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Wavelength-tunable 10 GHz actively harmonic mode-locked fiber laser based on semiconductor optical amplifier

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Abstract We demonstrate a widely wavelength-tunable actively mode-locked fiber laser based on semiconductor optical amplifier. Beneficiating from the actively mode-locking operation and the wavelength-tunable characteristics of a Fabry–Perot filter, different harmonic mode-locking orders, from the fundamental mode-locking order (18.9 MHz) to the 520th order (9.832 GHz), can be easily achieved. The spectral bandwidth corresponding to the fundamental repetition rate is 0.12 nm with the pulse duration of 9.8 ns, leading to the TBP value of 146, which is about 460 times the transform-limited value for soliton pulse. The highest repetition rate of the mode-locked pulses we obtained is 9.832 GHz, with a signal-to-noise ratio up to 50 dB. The theoretical transform-limited pulse duration is 21 ps. Meanwhile, the central wavelength can be continuously tuned over 43.4 nm range (1522.8–1566.2 nm). The higher repetition rate and the widely tuning wavelength range make the fiber laser to own great potential and promising prospects in areas such as optical communication and photonic analog-to-digital conversion (ADC).

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1 Introduction

Actively and passively mode locking are the routine techniques to generate ultrashort optical pulses in fiber lasers. Passively mode-locked fiber laser can generate ultrashort optical pulses with fs–ps pulse width; nevertheless, the repetition frequency of passive mode-locked lasers is fixed by the natural cavity optical length, usually in MHz, even if the repetition frequency with the harmonic mode locking can only reach 1–2 GHz. Actively mode-locked laser easily produces more than 10 GHz repetition frequency of laser pulses, which depends on the modulation frequency. In particular, the rational harmonic mode locking is one mandatory technology, which can deliver much high-repetition pulse train [1, 2]. Actively mode-locked fiber laser has attracted extensive attention for their compact constructions, high stability and low cost [3] and has the ability to generate wavelength-tunable high-repetition-rate short pulses [4]. Owing to the high-repetition-rate and short-pulse characteristics [5, 6], it has been widely used in the wavelength-division-multiplexed (WDM) communications [7], high-speed optical switching, high-speed optical time-division-multiplexed (OTDM) networks [1] and high-speed optical sampling systems [8].

Active mode-locked fiber laser basically has the following kinds, such as semiconductor mode-locked laser [9], mode-locked external cavity semiconductor laser [10], erbium-doped fiber (EDF) ring laser [11–14], semiconductor optical amplifier (SOA) fiber ring laser [15] and optical-injection SOA fiber laser [16–18]. Over the past decade, the all-optical cross-gain modulation (XGM) scheme has been performed for mode locking the SOA by periodically depleting its gain. Yan et al. [18] reported on a SOA-based actively mode-locked fiber laser by forward injecting an external pulse train. Lin et al. [2] experimentally demonstrated backward-optical-injection SOA fiber laser to achieve XGM mode locking. After linear chirp compensation, nonlinear soliton compression, and birefringent filtering, the shortest mode-locked pulse width of 15 ps at 1 GHz can further be compressed to 180 fs at wavelength tuning range of 1530–1560 nm.

Regular reported wavelength-tunable mode-locked fiber laser was obtained by using EDF [19] and ytterbium-doped fiber (YDF) as the gain medium [20]. It usually needs a pump light source, and it is difficult to achieve widely tuning range. In general, the wavelength-selective elements will have a limited tuning range or gain bandwidth that restricts the tunability of the pulsed source [21]. To define the output wavelength, the wavelength-tunable SOA-based laser usually contains a wavelength-selective element [22–24], and most of the published works have tuning ranges of about 30–50 nm [25]. In [21], an intra-cavity birefringence loop mirror filter (LMF) is used to define the output wavelength across a range of 97 nm, but it is difficult to adjust accurately the polarization controller (PC) inside the LMF.

In this paper, a wavelength-tunable high-repetition-rate actively mode-locked fiber laser using a $LiNbO_3$ intensity modulator and tunable F–P filter (TFPF) is proposed and experimentally demonstrated. Based on the modulator, the repetition rate of the fiber laser can turn from 18.9 MHz, the fundamental repetition rate, to 9.832 GHz, corresponding to the 520th harmonic order number. The signal-to-noise ratio of the pulses is more than 50 dB, signifying the good steady of the mode locking. Meanwhile, by adjusting TFPF, the mode-locking operation can work over a broad wavelength of 43.4 nm, range from 1522.8 to 1566.2 nm, which is limited by the bandwidth of the filter. Ultrahigh repetition frequency, short pulse and wide wavelength range would make the fiber laser gain much attention in many practical applications, such as optical communications and sensors.

