All-normal-dispersion passive harmonic mode-locking 220 fs ytterbium fiber laser

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Received 10 April 2014; revised 6 July 2014; accepted 9 July 2014; posted 9 July 2014 (Doc. ID 209810); published 4 August 2014

We report a stable passive second-harmonic mode-locked all-normal-dispersion ytterbium fiber laser based on nonlinear polarization evolution. This fiber laser has two polarization beam splitter output ports for optimizing the output spectrum 5 ps duration pulses with 187 mW average power being generated at the harmonic repetition rate of 99.6 MHz. By use of a pair of gratings to extracavity compensate the chirp, the pulse is further compressed to 220 fs. We measured that the peak-to-pedestal extinction of the radio frequency is about 80 dB corresponding to a pulse-to-pulse energy fluctuation of 0.32% and timing jitter of 3.2 ps. © 2014 Optical Society of America

OCIS codes: (320.7090) Ultrafast lasers; (140.3510) Lasers, fiber.

http://dx.doi.org/10.1364/AO.53.005088

1. Introduction

Ytterbium fiber lasers have attracted significant research interest recently because of their favorable properties, such as confined spatial mode, impressive bandwidth, good pump absorption, ease of alignment, and inherent compatibility [1]. At the same time, many scientific and technology applications, such as telecommunications and optical sampling, require pulse trains with high repetition rates. In particular, high-repetition-rate fiber lasers at 1 μm wavelength have been proposed to improve the performance of fusion laser systems, and an amplified and frequency doubled fiber laser can be used for photocathode illumination in photoemission electron guns for future particle accelerators such as the energy recovery linac [2,3].

The achievement of a high repetition rate at the fundamental cavity frequency requires impractically short cavities. In this case, harmonic mode locking (HML) offers many advantages. Particularly, passive HML is proposed to directly achieve high-repetition-rate generation directly from lasers with a simpler cavity setup, rather than active HML. Repetition-rate scalability has been demonstrated with passive HML mode in fiber lasers of different regimes. In soliton fiber lasers, Grudinin *et al.* achieved 1 GHz pulses by passive HML of an Er–Yb-doped fiber ring laser [4], and Zhou *et al.* obtained 1.5 GHz passive HML in a soliton Yb fiber laser that has a maximum single pulse energy of 100 pJ and a timing jitter as low as 6 ps [5]. In the stretched pulse lasers, Deng and Knox realized 585 MHz passive 10th HML with an average output power of 255 mW [6]. In all-normal-dispersion (ANDi) fiber lasers, due to the large normal dispersion, the output energy of ANDi fiber lasers is higher than other regimes. For example, in 2011, Kong *et al.* reported 37.8 MHz second-harmonic mode locking, which has single pulse energy of 1.2 nJ [7]. Shortly thereafter, Zhu *et al.* further achieved a 14th-order 35.97 MHz harmonic

1559-128X/14/235088-04$15.00/0

mode-locked Yb-doped fiber laser with maximum pulse energy of 0.97 nJ. At the 14th HML output, the cavity supermodes are suppressed to 23 dB [8]. Although the passive HML orders in ANDi regimes obtained a higher energy, the low repetition rate and the instability of Yb fiber lasers still remain the problem for practical application.

In this paper, we report a stable passive second-harmonic mode-locked Yb ANDi fiber laser, in which a repetition rate of 99.6 MHz is achieved. The output spectrum is better than the typical M-shaped one from an Yb-doped ANDi fiber laser. The peak-to-pedestal extinction of the radio frequency (RF) is about 80 dB, and the single pulse energy is 1.88 nJ. Compared to previous reports, our results offer progress on high-repetition-rate, high-pulse-energy, and quality pulses in a passive HML ANDi Yb fiber laser.

2. Experimental Setup

The experimental setup is illustrated in Fig. 1. The pump is a 976.44 nm diode laser (JDSU S30-7602-660) with 667 mW maximum output power. A benchtop LD current controller (Thorlabs LDC 220C) and a benchtop temperature controller (Thorlabs TED 200C) are connected to the butterfly mount. The LD is coupled into a 25 cm Yb-doped fiber (CorActive 1200 dB/m absorption at 976 nm) by a 980/1030 nm wavelength division multiplexer (WDM). Between the LD and the WDM, there is a band pass filter (BPF) to prevent the residual signal light. A 1 m long single-mode fiber (SMF) (HI 1060) is followed by the Yb-doped fiber. The spatial segments consist of two collimators, two half-wave plates (HWPs), two quarter wave plates (QWPs), two polarization beam splitters (PBSs), one birefringence filter, and one polarization-dependent isolator that has a center wavelength of 1030 nm. The isolator makes the laser operate unidirectionally and anticlockwise in Fig. 1. The birefringent spectrum filter is made from quartz crystal, which provides a Gaussian curve with a bandwidth of 10 nm for full width at half-maximum (FWHM), which is inserted at Brewster angle to ensure the maximum transmittance ratio. All of the spatial segments arranged linearly have a total distance of 23 cm between two collimators. Prior to the WDM, there is a segment of 2.5 m long SMF.

