An all-polarization-maintaining repetition-tunable erbium-doped passively mode-locked fiber laser

Zhao Guang-Zhen(赵光贞)[a], Xiao Xiao-Sheng(肖晓晟)[a], Meng Fei(孟 飞)[b], Mei Jia-Wei(梅佳伟)[a], and Yang Chang-Xi(杨昌喜)[a]†

[a] *State Key Laboratory of Precision Measurement Technology and Instruments, Department of Precision Instruments, Tsinghua University, Beijing* 100084, *China*

[b] *Division of Time and Frequency Metrology, National Institute of Metrology, Beijing* 100013, *China*

(Received 30 November 2012; revised manuscript received 23 January 2013)

An environmentally stable, repetition rate tunable, all-polarization-maintaining, Er-doped pulse fiber laser with a single-wall carbon nanotubes saturated absorber is demonstrated. The ring laser cavity includes a delay line enabling a tunable repetition rate to vary from 35.52 MHz to 35.64 MHz with continuous mode-locked operation. The laser output parameters confirm that the tunable mode-locked operations are stable. High environmental stability is also confirmed by the −130 dBc/Hz low phase noise, a 70-dB signal-to-noise ratio of radio frequency signals, a low amplitude fluctuation of 5.76×10^{-4}, and a low fluctuation of repetition rate of 12 Hz. The laser shows a high degree of polarization of 93%.

Keywords: fiber laser, modulation, tuning and mode locking, nanotubes

PACS: 42.55.Wd, 42.60.Fc, 61.46.Fg **DOI:** 10.1088/1674-1056/22/10/104205

1. Introduction

Compact and environmentally stable femtosecond (fs) pulse laser sources have many applications such as optical frequency combs, optical metrology, and supercontinuum generation.[1–3] Single-wall carbon nanotubes (SWNTs) have been used as mode-lockers in order to obtain femtosecond ultra-short pulse.[4] Compared with the nonlinear polarization rotation (NPR) mode-locked mechanism, which is sensitive to polarization change, the SWNT saturated absorber has advantages of self-starting. In addition, the SWNT-based saturable absorber has other advantages such as wide absorption bandwidth from 1 μm to 2 μm and potential to be integrated with micro-chip lasers due to its small footprint and simplified device preparation.[5]

Environmental stability is one of the key issues for fiber lasers. A laser can drop out of mode-locking because it is sensitive to environmental fluctuations or significant temperature changes. These instabilities can be largely eliminated by the use of polarization maintaining (PM) fibers in fiber lasers. Environmentally robust fs mode-locked pulse lasers based on PM fibers and a semiconductor saturable absorber mirror (SEAM) have been demonstrated.[6] All PM fiber wavelength-tunable or ultralow-repetition-rate Er-doped ultrashort pulse fiber lasers with SWNT film have also been investigated.[7,8] The radio frequency (RF) signal phase noise of the PM ultrashort pulse fiber laser emerges to have an excellent level as low as that of a commercially available ultrashort-pulse solid state laser,[6–8] indicating that the PM ultrashort pulse fiber laser is environmentally stable. A new PM fiber laser based on Nd^{3+}-doped gain fiber was investigated.[9] Recently, a PM ultrashort pulse fiber laser based on a graphene saturable absorber was reported.[10,11] Some reports also focused on Q-switched or high power PM fiber laser.[12,13] A stable fiber laser with a low phase noise is significant for some applications like optical frequency combs, optical metrology, and all-optical sampling systems.[14] The tenability of the repetition rate for an fs optical pulse source is highly demanded for all-optical sampling applications, fs spectroscopy or precision metrology, and frequency combs.[2,3,14] Repetition-rate tunable fiber lasers with ring, sigma, and nonlinear amplifying loop mirror (NALM) cavity configurations have been reported respectively.[2,3,14] The ring cavity configuration is simple, however, its operation stability suffers from polarization-APM bias drift.[15] A sigma cavity configuration with free-space section increases both the cavity complexity and phase noise.[3] By using an NALM, an SESAM and a delay line (DL) as reported in Ref. [14], the tunable passively mode-locked fiber laser shows good stability. However, the alignment between the SESAM and the DL and the 40% reflection of the SESAM require maintenance and a high pump threshold.