2 Experimental setup

Figure 1 shows a schematic diagram of the experimental setup of the actively mode-locked fiber laser. In this experimental system, there are three major components, which are an intensity modulator, a SOA and a TFPF. The intensity modulator (Plotline MXPE-LN-10) is a high-performance modulator that exhibits superior extinction ratio. Its specific design relies on proton exchange, a diffusion process that creates polarizing waveguides in the lithium niobate substrate and leads to extinction ratio higher than 40 dB.

SOA (Alphion SAC20r) supports a broad range of wavelengths from 1500 to 1600 nm, with gain options from 5 to 20 dB. SOA is suitable for using as widely tunable gain elements in the actively mode-locked ring fiber laser. TFPF is a broadly wavelength-tunable optical band-pass filter, which is designed by our research group (National Engineering Laboratory for Fiber Optic Sensing Technology). TFPF has a 3 dB bandwidth of about 0.15 and a 50 nm tunable range. It is employed to perform wavelength selection and tune the central wavelength of output pulse; meanwhile, it can reduce amplified spontaneous emission noise. EDFA compensates for the ~2.5 dB loss of TFPF, and it remains outputting the stable light of 20dBm.

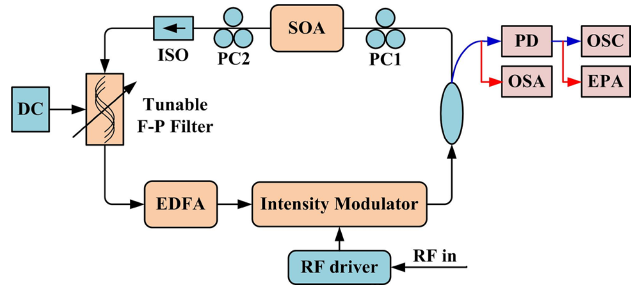

Fig. 1 Experimental setup of the actively mode-locked ring fiber laser based on SOA and intensity modulator. *EDFA* erbium-doped fiber amplifier, *ISO* isolator, *PC* polarization controller, *PD* photoelectric detection, *OSA* optical spectrum analyzer, *OSC* oscilloscope, *EPA* electrical spectrum analyzer

Optical isolator (ISO) is used to block the unidirectional operation of the laser in ring cavity. In the experimental setup, the operation direction of the mode-locked laser is the same as the propagation direction of SOA and the intensity modulator. Due to the polarization-sensitive characteristic of SOA, it is necessary that polarization controller1 (PC1) and polarization controller2 (PC2) are, respectively, used to adjust the polarization of input and output light of $LiNbO_3$ intensity modulator. Calculation of cavity length should include all devices in ring cavity including a single-mode fiber (SMF). The optical path length in a ring cavity is about 11 m, corresponding to the fundamental repetition rate of 18.9 MHz. If the power of RF signal generator meets the intensity modulator, the RF driver could be omitted as shown in Fig. 1. In the experiment, the frequency of RF signal generator (Anritsu 68347C) is adjusted from the fundamental frequency to ~10 GHz to match the ring cavity length. When the modulation frequency of RF signal is equal to the integer multiples of fundamental frequency, pulsed laser in a ring cavity starts to vibrate.

Experimental investigation involves the ring locking of fundamental and harmonic frequency-modulated active mode-locked laser. In the fundamental frequency mode locking, the pulse repetition frequency (f_c) was equal to C/L_c, where C is the speed of light and L_c is the path length of light in the cavity round trip in a circle. In the harmonic