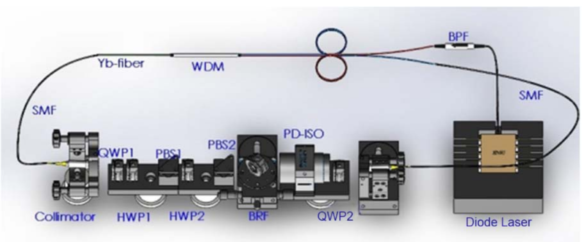

Fig. 1. Schematics of the ANDi fiber laser oscillator. QWP, quarter wave plates; BRF, birefringence filter; PBS, polarization beam splitter; HWP, half-wave plates; WDM, wavelength division multiplexer.

Nonlinear polarization evolution (NPE) as the saturable absorber is implemented through the QWPs, HWPs, and PBSs. It is well known that the cavity circulating pulse quality of an ANDi fiber laser is better than that of the NPE ejected. To obtain quality pulses, we set the second PBS as the main output port [9].

3. Results and Discussion

In the experiment, the fundamental repetition rate is 49.8 MHz, which corresponds to 4 m total laser cavity length. The standard SMF has a dispersion of approximately 23 fs^2/mm at 1 μm, and the total cavity dispersion is estimated to be 0.09 ps^2. The output pulse train is monitored by a photodetector/sampling oscilloscope (TEK DPO2024B) combination after our main PBS output port. The spectrum is analyzed by an optical spectrum analyzer (AQ6370 YOKOGAWA). When the pump power is more than 250 mW, stable fundamental mode locking can be obtained by adjustment of the wave plates. The output power from the two PBS ports can also be changed in the same way. As the pump power decreases to 220 mW, the mode-locked state will be unstable. This phenomenon of hysteresis results from the bistability between the mode-locked and the continuous regimes. When the pump power is 667 mW, and when rotating the wave plates, an output power of 203 mW at 49.8 MHz repetition rate is obtained from the main output port. At the same time, there are varieties of mode-locked operations along with the increase of pump power. As is shown in Figs. 2(b) and 2(c), when the pump power is larger than 400 mW, multipulses can be obtained by adjustment of the wave plates. At first, we observe a tendency of splitting into multipulses; then multipulse bunches containing two pulses in one bunch are observed. From the chart, we can see obvious amplitude fluctuations at the two states, which shows unstable phenomena. With the pump power increasing to 450 mW, stable second-harmonic mode-locked pulses can be achieved by adjustment of the wave plates and the birefringence filter. When we obtain a HML operation by rotating the wave plates, we can also change the operations periodically between the multiple pulses and HML by rotating the birefringence filter. The harmonic pulses can be stable with the increase of pump power from 450 mW to the maximum 667 mW. Finally, we obtained 187 mW output power of the second-harmonic mode-locking pulse of 99.6 MHz corresponding to single pulse energy of 1.88 nJ. The spectrum of the second-harmonic mode locking is shown in Fig. 3(a). Compared with the typical M-shaped spectrum from the Yb-doped ANDi fiber laser, it is obvious that there is less chirp around the edges of the spectrum. When operating in the multiple pulsing regimes, the lower energy per pulse leads to less nonlinearity. In spite of our second PBS to the output cavity circulating pulse, this can also contribute to the formation of quality pulse spectrum. The quality pulse has many advantages in the chirped pulse amplification system, which requires fewer

