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Highly-stable mode-locked PM Yb-fiber laser with 10 nJ in 93-fs at 6 MHz using NALM

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Abstract: We demonstrate highly stable mode-locked Yb-doped fiber oscillators using a nonlinear amplifying loop mirror, delivering linearly polarized laser pulses with high energy at a low repetition rate of several MHz. These lasers are composed of polarization-maintaining fibers and fiber-based components without intra-cavity dispersion compensation. The spectral and temporal characteristics are systematically investigated at different repetition rates. Spectral bandwidth of 31 nm is realized in the case of 6 MHz repetition rate, and the pulse energy reaches 10 nJ. A pair of gratings compresses the output pulse to 93 fs. RMS power stability is as low as 0.04% in 10 hours, which shows excellent stability. We believe that this type of fiber oscillator is an ideal seed for further high power amplification.

OCIS codes: (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers; (320.7090) Ultrafast lasers.

References and links

1. A. Tünnermann, T. Schreiber, and J. Limpert, "Fiber lasers and amplifiers: an ultrafast performance evolution," Appl. Opt. **49**(25), F71–F78 (2010).
2. W. Shi, Q. Fang, X. Zhu, R. A. Norwood, and N. Peyghambarian, "Fiber lasers and their applications," Appl. Opt. **53**(28), 6554–6568 (2014).
3. N. Nishizawa, H. Mitsuzawa, J. Takayanagi, and K. Sumimura, "Generation of 0.45–1.38 µm visible to nearinfrared widely broadened supercontinuum using Er-doped ultrashort-pulse fiber laser system," J. Opt. Soc. Am. B **26**(3), 426–431 (2009).
4. N. Leindecker, A. Marandi, R. L. Byer, K. L. Vodopyanov, J. Jiang, I. Hartl, M. Fermann, and P. G. Schunemann, "Octave-spanning ultrafast OPO with 2.6-6.1 µm instantaneous bandwidth pumped by femtosecond Tm-fiber laser," Opt. Express **20**(7), 7046–7053 (2012).
5. K. F. Lee, X. Ding, T. J. Hammond, M. E. Fermann, G. Vampa, and P. B. Corkum, "Harmonic generation in solids with direct fiber laser pumping," Opt. Lett. **42**(6), 1113–1116 (2017).
6. Z. Zhao and Y. Kobayashi, "Realization of a mW-level 10.7-eV (λ = 115.6 nm) laser by cascaded third harmonic generation of a Yb:fiber CPA laser at 1-MHz," Opt. Express **25**(12), 13517–13526 (2017).
7. B. Resan, R. Aviles-Espinosa, S. Kurmulis, J. Licea-Rodriguez, F. Brunner, A. Rohrbacher, D. Artigas, P. Loza-Alvarez, and K. J. Weingarten, "Two-photon fluorescence imaging with 30 fs laser system tunable around 1 micron," Opt. Express **22**(13), 16456–16461 (2014).
8. K. Wang, N. G. Horton, K. Charan, and C. Xu, "Advanced fiber soliton sources for nonlinear deep tissue imaging in biophotonics," IEEE J. Sel. Top. Quantum Electron. **20**(2), 50–60 (2014).
9. Á. Krolopp, A. Csákányi, D. Haluszka, D. Csáti, L. Vass, A. Kolonics, N. Wikonkál, and R. Szipőcs, "Handheld nonlinear microscope system comprising a 2 MHz repetition rate, mode-locked Yb-fiber laser for in *vivo*biomedical imaging," Biomed. Opt. Express **7**(9), 3531–3542 (2016).
10. T. M. Katz, B. F. Firoz, L. H. Goldberg, and P. M. Friedman, "Treatment of Darier's disease using a 1,550-nm erbium-doped fiber laser," Dermatol. Surg. **36**(1), 142–146 (2010).
11. Y. K. Madhukar, S. Mullick, and A. K. Nath, "An investigation on co-axial water-jet assisted fiber laser cutting of metal sheets," Opt. Lasers Eng. **77**, 203–218 (2016).
12. F. Ilday, J. Buckley, L. Kuznetsova, and F. Wise, "Generation of 36-femtosecond pulses from a ytterbium fiber laser," Opt. Express **11**(26), 3550–3554 (2003).

