er80-8/125, which exhibit absorptions of 110 and 80 dB/m and dispersions of +12 and −25.5 fs^2/mm, respectively, to obtain sufficient gain without excessive fiber length for dispersion compensation. The two fibers can partially compensate dispersions without losing too much gain, in contrast to a previous study[12] in which gain dispersion is anomalous and compensated by a pair of silicon plates.

We used a specially designed 980/1550 WDM collimator for pump power deposition. The WDM has a higher loss (3 dB) than our previous 980/1030 collimator for Yb:fiber lasers because of the large difference between the two wavelengths. The collimator size is 10 mm with a 10-cm-long pigtail. The WDM collimators were made in pairs to match each other in mode field and to ensure coupling efficiency.

The fiber section consists of 120-mm-long single-mode fiber tails for each WDM collimator. Each fiber is 170-mm long. The net cavity dispersion is 5 290 fs^2 at the central wavelength of 1 550 nm.

The laser is pumped by two 975-nm laser diodes that are combined to offer a pump power of up to 900 mW. The output continuous wave (CW) power is 93 mW at the maximum pump power of 900 mW, indicating an overall efficiency of 10.3%. The dependence of the output power from the PBS on the pump power is shown in Fig. 2. The mode-locking threshold is 865 mW. Mode locking can be easily initialized with the standard NPE above this threshold. When mode-locked, the laser average output power is 70 mW. Mode locking is very stable and self-starting; it can be sustained for more than one month even if exposed to open air.

As shown in Fig. 3(a), the fundamental repetition rate of mode locking is 325 MHz, as recorded by a radio frequency (RF) spectrum analyzer. As shown in Fig. 3(b), the RF spectrum shows a signal to noise ratio (SNR) of 50 dB.

Figures 4(a) and (b) show that the measured optical spectrum full width at half maximum (FWHM) is 24 nm in logarithm and linear scales, indicating that the mode locking is soliton-like. The measured fringe-resolved autocorrelation trace of the direct output pulse is shown in Fig. 5(a). Superimposed is the calculated autocorrelation trance from the spectrum. The two factors agree very well in most parts.

We performed frequency-resolved optical gating (FROG) measurement to determine the pulse width. As shown in Fig. 5(b), the measured FROG trace indicates that the pulse width is 123 fs, which is 1.36 fold of the transform-limited pulse duration of 90 fs. We attempted to optimize the composition of the gain fiber or

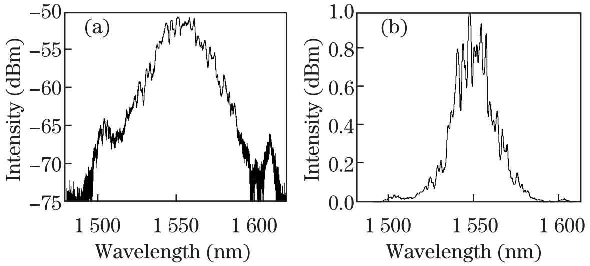


Fig. 4. Measured spectra in (a) logarithmic and (b) linear scales.

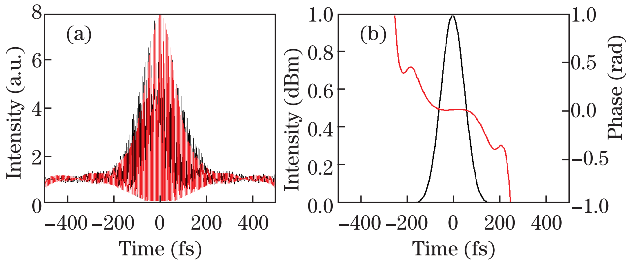


Fig. 5. (Color online) (a) Fringe-resolved autocorrelation trace of the direct output pulses: experimental (black) and transform-limited (red); (b) measured pulse intensity profile and phase with FROG.

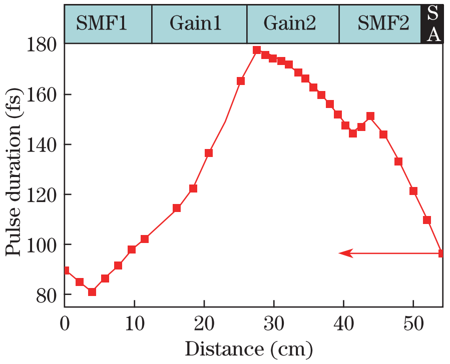


Fig. 6. Evolution of pulse duration inside the laser cavity. SMF1: tail fiber of the WDM collimator; SMF2: tail fiber of the collimator; Gain1: anomalous dispersion of the Er:fiber; Gain2: normal dispersion of the Er:fiber. The wave plate combination is used as the SA.

the intra-cavity dispersion. However, changing the composition of the two fibers or the intra-cavity dispersion only results in difficulty in mode lock initialization.