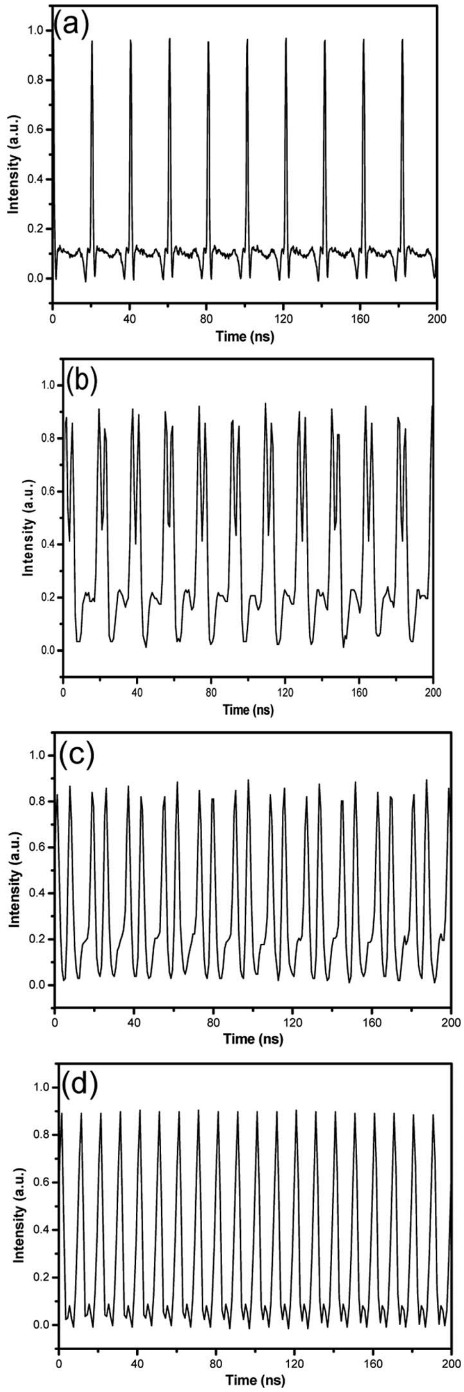

Fig. 2. Pulse train: (a) fundamental mode locking. (b) Beginning of multiple pulses. (c) Multiple pulses. (d) Second-harmonic mode locking.

nonlinear effects and so on. The bandwidth of the spectrum (FWHM) is 19 nm. The autocorrelation traces of the chirped and dechirped pulses are shown in Fig. 3(b). The pulse duration from the main output port is 5 ps, and the pulse duration dechirped outside of the cavity by grating pairs (300 lines/mm) is 220 fs, corresponding to approximately 300% larger than transform-limited duration. This result is attributed to the highly chirped pulse produced by the ANDi fiber laser. The peak-to-pedestal extinction of the RF

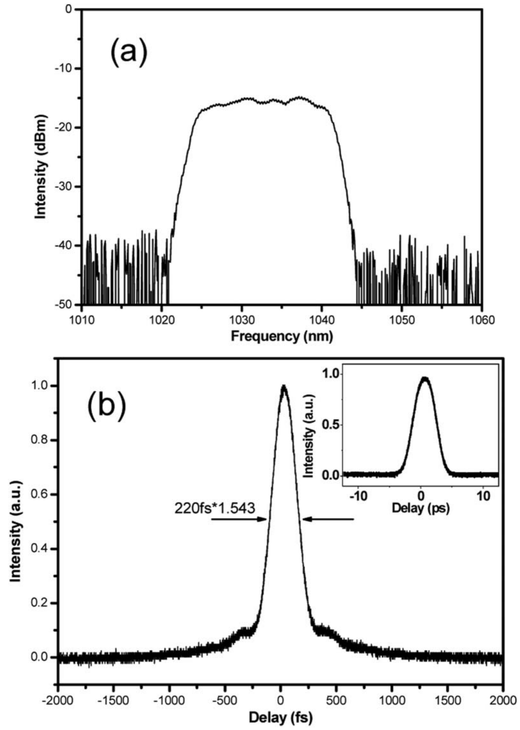

Fig. 3. (a) Second HML spectrum from the main port. (b) Intensity autocorrelation curve of the dechirped pulses; inset is the chirped autocorrelation curve.

spectrum measured by a frequency spectrum analyzer (Agilent E4407B) is 80 dB at least.

The main mechanism resulting in HML can be attributed to the oversaturation of the SA [10] and the frequency detuning of the spectral filter and the gain spectrum's central frequency [11]. In our ANDi fiber laser, NPE acts as an artificial fast SA and has a sinusoidal dependence of the transmittance curve on the intensity with attenuation. The transmittance of SA has a maximum value as the pulse energy increases to the first peak value. It begins to decrease beyond the maximum value so that the peak power of the pulse diminishes. Along with the increase of the energy of the ultrafast pulse or pump power, the transmittance peak of SA appears from one peak to the second peak. Then the laser emits multiple pulses looking like a bunch. In our opinion, the multipulsing effect in this experiment mainly results from the balance of the nonlinear and the dispersion in the fiber cavity. By adjusting the pumping power and the frequency detuning of the spectral filter, the multipulses can attract or repel each other with different values. When it shows the phenomena of repulsion, the multipulses in a soliton burst will repel each other to fill up the available time space and form a harmonically mode-locked state. In addition, other parameters such as group velocity dispersion and nonlinear phase shifts also affect this multipulse phenomenon. Better understanding and further research is necessary to solve the issue in detail.

