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Letters

A 110 GHz passive mode-locked fiber laser based on a nonlinear silicon-micro-ring-resonator

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Abstract

Mode-locked fiber lasers have many important applications in science and engineering. In this work, we demonstrate for the first time a 110 GHz high repetition rate mode-locked fiber laser using a silicon-based micro-ring resonator (SMRR) to act as an intra-cavity optical comb filter, as well as an optical nonlinear element. No electrical bias for the SMRR is required to reduce free carrier absorption. The SMRR has a free spectral range of 0.88 nm, enforcing laser mode-locking at the 110 GHz high rate. The optical nonlinearity of the SMRR also supports the dissipative four-wave mixing effect for generating the mode-locked optical pulse trains. The mode-locked pulse-width, optical 3 dB spectral bandwidth and the time–bandwidth product (TBP) are experimentally measured under different pump currents to the erbium-doped fiber-amplifier module inside the laser cavity. The relative intensity noise and the line-width of the proposed laser are also evaluated. Furthermore, a long-term monitoring is performed. The experimental results show that the optical pulse train generated by the SMRR-based mode-locked fiber laser has a 2.6 ps pulse-width (pump current at 400 mA) at a 110 GHz high repetition rate, narrow line-width (1 kHz), high stability (under observation of an hour), and nearly Gaussian transform-limited (TBP is 0.455).

Keywords: fiber lasers, fiber optics, communication optical

(Some figures may appear in colour only in the online journal)

1. Introduction

Mode-locked fiber lasers have many important applications in the fields of science and engineering [1]. For example, the sub-THz repetition rate mode-locked fiber laser can be used in millimeter-wave wireless communication [2] and high-resolution photonic analog-to-digital converters [3], etc. In the literature, many techniques have been investigated to enhance the repetition rates of mode-locked fiber lasers. The active rational harmonic mode-locking technique [4, 5] can be implemented by detuning the active electro-optical (EO) modulation frequency with the rational ratio of the cavity fundamental repetition frequency to achieve the multiplication of pulse repetition rate by using bandwidth-limited radio-frequency (RF) components. However, the achieved

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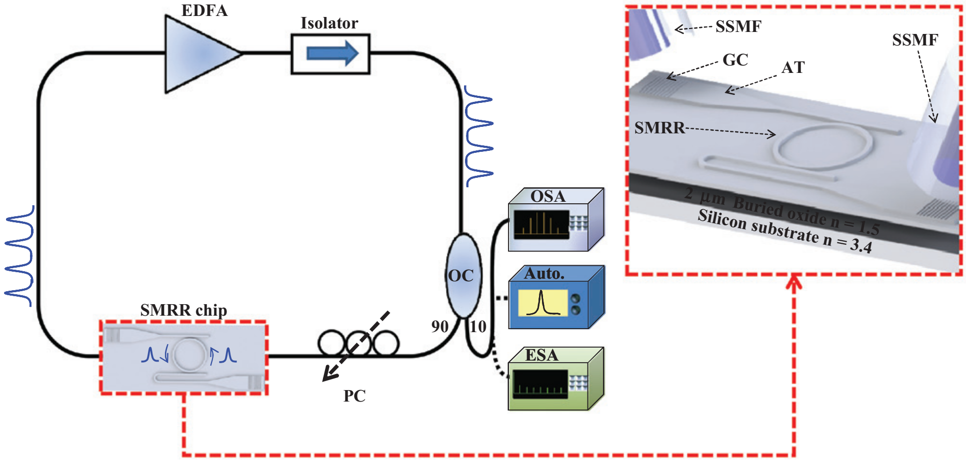

Figure 1. Experimental setup of the proposed 110 GHz mode-locked fiber laser using SMRR. Inset: SOI-based SMRR chip acts as the optical comb filter and Kerr optical nonlinear element.

repetition rate is still limited by the speed of the electronic components [5, 6] and additional pulse equalization schemes are required [7]. On the other hand, passive mode-locking techniques using an optical saturable absorber [8] or employing optical nonlinear effects to produce mode-locked pulse trains have also been developed [9–12]. High repetition rate optical pulse trains, employing optical nonlinear effects with an optical comb filter, have been demonstrated successfully, and the intra-cavity optical comb filter can be achieved by using a fiber Bragg grating [13, 14], a programmable optical processor [15], or a nonlinear doped-silica glass resonator [16].