We performed a simulation[19] to further investigate the output pulse performance in the fiber laser with two section gain fibers. Figure 6 shows the intra-cavity pulse evolution. The output pulse is almost the shortest in the cavity at the position of the pulse output port (after SA), which explains the near transform-limited output pulse without extra-cavity compression.

In conclusion, we demonstrate a femtosecon mode-locked Er:fiber ring laser operated at a fundamental repetition rate of up to 325 MHz. The innovative 980/1550 WDM collimator ensures that the laser is compact and stable. The two kinds of gain fibers with opposite dispersions allow partial compensation of the intra-cavity dispersion without losing gain. The optical spectrum FWHM is 24 nm and the direct output pulse duration is 123 fs without extra-cavity compression. The output power at the pump power of 900 mW is 70 mW, corresponding to the pulse energy of 0.22 nJ. Mode locking is self-starting and stable over a long period, and is benefited by the compact WDM collimator and the short fiber cavity. Further optimization of the cavity dispersion will depend on the available pump power.

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References

1. D. Tang, J. Zhang, Y. Liu, and W. Zhao, Chin. Opt. Lett. **8,** 630 (2010).
2. J. Peng, and R. Shu, Opt. Express. **15,** 4485 (2007).
3. T. Wilke, C. Lovis, A. Manescau, T. Steinmetz, L. Pasquini, G. Lo Curto, T. W. Hänsch, R. Holzwarth, and Th. Udem, Mon. Not. R. Astron. Soc. **405,** L16 (2010).
4. T. Hochrein, R. Wilk, M. Mei, R. Holzwarth, N. Krumbholz, and M. Koch, Opt. Express **18,** 1613 (2010).
5. T. R. Schibli, I. Hartl, D. C. Yost, M. J. Martin, A. Marcinkevicius, M. E. Fermann, and J. Ye, Nat. Photon. **2,** 355 (2008).
6. L. Nugent-Glandorf, T. A. Johnson, Y. Kobayashi, and S. A. Diddams, Opt. Lett. **36,** 1578 (2011).
7. S. T. Cundiff, J. Phys. D **35,** 43 (2002).
8. I. Hartl, A. Romann, and M. E. Fermann, in *Proceedings of Laser and Electro-optics (CLEO)* CMD3 (2011).
9. S. Yamashita, T. Yoshida, S. Y. Set, P. Polynkin, and N. Peyghambarian, Proc. SPIE **6453,** 64531Y (2007).
10. K. Tamura, E. P. Ippen, H. A. Haus, and L. E. Nelson, Opt. Lett. **18,** 1080 (1993).
11. P. Zhang, Y. Jiang, W. Wang, and X. Li, Chin. Opt. Lett. **10,** 061402 (2012).
12. J. L. Morse, J. W. Sickler, J. Chen, F. X. Kärtner, and E. P. Ippen, in *Proceedings of Laser and Electro-optics (CLEO)* CML1 (2009).
13. J. Peng, T. Liu, and R. Shu, in *Proceedings of Laser and Electro-optics/International Quantum Electronics Conference* CTuK3 (2009).
14. X. Wei, S. Xu, H. Huang, M. Peng, and Z. Yang, Opt. Express **20,** 24607 (2012).
15. A. Wang, H. Yang, and Z. Zhang, Opt. Express **19,** 25412 (2011).
16. H. Yang, A. Wang, and Z. Zhang, Opt. Lett. **37,** 954 (2012).
17. C. Li, G. Wang, T. Jiang, A. Wang, and Z. Zhang, Opt. Lett. **38,** 314 (2013).
18. H. Yang, A. Wang, Y. Ma, Z. Fan, G. Niu, J. Yu, Y. Liu, X. Zhang, and Z. Zhang, Chin. Opt. Lett. **10,** 033201 (2012).
19. F. O. Ilday, “Theory and practice of high-energy femtosecond fiber lasers”, PhD. Thesis (Cornell University, 2004).