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13. N. C. Becker, S. Hädrich, T. Eidam, F. Just, K. Osvay, Z. Várallyay, J. Limpert, A. Tünnermann, T. Pertsch, and F. Eilenberger, "Adaptive pre-amplification pulse shaping in a high-power, coherently combined fiber laser system," Opt. Lett. **42**(19), 3916–3919 (2017).
14. T. Eidam, S. Hanf, E. Seise, T. V. Andersen, T. Gabler, C. Wirth, T. Schreiber, J. Limpert, and A. Tünnermann, "Femtosecond fiber CPA system emitting 830 W average output power," Opt. Lett. **35**(2), 94–96 (2010).
15. A. Klenke, E. Seise, S. Demmler, J. Rothhardt, S. Breitkopf, J. Limpert, and A. Tünnermann, "Coherently-combined two channel femtosecond fiber CPA system producing 3 mJ pulse energy," Opt. Express **19**(24), 24280–24285 (2011).
16. W. Liu, D. N. Schimpf, T. Eidam, J. Limpert, A. Tünnermann, F. X. Kärtner, and G. Chang, "Pre-chirp managed nonlinear amplification in fibers delivering 100 W, 60 fs pulses," Opt. Lett. **40**(2), 151–154 (2015).
17. Y. Hua, G. Chang, F. X. Kärtner, and D. N. Schimpf, "Pre-chirp managed, core-pumped nonlinear PM fiber amplifier delivering sub-100-fs and high energy (10 nJ) pulses with low noise," Opt. Express **26**(5), 6427–6438 (2018).
18. A. Chong, W. H. Renninger, and F. W. Wise, "All-normal-dispersion femtosecond fiber laser with pulse energy above 20 nJ," Opt. Lett. **32**(16), 2408–2410 (2007).
19. W. H. Renninger, A. Chong, and F. W. Wise, "Self-similar pulse evolution in an all-normal-dispersion laser," Phys. Rev. A **82**(2), 021805 (2010).
20. X. Zhou, D. Yoshitomi, Y. Kobayashi, and K. Torizuka, "Generation of 28-fs pulses from a mode-locked ytterbium fiber oscillator," Opt. Express **16**(10), 7055–7059 (2008).
21. J. Szczepanek, T. M. Kardaś, C. Radzewicz, and Y. Stepanenko, "Ultrafast laser mode-locked using nonlinear polarization evolution in polarization maintaining fibers," Opt. Lett. **42**(3), 575–578 (2017).
22. B. Ortaç, M. Plötner, J. Limpert, and A. Tünnermann, "Self-starting passively mode-locked chirped-pulse fiber laser," Opt. Express **15**(25), 16794–16799 (2007).
23. H. Wang, H. Han, Y. Xie, Y. Yu, H. Teng, S. Fang, J. Zhu, and Z. Wei, "Stable SESAM-mode-locked Yb fiber laser in the similariton regime," in *Advanced Solid State Lasers Conference*, 2017 OSA Technical Digest (online) (Optical Society of America, 2017), paper JTh2A.37.
24. D. A. Pattison, W. Forysiak, P. N. Kean, I. Bennion, and N. J. Doran, "Soliton switching using cascaded nonlinear-optical loop mirrors," Opt. Lett. **20**(1), 19–21 (1995).
25. F. O. Ilday, F. W. Wise, and T. Sosnowski, "High-energy femtosecond stretched-pulse fiber laser with a nonlinear optical loop mirror," Opt. Lett. **27**(17), 1531–1533 (2002).
26. W. H. Cao and P. K. A. Wai, "Amplification and compression of ultrashort fundamental solitons in an erbium-doped nonlinear amplifying fiber loop mirror," Opt. Lett. **28**(4), 284–286 (2003).
27. N. J. Doran and D. Wood, "Nonlinear-optical loop mirror," Opt. Lett. **13**(1), 56–58 (1988).
28. M. E. Fermann, F. Haberl, M. Hofer, and H. Hochreiter, "Nonlinear amplifying loop mirror," Opt. Lett. **15**(13), 752–754 (1990).
29. D. Kim, S. Zhang, D. Kwon, R. Liao, Y. Cui, Z. Zhang, Y. Song, and J. Kim, "Intensity noise suppression in mode-locked fiber lasers by double optical bandpass filtering," Opt. Lett. **42**(20), 4095–4098 (2017).
30. A. Avdokhin, S. Popov, and J. Taylor, "Totally fiber integrated, figure-of-eight, femtosecond source at 1065 nm," Opt. Express **11**(3), 265–269 (2003).
31. J. W. Nicholson, S. Ramachandran, and S. Ghalmi, "A passively-modelocked, Yb-doped, figure-eight, fiber laser utilizing anomalous-dispersion higher-order-mode fiber," Opt. Express **15**(11), 6623–6628 (2007).
32. J. Szczepanek, T. M. Kardaś, M. Michalska, C. Radzewicz, and Y. Stepanenko, "Simple all-PM-fiber laser mode-locked with a nonlinear loop mirror," Opt. Lett. **40**(15), 3500–3503 (2015).
33. C. Aguergaray, R. Hawker, A. F. J. Runge, M. Erkintalo, and N. G. R. Broderick, "120 fs, 4.2 nJ pulses from an all-normal-dispersion, polarization-maintaining, fiber laser," Appl. Phys. Lett. **103**(12), 121111 (2013).
34. P. Bowen, M. Erkintalo, R. Provo, and J. D. Harvey, "Mode-locked Yb-doped fiber laser emitting broadband pulses at ultralow repetition rates," Opt. Lett. **41**(22), 5270–5273 (2016).
35. C. M. González Inchauspe and O. E. Martínez, "Quartic phase compensation with a standard grating compressor," Opt. Lett. **22**(15), 1186–1188 (1997).

