55-fs pulse generation without wave-breaking from an all-fiber Erbium-doped ring laser

Dinghuan Deng, Li Zhan*, Zhaochang Gu, Yi Gu, and Yuxing Xia

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

*Corresponding author: lizhan@sjtu.edu.cn

Abstract: We demonstrate the direct generation of 55 fs pulses from an all-fiber Erbium-doped ring laser oscillator using the nonlinear polarization rotation mode-locking. The average output power is 56.4 mW but limited by available pump power of 330 mW. The linear chirped pulse duration is 55 fs after recompression using standard single-mode fiber. The pulses show to resist optical wave breaking with a smooth spectrum without any side lobe and cw-breakthrough. This all-fiber laser exhibits relatively high transfer efficiency of 17% and the single pulse energy reaches 1.5 nJ.

OCIS codes: (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers; (190.5530) Nonlinear optics, Pulse propagation and temporal solitons

References and links

1. K. Tamura, E. P. Ippen, H. A. Haus, and L. E. Nelson, "77-fs pulse generation from a stretched-pulse mode-locked all-fiber ring laser," Opt. Lett. **18**, 1080-1082 (1993).
2. L. E. Nelson, D. J. Jones, K. Tamura, H. A. Haus, and E. P. Ippen, "Ultrashort-pulse fiber ring laser," Appl. Phys. B, **65**, 277 (1997).
3. F. Ö. Ilday, J. R. Buckley, W.G. Clark, and F. W. Wise, "Self-similar evolution of parabolic pulses in a laser," Phys. Rev. Lett. **92**, 213902 (2004).
4. A. Ruehl, H. Hundertmark, D. Wandt, C. Fallnich, and D. Kracht, "0.7W all-fiber Erbium oscillator generating 64 fs wave breaking-free pulses," Opt. Express **13**, 6305-6309 (2005), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-13-16-6305.
5. W. J. Tomlinson, R. H. Stolen, and A. M. Johnson, "Optical wave breaking of pulses in nonlinear optical fibers," Opt. Lett. **10**, 457-459 (1985).
6. J. E. Rothenberg, "Femtosecond optical shocks and wave breaking in fiber propagation," J. Opt. Soc. Am. B **6**, 2392-2401 (1989).
7. D. Anderson, M. Desaix, M. Lisak, and M. L. Quiroga–Teixeiro, "Wave breaking in nonlinear-optical fibers," J. Opt. Soc. Am. B **9**, 1358-1361 (1992).
8. P. Grelu, J. Béal, and J. Soto-Crespo, "Soliton pairs in a fiber laser: from anomalous to normal average dispersion regime," Opt. Express **11**, 2238-2243 (2003), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-11-18-2238.
9. M. Olivier, V. Roy, M. Piché, and F. Babin, "Pulse collisions in the stretched-pulse fiber laser," Opt. Lett. **29**, 1461-1463 (2004).
10. Ruehl, O. Prochnow, M. Schultz, D. Wandt, and D. Kracht, "Impact of third-order dispersion on the generation of wave-breaking free pulses in ultrafast fiber lasers," Opt. Lett. **32**, 2590-2592 (2007).

1. Introduction

At the 1550 nm wavelength band, the silica glass works on the anomalous group velocity dispersion (GVD) regime, but the GVD of optical fibers can be normal or anomalous by properly designing the waveguide. Therefore, by properly designing the cavity dispersion, the passively mode-locked fiber lasers may be operated in the soliton and nonsoliton regimes or so-called similariton regime. To date, the generations of sub-100 fs pulses have been demonstrated in these regimes [1-4]. Usually, the nonsoliton regime is considered as a better way to generate ultrashort pulses owing to its total cavity dispersion close to zero, as a result of reducing effective nonlinearity and a suppression of sidebands [2], which is called stretched-pulse fiber laser. But its nonlinear phase shift was still limited to π to avoid wave-

#104583 - $15.00 USD Received 26 Nov 2008; revised 11 Jan 2009; accepted 13 Jan 2009; published 3 Mar 2009

breaking or multiple pulses operation. Wave breaking is a key limitatiom for energy scaling [5-7]. In order to enlarge sustainable nonlinear phase shift, it demands a better dispersion management and uses the gain fiber as short as possible. For an Yb-doped fiber laser the short gain fiber is available for its high doping concentration. But for an Erbium-doped fiber (EDF) laser, long gain fiber should be used usually. Thus, sustainable nonlinearity restricted the bandwidth, which usually make the over driven of nonlinear phase shift, and therefore results in wave breaking. This makes poor quality pulses output or pulse split [8, 9] for energy scaling.