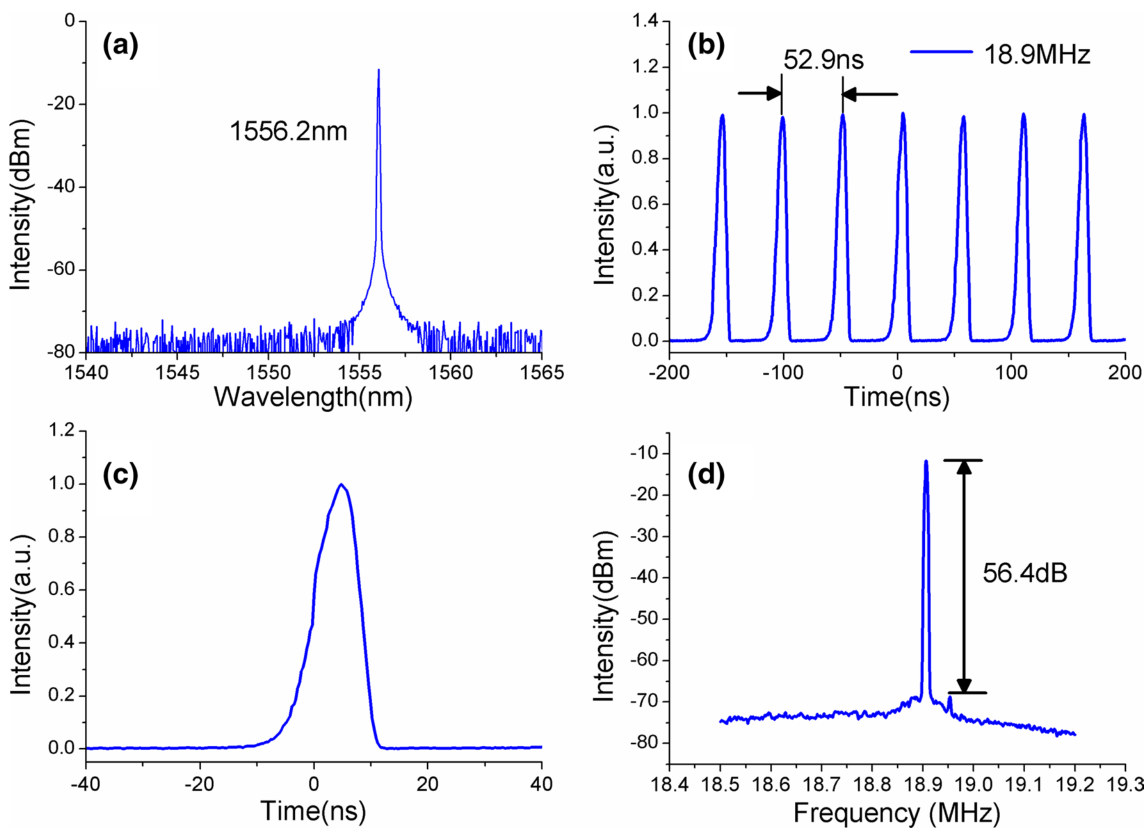

Fig. 2 Output characteristics of actively fundamental mode-locked pulses. **a** Optical spectrum, **b** pulse train at 18.9 MHz, **c** single pulse, **d** RF spectrum, RBW = 5 kHz

mode-locked operation, the frequency (f_m) of RF signal driving the modulator was theoretically derived as

$$f_m = mf_c, \tag{1}$$

where m is an integer. Obviously, the repetition frequency of harmonic mode-locked pulse is restricted by the frequency of driving RF signal and the frequency bandwidth of modulator.

At the output port from optical coupler (10:90), an optical spectrum analyzer (OSA: YOKOGAWA AQ6370C), a 100GS/s sampling oscilloscope (OSC: Tektronix DPO71254C) and an electrical spectrum analyzer (EPD: Agilent N9030A) with a 30 GHz photodetector (PD: Optilab PD-30-F) are used to measure the output pulse train. The time-domain waveform and the RF spectrum of mode-locked laser are measured through OSC and EPA via PD, respectively.

3 Experimental results and analysis

The mode-locked pulse can be generated when the current of SOA is well above the mode-locking threshold of 40 mA. Figure 2 depicts the measured characteristics of the actively fundamental mode-locked pulses at an average output power of 2.2 mW. In Fig. 2a, the spectrum of the mode-locked pulses is centered at 1556.2 nm with a 3 dB bandwidth of 0.12 nm. Figure 2b plots the measured pulse train with a time interval of ~52.9 ns between each pulse corresponding to a pulse repetition rate of 18.9 MHz, which is determined by the total cavity length. The pulse duration is 9.8 ns as shown in a large image in Fig. 2c,which is about 460 times the transform-limited pulse duration. As shown in Fig. 2d the SNR is suppressed better than 56.4 dB in the RF spectrum with a resolution bandwidth (RBW) of 5 kHz.