1. Introduction

Fiber lasers have attracted plenty of attentions in recent years since the outstanding thermo-optical properties, structural compactness, long-term stability, and excellent beam quality [1,2]. They have found applications in many fields, such as nonlinear optics [3, 4], harmonic generation [5, 6], multiphoton imaging [7–9], medical treatment [10], and industry processes [11], etc. Due to the high optical efficiency and low quantum loss of ytterbium ion, Yb-doped fiber lasers in 1010-1090 nm are candidates for obtaining high power femtosecond pulses [12–17].

The pulse properties (e.g., broad spectrum, high energy, and outstanding stability) of mode-locked fiber oscillator are crucial to fiber amplifiers because they affect temporal and spectral features of the amplified pulses. Various mode-locking methods have been developed to obtain energetic ultrashort pulses at 1 µm, such as nonlinear polarization evolution (NPE)

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[18–21], saturable absorber mirror (SAM) [22, 23], NOLM (nonlinear optical loop mirror), and NALM (nonlinear amplifying loop mirror)) [24–26]. A. Chong *et al.* reported an ANDi fiber laser using NPE mode-locked mechanism, which generated 140-fs pulses with 20-nJ pulse energy after external compressor [18]. W. H. Renninger *et al.* reported shorter pulse duration of 55 fs with energy of 5 nJ using the same mode-locking mechanism [19]. X. Zhou *et al.* obtained 28-fs dispersion managed (DM) mode-locked fiber laser based on NPE by inserting a pair of gratings in the oscillator cavity, but the pulse energy was less than 1 nJ [20]. Recently, SESAM mode-locked fiber laser producing 85-fs pulses with 0.5-nJ pulse energy was developed by H. Wang *et al.*, in which a chirped fiber Bragg grating was employed as compensator and output coupler [23]. To date, ultrashort pulses under 100 fs can be obtained by traditional NPE and SESAM fiber lasers, but the pulse energies are limited and cavities are non-polarization-maintaining (PM). Although ANDi fiber oscillator can achieve short pulses with high energy, the mode-locking state is sensitive to environmental conditions due to free space configuration. A 20.54-MHz all-PM mode-locked fiber oscillator using NPE was demonstrated in 2017, which generated 0.85-nJ, 150-fs pulses [21]. However, the pulse energy is low and the pulse is relatively long.