In this paper, we demonstrate an all-fiber constructed stretched-pulse Erbium-doped ring laser with pulse duration as short as 55 fs. Such pulses show to resist optical wave breaking with a smooth spectrum without any side lobe and cw-breakthrough. As the gain media, the high-doped EDF working at the positive dispersion near 1550 nm was also used for dispersion management and linearized the chirp of the pulse. This EDF has relatively large mode diameter, which significantly enlarges the output pulse energy and transfer efficiency. Under 330 mW available maximum pump power, the average output power was 56.4 mW. The pulse energy was improved to 1.5 nJ. The laser exhibits relatively high transfer efficiency of 17%.

2. Principle and experiment setup

In order to make the EDF working at positive dispersion regime near 1550 nm, large positive waveguide dispersion must be chosen to compensate the material dispersion of silica glass. This makes the EDF always have a smaller core diameter than the standard single-mode fiber (SMF), and thus the saturation of EDF limits the output pulse energy for the soliton area theorem [2]. In our experiment, an EDF has a relative large mode field diameter of 4.9 µm and a GVD parameter of -51 ps/(nm·km), is used to compensate the negative dispersion of SMF. Thus, the pulse experiences large positive and negative dispersion in the laser cavity, and therefore the pulse is stretched and compressed twice in the cavity, which reduces the nonlinear saturation in the amplification process. As a result, this ensures the output pulse even shorter and the pulse energy even higher at the same time. We optimized the EDF length to be 135 cm and cut the length of SMF to manage the cavity dispersion to generate the shortest pulse.

Figure 1 shows the configuration of our Erbium-doped fiber ring laser. The all-fiber ring cavity is made of a 135 cm EDF (80dB/m peak absorption ratio at 1530 nm), forward pumped by a 976 nm laser diode through a 980/1550 wavelength division multiplexer (WDM), a 330 cm single-mode fiber (SMF-28), and a 78 cm Nufern 980 fiber. The GVD parameters of the fibers are, respectively, -51, 18, and 4.5 ps/(nm·km). A 10% optical coupler (OC) is located after the EDF to output the signal. This output location may reduce suffering the nonlinear effect of the fiber. A polarization dependent isolator (PDI) sandwiched with two polarization controllers (PC1 and PC2) is used as the mode-locked component in the cavity. The output port is connected to a commercial second order autocorrelator, an optical spectrum analyzer (OSA) and a fast photodetector to monitor the characteristics of output pulses.

In the laser, the unidirectional operation was forced by the PDI. Mode-locking was initiated by nonlinear polarization rotation (NPR). The polarization controllers were adjusted to provide stable pulses that build from noise when the pump power exceeded the threshold. After experimental optimization, we found that the mode-locked status could be well maintained when the cavity length was about 4-6 m. Typically, the pulse width output from the OC pigtail is about 1-ps, but the pulse is highly chirped, which can be recompressed to sub 100 fs by dispersion compensation using a certain length of SMF. When the cavity is too long or too short, high-order mode or twin pulses operation [8] were observed on the oscilloscope. Three or more pulses operation was not observed in experiment for this limited pump power.