The stability and quality of the generated pulses are evaluated via the RF spectrum. As shown in

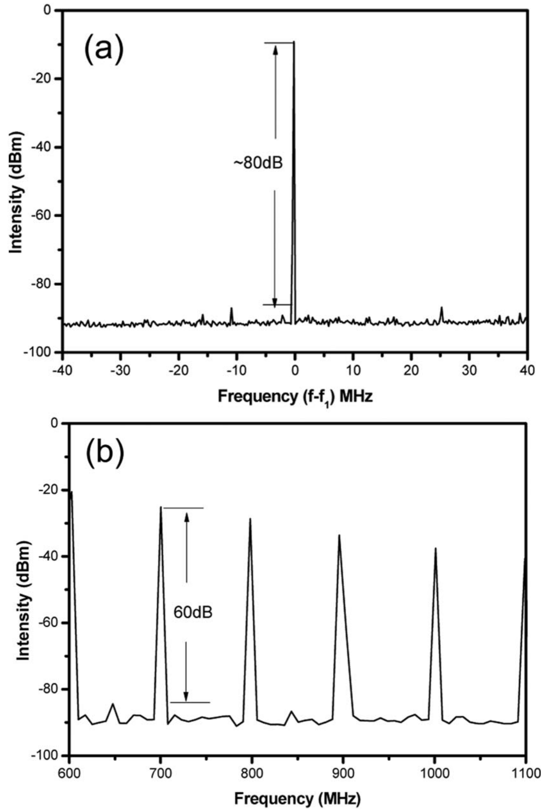

Fig. 4. RF spectra of the second HML: (a) fundamental and (b) seventh harmonic.

Fig. 4, the short-range spectrum spanning 50 MHz with a resolution of 1 kHz reveals a low-level pedestal component 80 dB from the central spike. We estimate the energy fluctuations as

$$\Delta E = \left[\frac{\Delta P \Delta f}{\Delta f_{\mathrm{Res.}}}\right]^{1/2}, \tag{1}$$

where ΔP is the power ratio between the central spike at f1 and the peak of the noise band, Δf is the frequency width of the noise, and $\Delta f_{\mathrm{Res.}}$ is the resolution bandwidth of the spectrum analyzer. $\Delta P = 1 \times 10^{-8}$, $\Delta f = 1$ MHz, $\Delta f_{\mathrm{Res.}} = 1$ kHz, and the pulse-to-pulse energy fluctuation $\Delta E = 3.2 \times 10^{-3}$.

The timing jitter can be evaluated as

$$\frac{\Delta T}{T} = \frac{1}{2\pi n}\left[\frac{\Delta P_n \Delta f}{\Delta f_{\mathrm{Res.}}}\right]^{1/2}, \tag{2}$$

where T is the cavity period, and n is the harmonic order. The timing jitter evaluated at the second harmonic is estimated as $\Delta T/T = 1.6 \times 10^{-4}$. $T = 20$ ns, $\Delta T = 3.2$ ps, which shows a low timing jitter [12,13].

4. Conclusion

In conclusion, we have demonstrated a stable 99.6 MHz second-harmonic mode-locked ytterbium ANDi fiber laser at a repetition rate of 99.6 MHz. Two output ports are set in order to obtain quality pulses. The laser is mode locked by an NPE mechanism and self-starting. The output power is 187 mW corresponding to single pulse energy of 1.88 nJ. The output pulses can be dechirped from 5 ps to 220 fs outside of the cavity. The peak-to-pedestal extinction of the RF spectrum is about 80 dB corresponding to a pulse-to-pulse energy fluctuation of 0.32% and a low timing jitter of 3.2 ps. It is believed that an ANDi Yb-doped fiber laser with controllable pulse numbers will find a variety of applications in high-energy fiber amplifiers.

This work was partially supported by the National Major Instrument Program of China (Grant No. 2012YQ120047), the Fundamental Research Funds for the Central Universities (No. K5051305008), and the National Natural Science Foundation of China (No. 61205130).

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