NOLM and NALM were proposed as the mode-locking component in 1988 and 1990, respectively [27, 28]. Since then, Er-doped and Yb-doped fiber oscillators incorporating these two devices have been extensively studied [29–31]. Due to no need of intra-cavity free-space configuration and saturable materials, Yb-doped PM NOLM and NALM oscillators are insensitive to vibration and temperature, leading to high environmental stability [32]. Moreover, a 10-MHz NALM fiber oscillator producing 4.5-nJ 120-fs pulses was demonstrated in 2013 [33]. Besides, NOLM or NALM fiber oscillators can operate at long cavity with low repetition rate. NALM oscillator with 506-kHz repetition rate and 6.9-nJ pulse energy was reported recently [34]. However, PM NOLM and NALM fiber oscillators with short (100 fs) pulse duration, low (<10 MHz) repetition rate, and high (~10 nJ) pulse energy have not been reported.

In this paper, we report highly-stable mode-locked all-PM Yb-doped fiber oscillators using NALM, delivering linearly polarized pulses at repetition rates of several MHz. The spectral and temporal characteristics of laser output at different repetition rate (4 MHz, 6 MHz, and 8 MHz) were intensively studied. Comparison of spectral bandwidth at different repetition rate shows that much better dispersion management in cavity was realized at the 6-MHz repetition rate. The 6-MHz oscillator delivers 10-nJ, 14.4-ps pulses with 31-nm spectral bandwidth. The pulses were compressed to 93 fs by a pair of gratings. The output power stability was measured to be as low as 0.04% (RMS) in 10 hours, which shows excellent environmental stability.

2. Experimental setup

The schematic of the experiment setup is shown in Fig. 1. Two optical loops (main loop on the left and NALM loop on the right) with all-PM fiber components is employed in this figure-of-eight cavity, pumped by laser diodes centered at 976nm. Loops are connected by a 2 × 2 coupler with splitting ratio of 40:60. The main loop provides cavity for oscillation while the NALM loop enables mode-locking. Yb-doped fibers (YDF, YB 401-PM, Coractive) are employed in both loop to provide gain to pulses. A fiber isolator (ISO) located behind the gain fiber ensures the unidirectional operation of the oscillation. A bandpass filter (BPF) centered at 1030 nm with 3 dB-bandwidth of 2 nm is placed in the main loop to remove the enormous chirp accumulated from each round trip. To maintain enough intra cavity power density, a coupler with output rate of 20% is used as the output coupler (OC). Single mode fiber (SMF) is used to change the cavity length to achieve different repetition rates. The rest of the cavity is mainly constructed by fiber pigtailed components. The cavity length and repetition rate was easily changed by changing the length of SMFs in two spools.