#104583 - $15.00 USD Received 26 Nov 2008; revised 11 Jan 2009; accepted 13 Jan 2009; published 3 Mar 2009

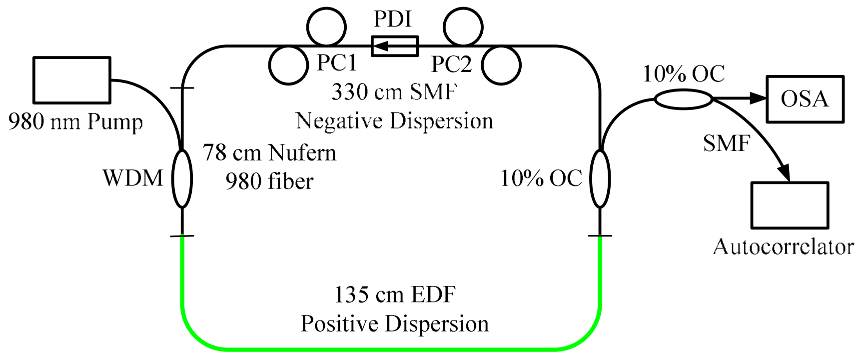

Fig. 1 Experimental configuration of the erbium fiber ring oscillator

3. Results and discussion

Through the dispersion compensation optimization in the experiment, we found the optimized cavity length is 543 cm. Here, the net GVD β'' was calculated to be about +0.012 ps^2 at 1550 nm. Under this cavity length, we observed the best autocorrelated signal by optimizing the length of output lead for external recompression, which is shown in Figure 2. The small wings at the two sides can be seen under this high peak power of the pulse, because the third-order dispersion (TOD) and other nonlinear effect in the output fiber could not be neglected. The TOD compensation could not be performed in experiment, because all the materials we used in the laser have positive TOD. The accumulated TOD makes the pulses to be a bit asymmetry, which developed pedestal on the autocorrelated trace [10]. This also confirmed by the output spectrum, which is also a bit asymmetry. For most set of the PC, the pulse duration is >100 fs, which was due to wave breaking by over driven of NPR or a cw-breakthrough. But for one set, the signal on autocorrelator increased and the pulse duration decreased dramatically at the same time, when we carefully tune the PC. The spectrum got smoothly and its wings decayed faster. The shortest autocorrelated signal obtained in the experiment was 78.1-fs, which was automatically measured by a commercial autocorrelator. Assuming the pulse has a Gaussian-form profile, the corresponding pulse duration should be 55-fs.

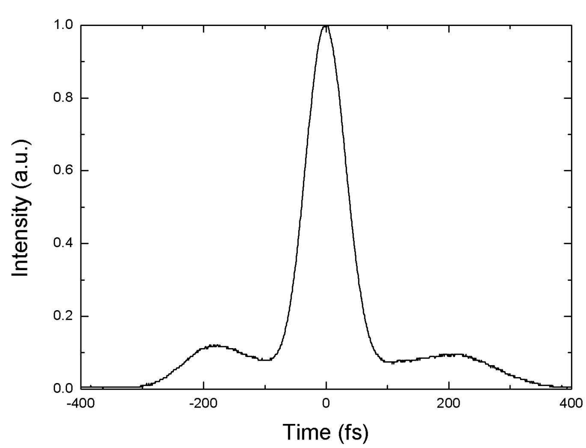

Fig. 2 The autocorrelation trace of output pulses.

#104583 - $15.00 USD Received 26 Nov 2008; revised 11 Jan 2009; accepted 13 Jan 2009; published 3 Mar 2009

When we observed the shortest pulse of 55 fs, the spectrum got smoothly with no side lobe or cw-breakthrough. Figure 3 is the corresponding spectrum of the 55 fs output pulses. The 3 dB spectrum width is 61 nm and the center wavelength is about 1570 nm, so the time-bandwidth product is 0.41. Such an efficient recompression means that the generated pulses are almost linear chirped and almost approach the transform limit. Figure 4 shows the typical output pulses train with 37.8 MHz repetition rate. When we increased the pump power the spectrum shows no change on shape. The average output power increased linearly to 56.4 mW when we got the maximum pump power of 330 mW, the single pulse energy reached 1.5 nJ. Considering the pulse energy contained in the satellite pulse and the tail, which should be less than 23% of the main pulse as estimated from the autocorrelation trace, the peak power is 23 kW. The smooth spectrum without any side lobe and relatively small wings of the autocorrelation trace indicated that good mode-locked condition and single pulse operation were generated in the laser. The decreasing of spectrum at 1530 nm was due to the ground state absorption for the long gain fiber was not fully pumped by 980 nm light. The gain bandwidth from 1530 nm to 1610 nm just work as a filter that limits the output spectrum bandwidth, but also eliminates the generation of side bands.