In this paper, we report on a stable all-PM-fiber SWNT low noise MHz repetition rate tunable erbium-doped passively mode-locked laser. The ring cavity configuration is simple, free maintaining, and has a low pump threshold. Besides, the laser shows good stable features in continuously tunable uninterrupted mode-locked operations. The laser repetition rate can be tuned from 35.52 MHz to 35.64 MHz continuously. Other parameters of the laser output, e.g., 3-dB optical spectrum width, full width of half maximum (FWHM) of pulse, signal-to-noise ratio (SNR) of ratio frequency (RF) signals,

†Corresponding author. E-mail: cxyang@tsinghua.edu.cn

© 2013 Chinese Physical Society and IOP Publishing Ltd

almost keep constant with repetition rate tuning, confirming stable continuously mode-locked operation during the change of cavity length by the DL. The ∼70 dB SNR of RF signals, low phase noise, low repetition rate fluctuation (12 Hz), and low amplitude fluctuation of 5.76×10^{-4} show the robust environmental stability of PM fiber laser.

2. Experimental setup

Figure 1 shows the setup of an all-fiber PM tunable erbium-doped SWNT passively mode-locked laser. A maximum output 450-mW laser diode (LD) of 980 nm was used as a pump, which was coupled into the cavity through a PM 980/1550 wavelength division multiplexer (WDM). A polarization dependent isolator was used to ensure unidirectional operation and single polarization operation, with the polarization orientation being along the slow axis. A 1.2-m long Nufern ESF-7/125 (peak absorption is 55 dB/m at 1530 nm) PM Er-doped fiber was used as gain medium to amplify pulses. The 70% port of a 30/70 PM-coupler (PM-CO) was used to recycle laser back to ring cavity, the output was through a 30% port. The SWNT saturable absorber film was easily inserted between a pair of angled-polished FC/APC fiber connectors so that the ring laser was simple and compact. The total length of the cavity was ∼ 5.8 m. A spectrum analyzer (Agilent 86142B) and a sort of 10-GHz fast photo-detector and a 2-GHz oscilloscope (Agilent infiniium, DSO80204B) were used to the monitor pulse spectrum and the pulse repletion rate, respectively. The pulse duration and stable property were monitored by an autocorrelator (FR-103XL) and a 13.2-GHz signal source analyzer. A PM DL which was well packaged and had two PM pigtail fibers at its input and output ports, and 2.5-cm tuning range was used to continuously change repetition rate. The insert loss of the delay line was less 0.6 dB in the whole tuning range.

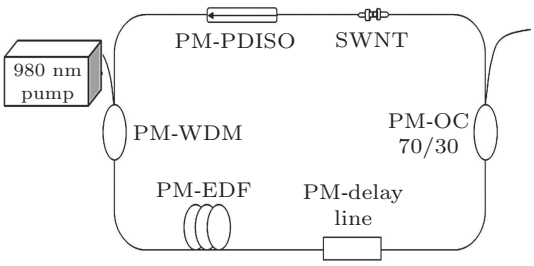


Fig. 1. The setup of the all-fiber, repetition rate tunable, polarization-maintaining erbium-doped SWNT-PI saturable absorber passively mode-locked laser.