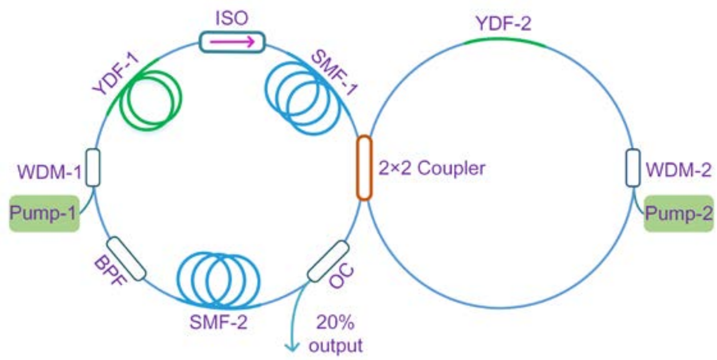

Fig. 1. Experimental setup of mode-locked all-PM Yb-doped NALM fiber laser oscillators. Fiber elements used in this experiment are all polarization maintained. Main loop: left loop; NALM: Nonlinear Amplifying Loop Mirror on the right; Pump-1, Pump-2: laser diodes operating at 976 nm; YDF-1 and YDF-2: Yb-doped fiber; SMF-1 and SMF-2: single mode fiber; WDM-1 and WDM-2: wavelength division multiplexer; ISO: isolator at 1030 nm; BPF: bandpass filter; OC: output coupler.

3. Experiment results

We constructed three Yb-doped NALM fiber oscillators at different repetition rates (8 MHz, 6 MHz, and 4 MHz) in order to reveal the relation between output parameters and lengths of YDFs and SMFs. In order to start mode locking, we gradually increased the pump power of the main loop and NALM loop. The pump powers for mode-locking the oscillators at 8 MHz, 6 MHz, and 4 MHz are shown in Table 1. The spectrum of the mode-locked pulse was measured using an optical spectrum analyzer (OSA, YOKOGAWA AQ6370C). For the 8-MHz oscillator, the total cavity length is 25 m, including 10-m SMF. SMF is placed right behind the output coupler (at SMF-2) to reduce the power density. The mode-locking states changed with the length of YDF-1 and YDF-2. We monitored the output spectrum while changing the length of the 2 segments of YDF. The spectral bandwidth of 28 nm in saddle-shape, as shown in Fig. 2(a), was achieved when the lengths of YDF-1 and YDF-2 were set to 1.85 m and 1.4 m. When SMF-2 was increased to 18 m and the length of YDF-1 and YDF-2 remained unchanged, the mode-locking at 6 MHz repetition rate was optimized to obtain broad and smooth spectrum for producing much shorter compressed pulses after the external-cavity grating compressor. Mode-locked pulses with 31-nm spectral bandwidth was realized easily, as shown in Fig. 2(b).

Furthermore, the fiber length of SMF-2 was increased to achieve mode-locking at lower repetition rate. When the length of SMF was increased to 35 m, corresponding to 50-m cavity length and 4-MHz repetition rate, the mode locking cannot be realized under previous setups. The intra-cavity pulse experienced stronger pulse splitting in the longer fiber length compared with the 8-MHz oscillator and the 6-MHz oscillator. We divided the 35-m SMF into two segments and placed them at different positions in the cavity to reduce the splitting. We optimized the length of YDF-1 and YDF-2 gradually. Stable mode-locking was achieved when the SMF was divided to SMF-1 (15 m) and SMF-2 (20 m), and YDF-1 and YDF-2 were set to 2.5 m and 1 m. Spectrum of 16 nm in full width at half maximum (FWHM) was generated, as shown in Fig. 2(c). Comparing the bandwidth of spectrum at different repetition rates shows that the broadest bandwidth is 31 nm generated by the 6-MHz oscillator. The 6-MHz oscillator operates with the highest pulse energy, which leads to the strongest self-phase modulation (SPM) in the cavity, the broadest spectrum, and the shortest pulse duration. In the case of 8-MHz repetition rate, the pulse energy is lower due to higher repetition rate and less pump power of pump-2. Compared with 6-MHz repetition rate, the lower pulse energy at 8-MHz repetition rate results in less intra-cavity nonlinearity, including self-phase modulation (SPM). Consequently, spectrum at 8-MHz repetition rate is slightly narrower. Although pulse energy approaching to 10 nJ was achieved from the 4-MHz oscillator, the intra-cavity pulses experienced much more dispersion in longer fiber cavity, resulting in a narrower spectrum. Detailed experiment parameters are listed in Table 1.