The SOA-based fiber ring laser can operate in the harmonically mode-locked regime by multiplying the modulation frequency and careful tuning polarization of two PCs to realize stable higher-order harmonic mode locking. EDFA has a certain dynamic range for the power of input optical, so we need not adjust the working current of SOA. The measured pulse trains under different harmonic orders without detuning are shown in Fig. 3. The stable active 3rd-, 20th-, 61th- and 242th-order harmonic mode-locked pulse trains are obtained at pulse repetition rates of 56.7, 378.6, 1145.1 and 4580.2 MHz, respectively.

The highest repetition rate of mode-locked pulses is scaled up to 520th in accord with the 520th harmonic order

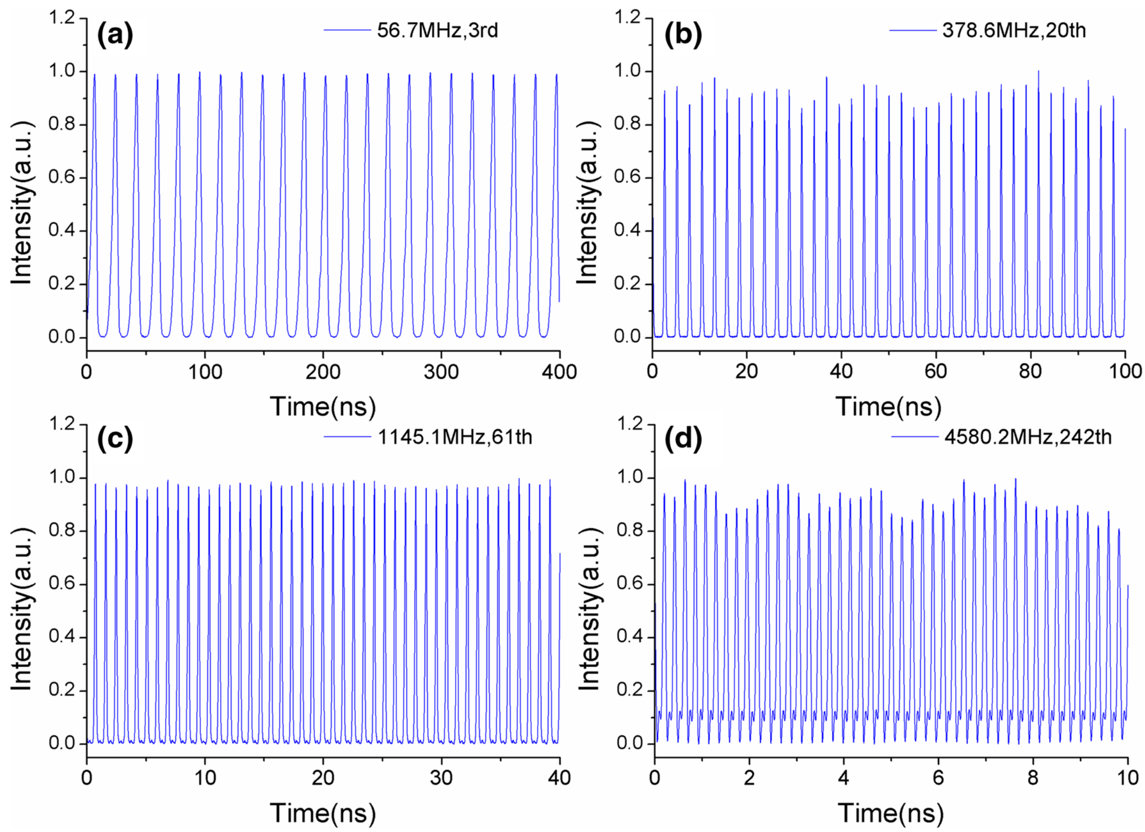

Fig. 3 Output mode-locked pulse trains for the **a** 3rd, **b** 20th, **c** 61th, and **d** 242th harmonic orders