3. Experimental results

The well self-started passive mode-locking is achieved stably by SWNT saturable absorber without any polarization control. The SWNT saturable absorber is fabricated by chemical vapor deposition (CVD) method with an SWNT concentration of 2 wt%, and its properties were reported in Ref. [16]. The laser pump threshold is 80.3 mW, which is comparable to that of the laser started at a lower pump threshold.[3,14] This is due to the low insert loss (0.6 dB) of the DL. For a pump power of 86.3 mW, the laser works in a single soliton regime with the output pulse as shown in Fig. 2(a), pulse fundamental repetition rate is 35.58 MHz, the pulse degree of polarization (DOP) is 93.5%, which is detected by a polarization measurement system (General Photonics, PSGA-101-A). In the experiment, there is 2.5-m non-polarization-maintaining single mode fiber used for leading pulse signal to polarization measurement system, which would degenerate pulse DOP. However, the pulse has already shown a high DOP (93.5%). When pump power is increased to 93.34 mW, the laser operates in a multisoliton regime as reported in Ref. [17], and then there appears a new unstable soliton as shown in Figs. 2(b) and 2(c) The soliton pulses exchange their energies when they propagate in the cavity. As can be seen from Figs. 2(b) and 2(c), the relative intensities of pulses are changed. When pump power is 99.6 mW, two stable solitons are detected in one pulse period time of the laser cavity as shown in Fig. 2(d) and the multisoliton operation is due to soliton shaping of dispersive waves,[17] which is different from the multisoliton generation in the ultralong fiber laser which is due to soliton energy quantization effect.[18] The DL length can be tuned in a high accuracy (minimum resolution is 10 microns, ODL-200) in our laser, which confirms an accurate change of the laser cavity length and a high stability of fundamental repetition rate. By changing the DL length, a tunable pulse repetition rate is continuously varied from 35.52 MHz to 35.64 MHz, thus no interrupted mode-locked operation is obtained. To confirm the robust environmental stability of the laser, we measure stable parameters of the laser at different repetition rates. The measurement results show that the tunable laser operated in a high stable state. In our experiment, we continuously change the repetition rate through tuning the DL, and mode-locked operations with equal 0.02-MHz repetition rate interval are investigated.

Figure 3(a) shows the output spectra of mode-locked operations with the DL continuously tuned when pump power is 86.3 mW, all of the 3-dB spectrum widths are almost the same (around 6.2 nm); the obvious soliton band indicates that the laser works in the soliton regime. Figure 3(b) shows the pulse autocorrelator profiles, which are also almost the same, whose pulse FWHM are around 460 fs. These results in turn show that the time-bandwidth products are ∼0.35, indicating the pulses are transformed within the tuning process. In order to indicate that the laser can be continuously tuned and work in stable operations between the minimum and the maximum delay-line length, the repetition rate RF signal spectra of the laser are monitored by a signal source analyzer with resolution