Table 1. Experimental setups of Yb-doped NALM fiber laser oscillators at different repetition rate[a]

F_{rep} (MHz)	L_{YDF-1} (m)	L_{YDF-2} (m)	L_{SMF-1} (m)	L_{SMF-2} (m)	P_{pump1} (mW)	P_{pump-2} (mW)	P_{av} (mW)	E_p (nJ)	Δλ (nm)	τ_{uc} (ps)	τ_c (fs)
8	1.85	1.4	0	10	520	540	48	6	28	6.7	126
6	1.85	1.4	0	18	418	556	60	10	31	14.4	93
4	2.5	1	15	20	148	523	37	9.25	16	17.2	140

[a]F_{rep}, repetition rate in MHz; L_{YDF-1} and L_{YDF-2}, fiber lengths of YDF-1and YDF-2 in meters; L_{SMF-1} and L_{SMF-2}, lengths of SMF-1 and SMF-2 in meters; P_{pump1} and P_{pump2}, pump powers of pump-1 and pump-2 in mW; P_{av}, average power exported from the laser oscillator in mW; E_p, pulse energy in nJ; Δλ, full width at half maximum of spectrum in nm; τ_{uc}, uncompressed pulse duration in ps; τ_c, compressed pulse duration in fs.

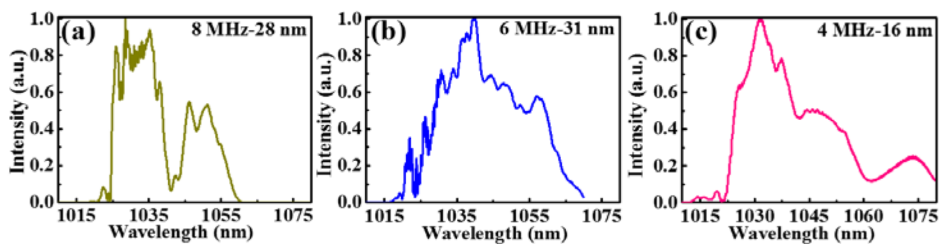

Fig. 2. Optical spectrum of mode-locked all-PM Yb-doped NALM fiber laser oscillators at different repetition rates. Spectrum of (a) 8-MHz oscillator, (b) 6-MHz oscillator and (c) 4-MHz oscillator.

Table 1 shows the average output powers from the oscillators. Benefiting from the low repetition rate and large gain employed in our cavity, pulse energy extracted out of the oscillators exceeded 6 nJ for the three oscillators. Lower pump power was required to realize stable mode-locking in the case of lower repetition rate. With a NALM as the secondary loop, the intra-cavity pulse was amplified in YDF-2. YDF-2 of 1.4 m was used in the 8-MHz oscillator as well as in the 6-MHz oscillator while higher pulse energy was achieved in the 6-MHz oscillator, caused by higher pump power of pump-2. For the 4-MHz oscillator, pump power of pump-1 was much lower than that for the 8-MHz oscillator and the 6-MHz oscillator because the mode-locking threshold decreased along with the increased cavity length. Although the average power is lower than others, the pulse energy from the 4-MHz oscillator approaches 10 nJ resulting from lower repetition rate.

The output pulses from these NALM fiber oscillators are highly chirped because all the components exhibit normal dispersion and intra-cavity dispersion compensation is absent. The estimation of intra-cavity dispersion based on material dispersion is listed in Table 2. According to the Sellmeier equation, the group-velocity dispersion (GVD) of an optical fiber can be estimated by the following equation:

$$\beta_2(\lambda) = -\left(\frac{\lambda^2}{2\pi c}\right) \Big/ D(\lambda). \tag{1}$$

$\beta_2(\lambda)$ is the GVD parameter, calculated to be about 23 fs^2/mm at 1.03 μm. Figures 3(a)-3(c) show the autocorrelation curves of the chirped pulses at the repetition rate of 8 MHz, 6 MHz, and 4 MHz, respectively. The autocorrelation curves of the chirped and dechirped pulses were measured by intensity autocorrelator (pulseCheck, A.P.E.). Figures 3(d)-3(f) indicate the autocorrelation traces of the dechirped pulses, which are compressed with a pair of external transmission gratings (TG) (1000 line/mm, LightSmyth). The pulse duration is compressed to 93 fs ($Sech^2$ fitted) at repetition rate of 6 MHz. The transform-limited pulse duration is 37 fs.