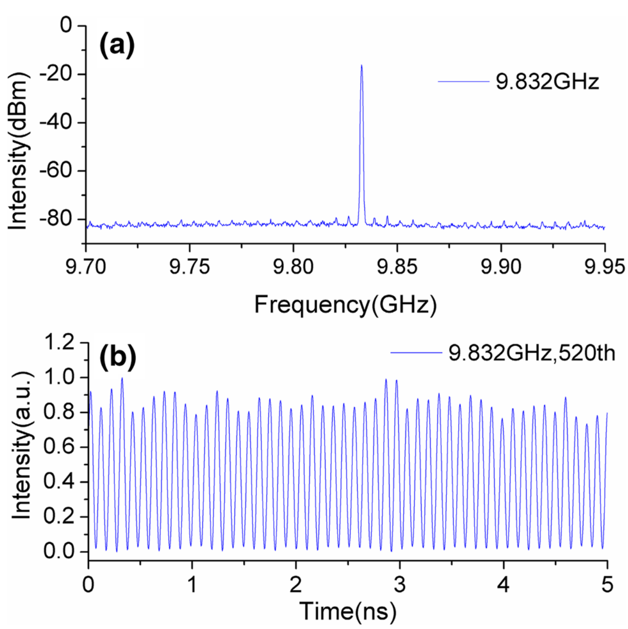

Fig. 4 RF spectrum and pulse trains for the 520th harmonic orders

of the fundamental repetition rate as shown in Fig. 4a. The repetition rate is 9.832 GHz, and the SNR is suppressed better than 58.2 dB in the RF spectrum. The theoretical transform-limited pulse duration corresponding to 0.12 nm spectral bandwidth is 21 ps. As shown in Figs. 4b and 3, there is the amplitude jitter in all mode-locked pulse trains. As is known to all, the pulse amplitude jitter is the intrinsic jitter of the laser [9], which originates from spontaneous emission and carrier noise. Meanwhile, the pulse amplitude jitter of high harmonic order mode-locked pulses is larger than that of low harmonic order pulses.

Under the mode-locking state, the RF frequency of Anritsu 68347C is fixed and then adjusts the center wavelength of TFPF through tuning the supply voltage of DC. With this setup, we can tune the wavelength of TFPF continuously from 1520 to 1570 nm in about 2-nm interval, which is limited by the amplification range of EDFA used in our experiment. The optical intensity of center wavelength is measured by OSA, and the superimposed optical spectrums are shown in Fig. 5. We have experimentally demonstrated that the laser wavelength can be tuned between 1522.8 and 1566.2 nm with power fluctuation less than 6 dB. When the wavelength of mode-locked laser is 1522.8 nm, the light intensity reaches the critical power of mode locking. The dotted line represents the spontaneous emission intensity of SOA.

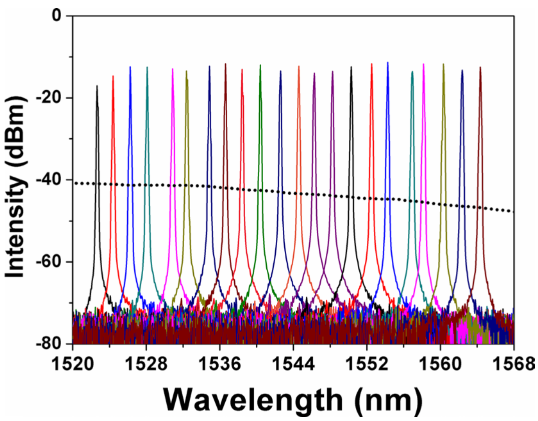

Fig. 5 Superimposed optical spectra of the output pulses throughout the 43.4 nm tuning range

The insertion loss of the intensity modulator and the attenuation of TFPF make the SOA-based ring fiber laser uncomfortably convert to the mode locking and affect the stability of the fiber laser. For the fiber laser with EDFA, the laser intensity is greatly improved; therefore, the mode locking is more easily achieved. However, the range of wavelength tuning is restricted by the gain bandwidth of EDFA. Therefore, increasing the gain bandwidth of EDFA and reducing the attenuation of TFPF are the focus of the experimental research in the next design of the SOA-based ring fiber laser.

4 Conclusions

A 10 GHz broadly wavelength-tunable high-repetition-rate actively mode-locked fiber laser, consisting of a $LiNbO_3$ intensity modulator, a TFPF and a SOA, has been proposed and demonstrated experimentally. The laser can deliver pulse trains with a fundamental repetition rate of 18.9 MHz. The corresponding spectral bandwidth is 0.12 nm with the pulse duration of 9.8 ns, leading to the TBP value of 146, which is about 460 times the transform-limited value for soliton pulse. The output power is only 2.2 mW. Benefiting from the $LiNbO_3$ intensity modulator, the highest repetition rate of the pulse we can obtain is up to 9.832 GHz, and the corresponding SNR is more than 58.2 dB, indicating the good quality of the mode-locking pulse. Under the 9.832 GHz mode-locking operation, with the help of the tunable FP filter, the working wavelength can turn from 1522.8 to 1566.2 nm, making this laser a good choice to meet applications in optical communication, photonic ADC and others.

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