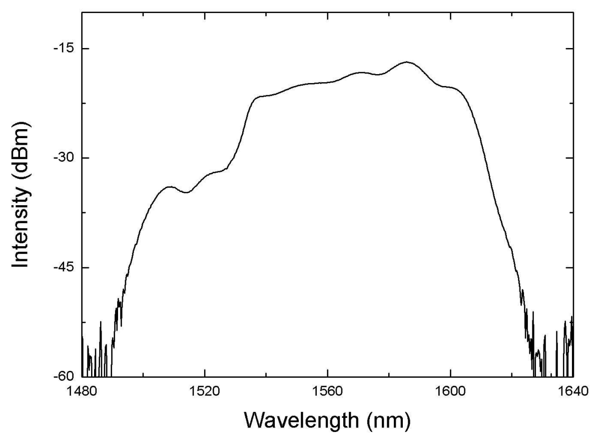

Fig. 3 The output spectrum under 55 fs pulses output from the laser.

Once the mode-locking was attained, the laser could work stably for several hours. The oscilloscope screen showed no change on the pulse shape during the period of several hours, if there were no disturbance and no back reflection into the laser cavity. Here, the EDF used in the laser has a relative large mode field diameter of 4.9 μm and its peak absorption ratio is 80 dB/m. This greatly improves transfer efficiency in the laser, and thus improves output pulse energy, which is almost an order of magnitude higher than the same all-fiber configuration. It is well known that further increasing the pump power to a certain threshold, the pulse would split into twin or triple pulse for a single round trip in the cavity, which is the common behavior of both soliton and stretched-pulse fiber laser[8, 9]. Since the threshold for multiple pulses operation in stretched-pulse fiber laser is much higher in soliton fiber laser and the available peak power is depended on output pulse quality, so the stretched-pulse fiber laser could scale up the peak power of pulses. The gain fiber we used could have higher transfer efficiency and better management of dispersion in the laser, as a result of reducing effective nonlinearity and a suppression of sidebands, so the spectrum without wave breaking and pulses as short as 55 fs with high single pulse energy could be present.

#104583 - $15.00 USD Received 26 Nov 2008; revised 11 Jan 2009; accepted 13 Jan 2009; published 3 Mar 2009

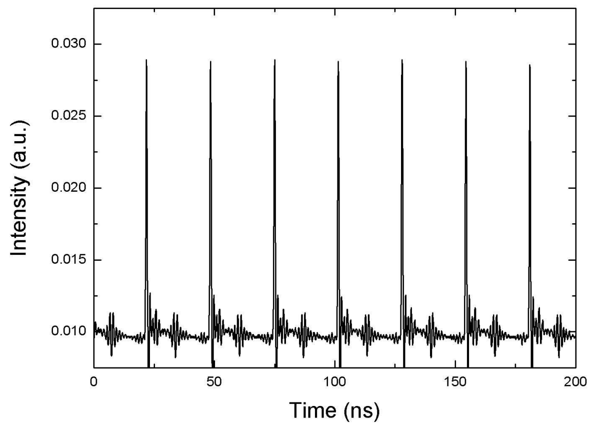

Fig. 4 Output pulses train observed in oscilloscope

4. Conclusion

In conclusion, we have demonstrated the direct generation of 55 fs pulses in the all-fiber stretched-pulse ring laser. The smooth output spectrum without optical wave-breaking shows the single pulse operation in the laser. The dispersion management through both the usage of the positive dispersion EDF and negative dispersion SMF in the laser both shorten the pulse duration and increase the output pulse energy. The laser exhibits relatively high transfer efficiency of 17% and the single pulse energy can reach 1.5 nJ. All-fiber construction makes the laser compactable, portable and easy operation.

Acknowledgments

The authors acknowledge the support from the National Natural Science Foundation of China under the grant 10874118, and the "SMC Young Star" scientist Program of Shanghai Jiao Tong University.

#104583 - $15.00 USD Received 26 Nov 2008; revised 11 Jan 2009; accepted 13 Jan 2009; published 3 Mar 2009