The pulses was not compressed to transform-limited duration due to the uncompensated excessive high-order dispersion from the long cavity. By use of prism pair that can offer negative third-order dispersion [35], it is possible to compress the pulses close to the Fourier-transform-limited duration.

Table 2. Group delay dispersion of Yb-doped NALM fiber laser oscillators at different repetition rate[a]

Frep (MHz)	$L_{YDF\text{-}1}$ (m)	$D_{YDF\text{-}1}$ (ps^2)	$L_{YDF\text{-}2}$ (m)	$D_{YDF\text{-}2}$ (ps^2)	$L_{SMF\text{-}1}$ (m)	$D_{SMF\text{-}1}$ (ps^2)	$L_{SMF\text{-}2}$ (m)	$D_{SMF\text{-}2}$ (ps^2)	D_c (ps^2)	L_{total} (m)	D_{total} (ps^2)
8	1.85	0.04255	1.4	0.0322	0	0	10	0.23	0.27125	25	0.576
6	1.85	0.04255	1.4	0.0322	0	0	18	0.414	0.27025	33	0.759
4	2.5	0.0575	1	0.023	15	0.345	20	0.46	0.2645	50	1.15

[a]F_{rep}, repetition rate in MHz; $L_{YDF\text{-}1}$ and $L_{YDF\text{-}2}$, fiber lengths of YDF-1 and YDF-2; $L_{SMF\text{-}1}$ and $L_{SMF\text{-}2}$, lengths of SMF-1 and SMF-2; L_{total}, lengths of the cavity; $D_{YDF\text{-}1}$, $D_{YDF\text{-}2}$, $D_{SMF\text{-}1}$, $D_{SMF\text{-}2}$, Dc and D_{total}, group delay dispersion of YDF-1, YDF-2, SMF-1, SMF-2, fiber components and the cavity.

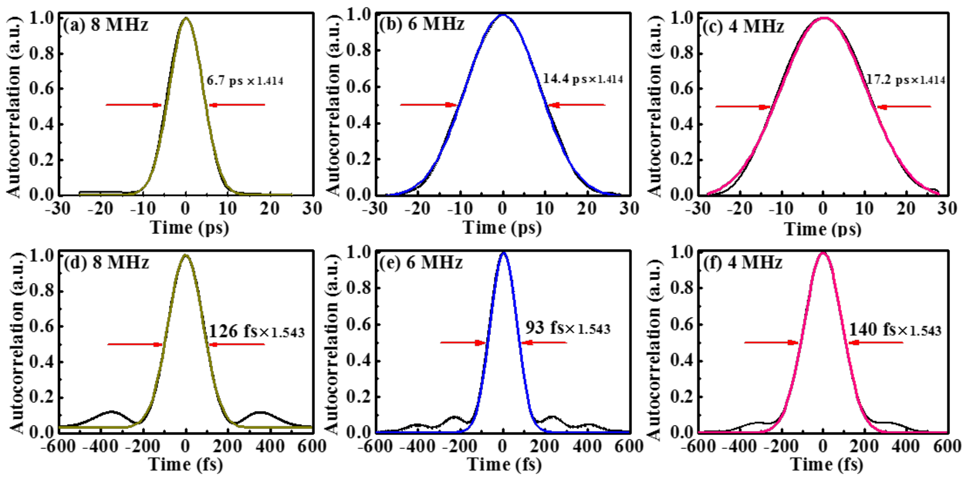

Fig. 3. Measured autocorrelation traces (black curves) and fitting traces (color curves) of output chirped laser pulses from all-PM Yb-doped NALM fiber oscillators at 8MHz (a), 6MHz (b) and 4MHz (c), and compressed pulses at 8 MHz (d), 6 MHz (e) and 4 MHz (f) respectively.