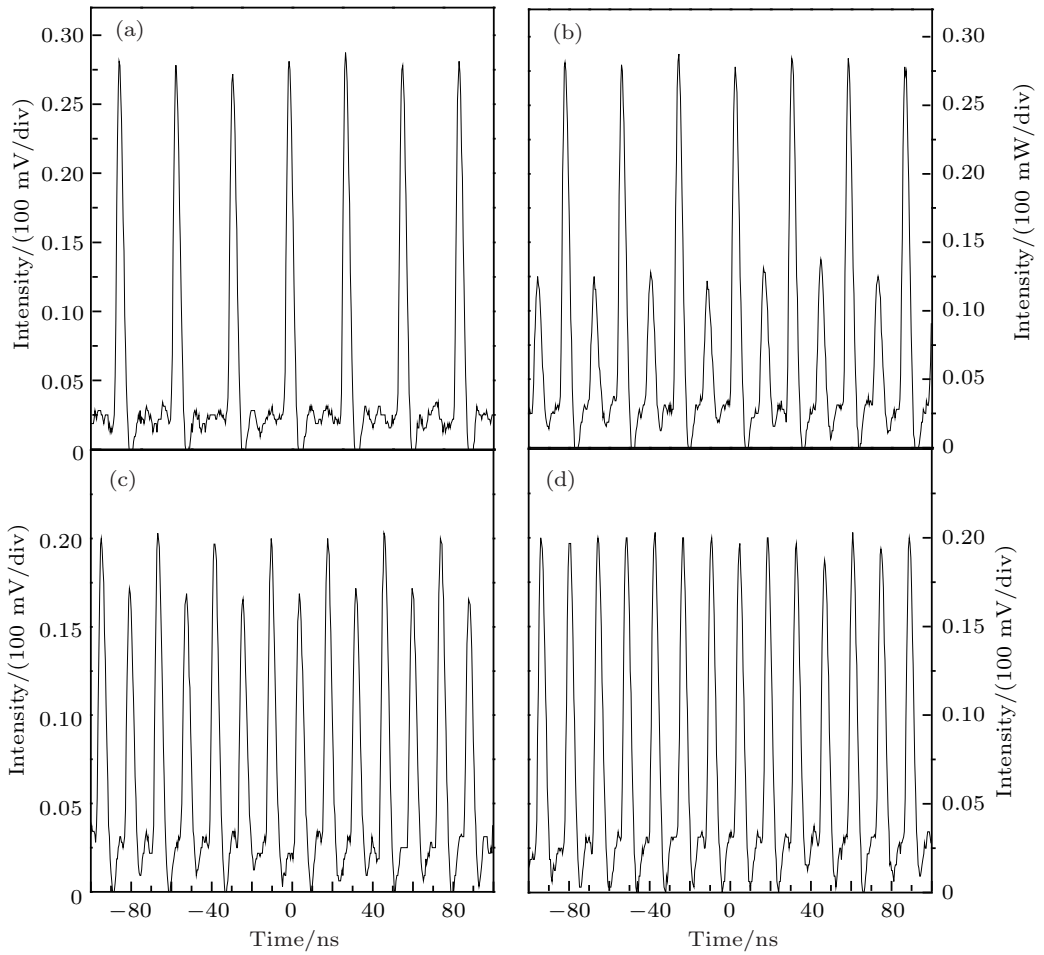


Fig. 2. (a) The 35.58-MHz pulse output of laser operated in a single soiton regime, (b) and (c) unstable two-soliton operation at a pump power of 93.34 mW, (d) stable two-soliton operation at a pump power of 96.6 mW.

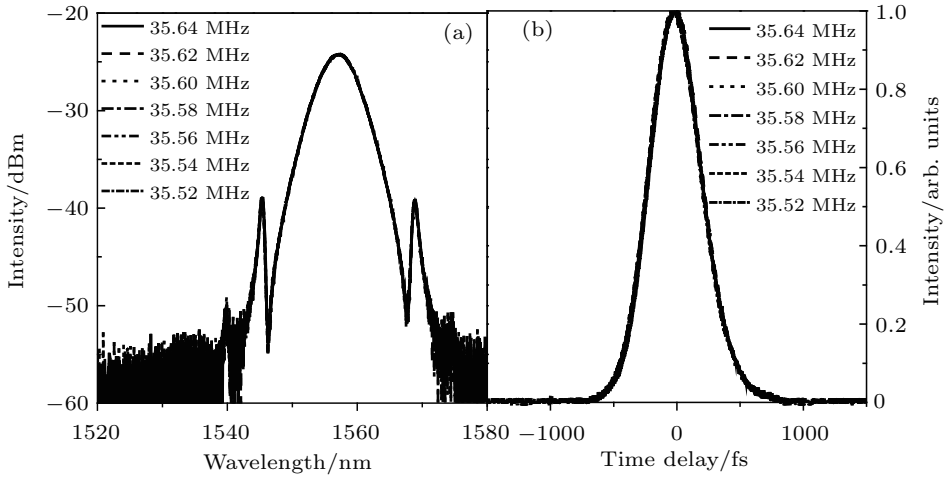


Fig. 3. (a) Output spectra and (b) output pulse autocorrelator profiles of the mode-locked laser with different repetition rates.

