44.6 fs pulses from a 257 MHz Er:fiber laser mode-locked by biased NALM

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44.6 fs pulses from a 257 MHz, mode-locked non-polarization maintaining Er-doped fiber laser based on a biased nonlinear amplifying loop mirror are reported. The output power is 104 mW and the single-pulse energy is 0.4 nJ. The minimum pulse duration of the direct output is 44.6 fs, which is the shortest in this kind of laser.

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Passively mode-locked fiber lasers with a high repetition rate and ultrashort pulses play an important role in many applications, such as frequency metrology, optical arbitrary waveform generation, highly efficient material processing[1], and optical frequency combs[2].

Nonlinear amplifying loop mirror (NALM)[3–7] based fiber lasers have attracted a lot of interest in recent years due to their fast switching time and high stability by using polarization-maintaining fibers. The mode-locking process of this kind of laser is based on the interference between two counterpropagating pulses induced by the beam splitter inside the loop. One problem of NALM-based fiber lasers is the difficulty in self-starting, due to the weak intensity dependence offered by the phase difference between the clockwise and counterclockwise propagating pulses. One method to solve it is to adopt a beam splitter with a higher splitting ratio[8]. Another way is to introduce a phase bias to the loop mirror that offers a linear phase offset to release the requirement of nonlinear phase shift. Consequently, this lowers the mode-locking threshold, as the nonlinear phase shift is induced by the Kerr effect related to the peak pulse energy[9–11].

Recently, Hänsel *et al.* proposed a NALM configuration with a nonreciprocal beam splitter that combined the low losses of a NALM configuration in the transmission with the advantage of a reflective type. Such an all polarization maintaining (PM) Er-doped fiber laser has a repetition rate as high as 250 MHz with an output power of 3 mW at the pump power of 280 mW[12]. Although they did not measure the pulse width, they reported that the Fourier transform limit pulse is 72 fs. Moreover, the pump power is limited to −15% around the proper value to ensure single pulse operation. A higher pump power will cause either continuous wave (CW) components or a multiple pulse operation.

In this Letter, we demonstrate a NALM mode-locked non-PM Er:fiber laser that delivers pulses as short as 44.6 fs at a repetition rate of 257 MHz. The laser delivers an output power as high as 104 mW without multiple pulse instability.

The schematic of the NALM-based fiber laser is shown in Fig. 1. In order to shorten the cavity length for a higher repetition rate, we adopted integrated wavelength division multiplexer (WDM)-collimators instead of coupler and collimators in the ring cavity. Although an all-PM fiber configuration can increase the stability of mode locking, using a highly doped non-PM fiber enables a shorter cavity length and a higher output power. When the laser achieves a higher repetition rate in further designs, the mode locking can be robust even if the fiber is non-PM, because the slight disturbance of a short fiber may not change the polarization as much as $\pi/2$[13].

The single mode Er-doped fiber (Er80-8/125) is 60 cm long with a core absorption of 80 dB/m at 1530 nm and a group velocity dispersion of 17 fs/(nm · m) at 1550 nm. The small negative net dispersion in the cavity makes the laser easier to achieve mode locking without a large

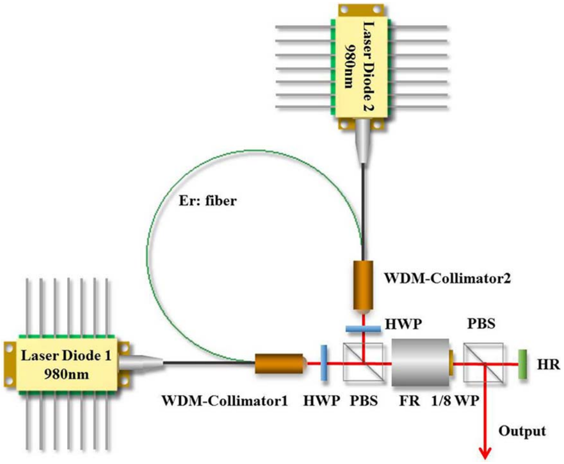

Fig. 1. Schematic of the mode-locked fiber laser based on the NALM. HWP, half-wave plate; PBS: polarizing beam splitter; WDM-Collimator, a combination of a collimator and wavelength division multiplexer; FR, Faraday rotator; HR, high reflection mirror.

deviation between the output pulse duration and Fourier transform limit.