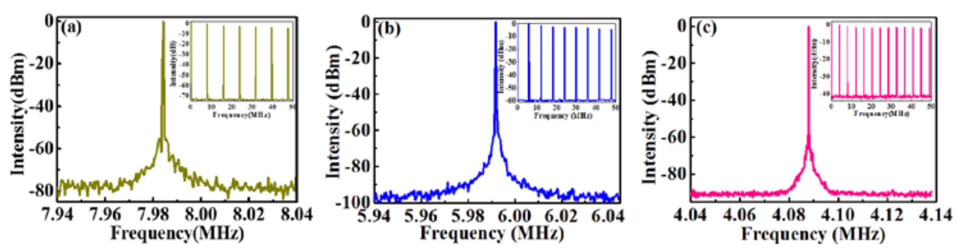

Fig. 4. RF spectrum of output laser pulses from all-PM Yb-doped NALM fiber oscillators at repetition rate of 8-MHz (a), 6-MHz (b), 4-MHz (c) with resolution bandwidth of 1 kHz. The inset of (a)-(c) correspond RF spectrum measured at 50 MHz span with resolution bandwidth of 100 kHz.

Figure 4 shows radio-frequency (RF) spectra of the mode-locking at different repetition rates measured with a fast photodetector connected to a RF spectrum analyzer (E4402B, Agilent). The RF traces indicate that mode-locked pulses are of high quality without any sign of Q-switching, which often occurs along with mode locking and pulse splitting. Moreover, the intra-cavity pulses may split into several pulses when the pulse energy reaches nano-joule level in conventional fiber cavity design. We obtained 10 nJ pulse energy without pulse

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splitting, which is mainly due to the high-energy tolerable ANDi fiber cavity and the ideal amount of the SMF.

Power stability of output laser was measured by a power meter (LabMax-TOP, Coherent). When the laser operated at 6 MHz, we monitored the laser power and the mode-locked pulse train simultaneously using a 95:5 fiber coupler. The fluctuation of the average power is only 0.04% (RMS) in 10 hours, as shown in Fig. 5 (a). The stability of the NALM fiber laser benefits from the all-fiber configuration, only affected by pump power. Output pulse train was recorded by a fast photodetector and an oscilloscope (DS4024, RIGOL), as shown in Fig. 5 (b). The results verified the excellent mode locking performance with environmental robustness.

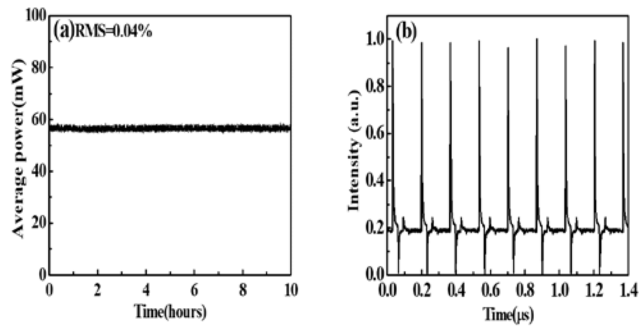

Fig. 5. Power stability and pulse train of output laser from all-PM Yb-doped NALM fiber oscillators at 6 MHz. (a) power stability in 10 hours. (b) mode-locked pulse train detected by oscilloscope.

4. Conclusion

In conclusion, we have studied mode locking performances of all-PM Yb-doped fiber oscillators based on NALM with different repetition rates of 8 MHz, 6 MHz, and 4 MHz, respectively. The properties of optical spectrum, pulse duration, and RF spectrum from oscillator are discussed. The broadest spectrum of 31 nm with 10-nJ pulse energy was achieved at 6-MHz repetition rate, and the pulses were compressed to 93 fs by a pair of gratings. The fluctuation of the average power in 10 hours is 0.04% (RMS), which shows that the mode-locking state has excellent environmental stability. This highly-stable mode-locked all-PM NALM fiber oscillator is suitable for all-fiber amplifiers, which promise many important scientific applications.

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