width 300 Hz as shown in Fig. 4(a), the SNRs of all mode-locked operations are almost equal. Figure 4(b) shows that in the whole tuning process the RF signal SNR is ~ 77 dB with resolution bandwidth 30 Hz, the high SNR indicates that the stability of the laser is excellent. The output pulse amplitude fluctuation of the laser is $\Delta E/E = \sqrt{\Delta P * \Delta f / f_{\rm res}}$, where Δf and $f_{\rm res}$ are frequency jitter bandwidth and resolution respectively.[19] They are 500 Hz and 30 Hz respectively in our experiment (Fig. 4(b)). The amplitude fluctuation is as low as $\Delta E/E \approx 5.76 \times 10^{-4}$. The 3-dB spectrum width and pulse time-bandwidth product versus repetition rate are shown in Fig. 5(a), and the fluctuations of 3-dB spectrum width and pulse time-bandwidth product versus repetition rate are 0.04 nm and 0.003 nm, respectively. Figure 5(b) shows

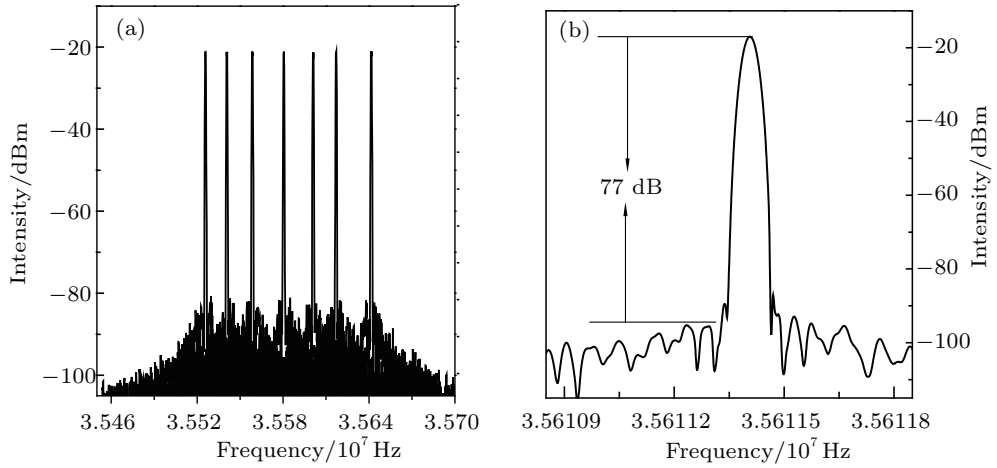


Fig. 4. (a) RF signal spectra for mode-locked operations with resolution bandwidth of 300 Hz, and (b) RF signal spectrum at a repetition rate of 35.61 MHz, with resolution bandwidth $f_{\rm res} = 30$ Hz, and $\Delta f = 500$ Hz.