The cavity is pumped from both sides through the WDM-collimators. The half-wave plates placed in front of the WDM-collimators are used to control the polarization in the loop. A 45° Faraday rotator together with a $\lambda/8$ wave plate placed between the two polarizing beam splitters (PBSs) serves as a nonreciprocal phase shifter to introduce a phase bias. After counterpropagating through the phase shifter twice, both perpendicularly polarized beams gain a $\pi/2$ phase delay difference and enter the other collimator inside the loop. The phase bias shifts the round-trip transmission in the loop mirror from near 0 to about 50% at a near zero nonlinear phase shift, which enables the cavity to work in the positive feedback region.

The initial mode locking relies on the rotation of the $\lambda/8$ wave plate to find the exact axis for the phase bias. Then the self-start mode locking can be achieved routinely by setting the pump power of 650 mW through WDM-collimator 1, plus a pump power of 450 mW through WDM-collimator 2, without the need to flap or shake the fiber. Unlike other NALM-based fiber lasers, it does not need to increase the pump power to a very high value to start mode locking and then to lower the pump power down for stable mode locking. This is a great advantage of lasers operating at a high repetition rate.

The dependence of the output power on the power from pump 2 is shown in Fig. 2. The power from pump 1 was set to 650 mW. The mode locking starts at 450 mW and maintains stability to 900 mW from pump 2. At this point, the average output power is 104 mW. No CW component in the spectrum or multipulse in the time domain was observed. Further increasing the power of pump 2 would cause CW breakthrough in the spectrum. Reducing the pump 2 power to less than 350 mW would stop the mode locking. Figure 3 shows the radio frequency spectrum of the laser at the resolution bandwidth of 1 kHz. The fundamental frequency is 256.9 MHz, which indicates that the maximum single pulse energy is about 0.4 nJ.

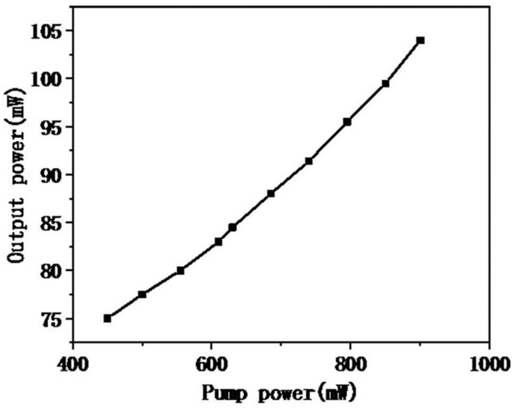

Fig. 2. The average output power as a function of pump 2 power. Pump 1 power was fixed to 650 mW.

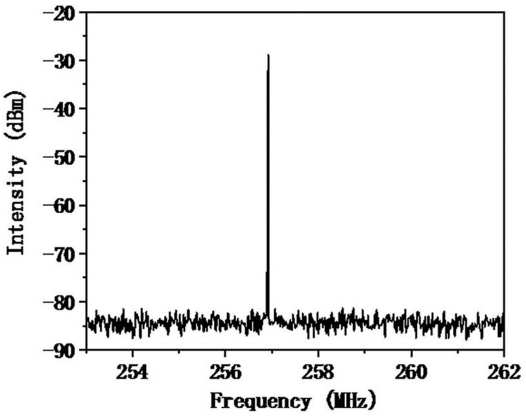

Fig. 3. Radio frequency spectrum at the resolution bandwidth of 1 kHz.