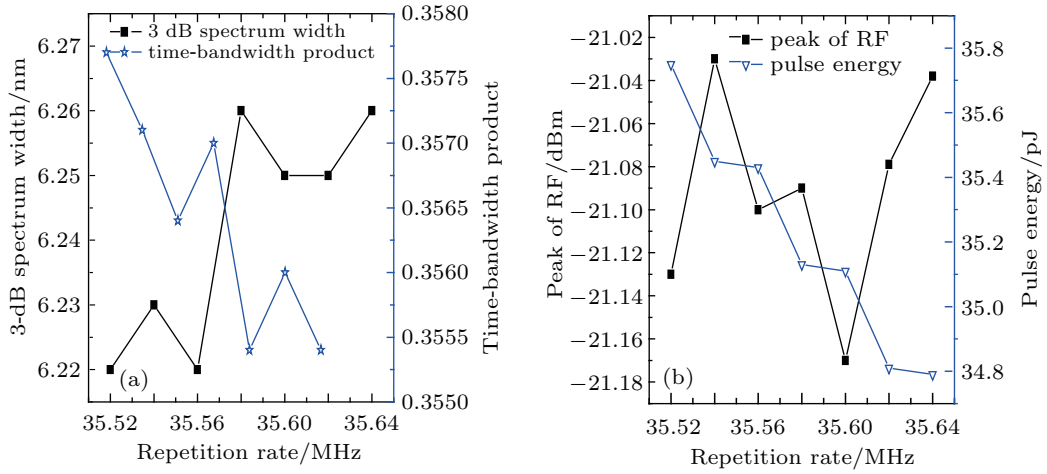


Fig. 5. (color online) (a) 3-dB spectrum width and time-bandwidth product of mode-locked operations versus repetition rate, and (b) peak power of RF signal and pulse energy of mode-locked operations versus repetition rate.

the variations of peak intensity of RF signals and pulse energy with repetition rate, and the variations of the peak intensity of RF signals and pulse energy with repetition rate are 0.14 dB and 1 pJ. The pulse DOP of these mode-locked operations are detected to be 93.21%, 93.42%, 93.45%, 93.5%, 93.37%, 93.56%, and 93.42% respectively. The timing jitter is an important optical pulse stable parameter, and low timing jitter pulse is useful in all-optical sampling systems and communication networks.[14] Timing jitter can be evaluated by measuring the phase noise of the mode-locked pulse train. The relationship between the phase noise and the timing jitter is

$$\Delta t = \frac{1}{2\pi f_0}\sqrt{2\int_{f_{\rm low}}^{f_{\rm high}} L(f)\,{\rm d}f},$$

where the $L(f)$ is phase noise power spectral density and is expressed in dBc in a 1-Hz resolution bandwidth, f is the offset frequency, and f_0 is the pulse repetition rate. We examine the RF signal phase noise of the fiber laser using the single sideband method. A fast 10-GHz photodetector and signal source analyzer are used for the measurement. RF signal phase noise at repetition rate 35.64 MHz is shown in Fig. 6(a). The result in Ref. [14] shows that the phase noise at the offset frequency 100 kHz is $\sim$ 115 dBc/Hz. Our laser shows low phase noise $\sim$ 117 dBc/Hz at the offset frequency 100 kHz and 130 dBc/Hz at the offset frequency 1 MHz, which indicates that though the PM laser is made of all anomalous dispersion single mode fibers and emits soliton pulse, it also shows low timing jitter as reported in Ref. [14] without needing the dispersion adjustment, indicating that PM fibers enforce the laser stability. Meanwhile, we measure the phase noise of the internal 50-MHz signal of an Agilent N5181A MXG and denote it as the dashed line in Fig. 6(a), indicating that the stability of the PM fiber laser is excellent. The stability of the laser is also tested by monitoring the output pulse repetition rate using a frequency counter. The laser is just placed on the base plate without any temperature and feedback circuit control. Figure 6(b) shows the measured results of pulse repetition rate at 35.64 MHz in a time range of 0–5000 s (the gate time is 1 s), and the frequency fluctuation is found to be only 12 Hz.

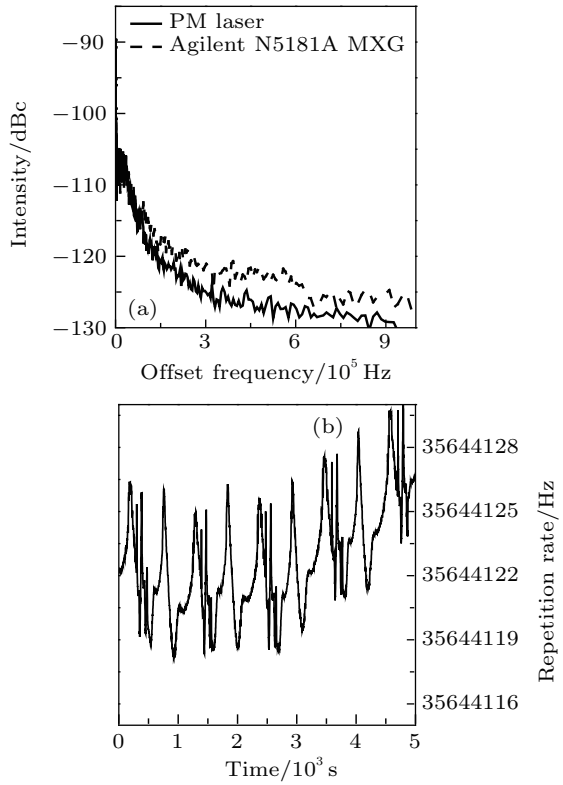


Fig. 6. (a) The RF phase noise of the fiber laser using the single sideband method at a repetition rate of 35.64 MHz, and (b) pulse repetition rate measured at 35.64 MHz in 5000 s.

4. Discussion and conclusion

In the large linear birefringence PM mode-locked fiber laser, linearly polarized pulse light along the slow axis is robust against perturbation.[20] The propagation of the slow variable pulse envelope in the PM mode-locked fiber laser can be described by a nonlinear Schrödinger equation.[21] The difference is that in the weakly birefringent mode-locked fiber laser, the two pulsed linearly-polarized light beams propagate in the fiber as a vector solution, the propagation of the envelope of two slowly varying orthogonally polarized pulses is described by the coupled complex nonlinear Schrödinger equations.[21] In the weakly birefringent mode-locked fiber laser, the pulse envelope amplitude, position, carrier frequency, polarization angle, and phases of two normalized slowly varying pulse envelope parameters evolve slowly with distance z in the presence of perturbations.[21] The pulse repetition rates of the envelopes of two slowly varying orthogonally polarized pulses are $f_{i,\mathrm{rep}} = c/(L*n_i)$, $i = U,V$, U and V are envelopes of two slowly varying orthogonally polarized pulses, the L is laser cavity length, $n_i = n_{0i} + n_{2i}I_i$, where n_{0i}, n_{2i}, and I_i are the linear index, nonlinear index, peak intensity of two linear polarized pulses respectively, hence the $f_{i,\mathrm{rep}}$ is power-dependent.[22] Following polarization angle evolution, the two linear polarized amplitudes change, thus $f_{i,\mathrm{rep}}$ fluctuates with perturbation. Besides, the $f_{i,\mathrm{rep}}$ is also spectral shift-dependent,[22] the phase parameter evolution in the weakly birefringent mode-locked fiber laser also affects the stability of $f_{i,\mathrm{rep}}$. On the contrary, in the all-PM-fiber laser, equation (45) in Ref. [21] shows that the polarization angle and phase evolution influenced factors can be neglected completely.[21–23] As our experimental results show that the laser can sustain in low frequency fluctuation and low timing jitter, meanwhile, the linear beat length is short compared with the nonlinear self-phase-modulation length in our experiment, the f_{rep} of a linearly polarized pulse along the slow axis is stable.[23] Besides, in the all-PM-fiber laser, the effects of perturbations and cross phase modulation can be neglected; there is no orthogonally polarized pulses that power exchange and pass through each other, hence the laser output time domain and spectrum domain parameters are stable.[22] The PM laser eliminates the environmental effect on the mode-locked laser-like cavity length and birefringence change, so the environmentally induced noise can be reduced.[24–27] The PM mode-locked fiber laser shows excellent environmental stability, and it is a reliable pulse source for sampling and frequency combs.[26,27] In our experiment, the repetition rate tunable range is limited by the length change range of the DL, and we achieve 0.12-MHz tunable repetition rate output. A fiber frequency comb based on this repetition rate tunable mode-locked fiber laser can be used for precision metrology or tests of the stability of other frequency combs.[2]

In conclusion, a stable all fiber SWTN tunable polarization — maintaining erbium-doped passively mode-locked laser is reported. The laser shows well stable features in continuously tunable uninterrupted mode-locked operation. The tunable range of repetition rate is 0.12 MHz (from 35.52 MHz to 35.64 MHz) with continuous, uninterrupted mode-locked operation. Little changes are observed in the 3-dB optical spectrum width, the FWHM, RF signal peak value, and time-bandwidth product with DL tuned confirming stable mode-locked operation during the introduced cavity length changes. The ∼70-dB SNR of RF signals, low phase noise, low amplitude fluctuation, and low frequency fluctuation also show robust environmental stability.