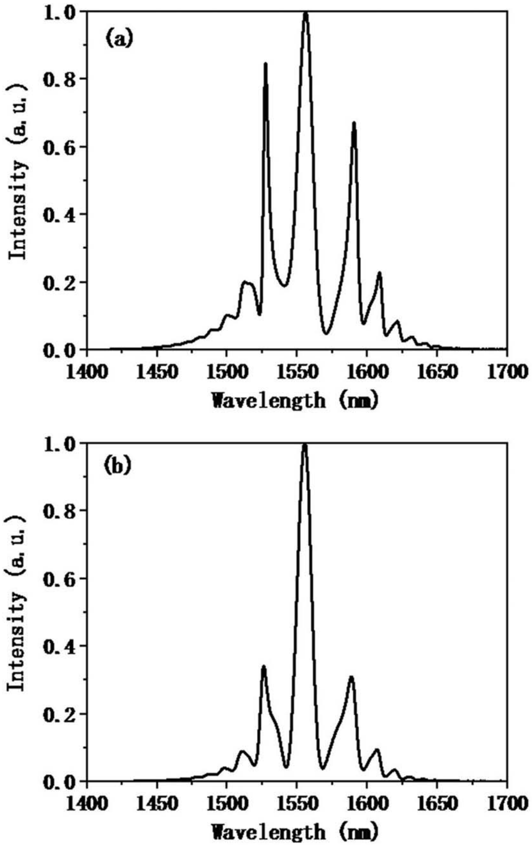

Fig. 4. Measured spectra of output pulses. The modulation state of the spectra can be changed by rotating the $\lambda/8$ wave plate in the cavity. (a) Highly modulated spectrum, with an output power of 104 mW. (b) Less modulated spectrum, with an output power of 135 mW.

Figure 4 shows the measured pulse spectra. The initial spectrum when mode locking is achieved is highly modulated [Fig 4(a)]. The two peaks beside the central peak are induced by the interference of two counterpropagating beams at the output port of the PBS. It is noticed that the modulation of the spectra is sensitive to the rotation of the $\lambda/8$ wave plate in the cavity. Slightly rotating the $\lambda/8$ wave plate can suppress the side peaks of the spectrum [Fig 4(b)]. The respective output power is 104 mW

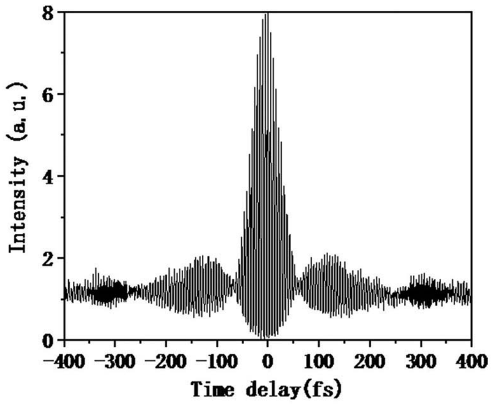

Fig. 5. Fringe-resolved autocorrelation trace of output pulses.

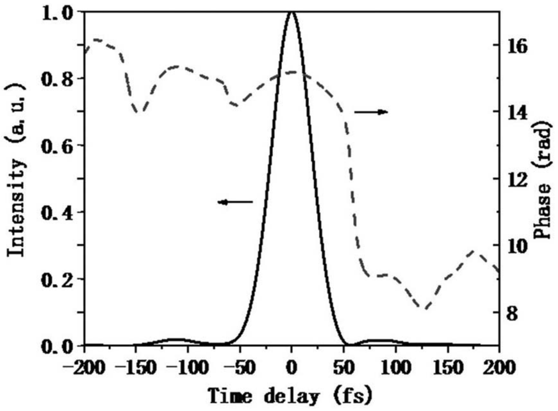

Fig. 6. PICASO retrieved intensity and phase of the output pulse. The retrieved pulse duration is 44.6 fs.

and 135 mW. This can be explained by the function of changing the splitting ratio of two beams by rotating the $\lambda/8$ wave plate. The slight difference in pulse energy between two pulses causes the modulation of the spectrum. Excessive rotation makes the mode locking stop. The operating point can be chosen according to the actual requirement. We chose to let the laser system mode lock at the point shown in Fig. 4(a), where the $\lambda/8$ wave plate is rotated slightly away from its initial angle. Although the spectrum is multipeaked, the shortest pulse duration was obtained at this point.

The normalized autocorrelation trace of the direct output pulse is shown in Fig. 5. As the pulse spectrum is highly modulated and the fringe resolved autocorrelation has wings, it is not appropriate to assume the shape of the pulse for de-convolution. We employed a PICASO algorithm[14] to retrieve the phase of the pulse, and to estimate the pulse duration. Both the intensity and the phase of the PICASO retrieved pulse are shown in Fig. 6, indicating that the retrieved pulse duration is 44.6 fs. This is the shortest pulse obtained in NALM mode-locked fiber lasers in the 1550 nm wavelength region.

In conclusion, we have demonstrated a 257 MHz repetition rate mode-locked Er-doped fiber laser based on biased NALM. The maximum output power is 104 mW and the single-pulse energy is 0.4 nJ. The minimum pulse duration is 44.6 fs. We believe that this is the shortest pulse in the NALM mode-locked Er:fiber laser. This laser has the potential to reach 500 MHz by using a shorter fiber and a more compact mechanical design. The self-starting and robustness of such lasers will have potential applications in frequency comb and ranging[15,16].

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