References

[1] Schibli T R, Minoshima K, Hong F L, Inaba H, Onae A and Matsumoto H 2004 *Opt. Lett.* **29** 2467
[2] Washburn B R, Fox R W, Newbury N R, Nicholson J W, Feder K, Westbrook P S and Jorgensen C G 2004 *Opt. Express* **12** 4999
[3] Hundertmark H, Kracht D, Engelbrecht M, Wandt D and Fallnich C 2004 *Opt. Express* **12** 3178
[4] Chong A, Renninger W H and Wise F W 2008 *Opt. Lett.* **33** 1071
[5] Okhotnikov O, Grudinin A and Pessa M 2004 *New J. Phys.* **6** 22
[6] Nishizawa N, Seno Y, Sumimura K, Sakakibara Y, Itoga E, Kataura H and Itoh K 2008 *Opt. Express* **16** 9429
[7] Senoo Y, Nishizawa N, Sakakibara Y, Sumimura K, Itoga E, Kataura H and Itoh K 2009 *Opt. Express* **17** 20233
[8] Senoo Y, Nishizawa N, Sakakibara Y, Sumimura K, Itoga E, Kataura H and Itoh K 2010 *Opt. Express* **18** 20673
[9] Ren G J, Zhang Q, Wang P and Yao J Q 2003 *Acta Phys. Sin.* **52** 3917 (in Chinese)

[10] Sobon G, Sotor J and Abramski K M 2012 *Laser Phys. Lett.* **9** 581
[11] Sotor J, Sobon G and Abramski K M 2012 *Opt. Lett.* **37** 2166
[12] Ren G J, Wei Z and Yao J Q 2009 *Acta Phys. Sin.* **58** 941 (in Chinese)
[13] Dong X L, Xiao H, Ma Y X, Zhou P and Guo S F 2012 *Acta Phys. Sin.* **61** 064207 (in Chinese)
[14] Liu Y S, Zhang J G, Chen G F and Bai J 2010 *J. Opt.* **12** 095204
[15] Jones D J, Nelson L E, Haus H A and Ippen E P 1997 *IEEE. J. Sel. Top. Quant.* **3** 1076
[16] Gui L L, Yang X, Zhao G Z, Yang X, Xiao X S, Zhu J S and Yang C X 2011 *Appl. Opt.* **50** 110
[17] Tang D Y, Zhao L M, Zhao B and Liu A Q 2005 *Phys. Rev. A* **72** 043816
[18] Liu X M 2011 *Phys. Rev. A* **84** 023835
[19] Sun Z P, Hasan T, Wang F Q, Rozhin A G, White I H and Ferrari A C 2010 *Nano Res.* **3** 404
[20] Chong A, Renninger W H and Wise F 2008 *Opt. Lett.* **33** 1071
[21] Midrio M and Wabnitz S 1996 *Phys. Rev. E* **54** 5743
[22] Holman K W, Jones R J, Marian A, Cundiff S T and Ye J 2003 *Opt. Lett.* **28** 851
[23] Ding E and Kutz J N 2009 *J. Opt. Soc. Am. B* **26** 1400
[24] Blow K J, Doran N J and David W 1987 *Opt. Lett.* **12** 202
[25] Nicholson J W and Andrejco M 2006 *Opt. Express* **14** 8160
[26] Stumpf M C, Pekarek S, Oehler A E, Südmeyer H T, Dudley J M and Keller U 2010 *Appl. Phys. B* **99** 401
[27] Newbury R N and Swann W C 2007 *J. Opt. Soc. Am. B* **24** 1756