In light of the recent development of silicon photonics, it will be very interesting to utilize the SMRR instead for building high repetition rate mode-locked fiber laser sources. Based on mature silicon manufacturing processes [17–19], the SMRR [20] has great potential as a cost-effective comb generation device with a high quality factor (Q-factor), as well as a precise and controllable free spectral range (FSR).

In this work, we demonstrate for the first time a 110 GHz high repetition rate mode-locked fiber laser using a SMRR to act as intra-cavity optical comb filter as well as an optical nonlinear element. The SMRR has a FSR of 0.88 nm and it acts as an optical filter for enforcing mode-locking at the 110 GHz high rate. The optical nonlinearity of the SMRR can also support the dissipative four wave mixing (FWM) effect to generate the mode-locked optical pulse trains. Due to better design, no electrical bias for the SMRR is required to reduce free carrier absorption (FCA) [20]. The laser can be successfully mode-locked through the dissipative FWM mechanism. The mode-locked pulse-width, optical 3 dB spectral bandwidth and the TBP are measured under different pump currents to the erbium-doped fiber-amplifier (EDFA) module inside the laser cavity. The relative intensity noise (RIN) and the line-width of the proposed laser are also evaluated. Furthermore, long-term monitoring is performed to verify that the laser can stay in stable mode-locking without any additional feedback mechanism.

2. Experimental setup

The proposed configuration of the 110 GHz passive harmonic mode-locked Er-doped fiber laser is shown in figure 1. The fiber laser is composed of the following components: (i) a commercially available C-band EDFA module acting as the gain medium (GIP, S-Series Booster EDFA) with 22 dBm output saturation power; (ii) a polarization controller (PC); (iii) a silicon-on-insulator (SOI)-based SMRR chip acts as the optical comb filter and Kerr optical nonlinear element.

Inside the laser cavity, the polarization independent optical isolator enforces the optical pulses to propagate in a single direction and avoids back-scattering light. The SMRR only allows the resonant modes with 0.88 nm spacing to build up by the filtering effect. The phases of these different optical modes will be locked by the FWM effect from the Kerr nonlinearity of the SMRR. The lights are coupled between the optical fiber and the SMRR via the tapered grating couplers (GCs) [21]. Since the GC is polarization sensitive, the PC must be adjusted correctly to reduce the coupling loss between the signal mode fiber and the TE-polarized SMRR. With all of these set up properly, the laser can be mode-locked steadily by simply adjusting the PC. A 90 : 10 optical coupler (OC) is used to take out 10% of the optical power in the fiber laser cavity. An optical spectrum analyzer (OSA) with 0.01 nm resolution (Advantest, Q8384), a 26.5 GHz RF analyzer (ESA) (Agilent, E4440A) together with a 1.2 GHz photodetector (Thorlabs, DET01CFC), and an autocorrelator (Femtochrome FR-103XL) are used to monitor the laser output.

It is calculated that the SMRR nonlinearity coefficient γ is $7.3 \times 10^{-4}\,W^{-1}\,km^{-1}$. The SMRR chip was fabricated using deep-ultra-violet (DUV) 193 nm lithography and reactive ion etching (RIE) techniques on a SOI wafer with a 0.22 μm top silicon layer and a 2 μm buried oxide (BOX) layer. The GCs are 16.7 μm long and 9.7 μm wide with 580nm in period and 70nm in depth. The GCs are designed for coupling lights onto the TE mode of the waveguide. The optimum incident angle from the signal mode fiber to the GC is an off-vertical tilt angle of 10° and the measured net coupling loss is ~7 dB/GC. Within the offset range of

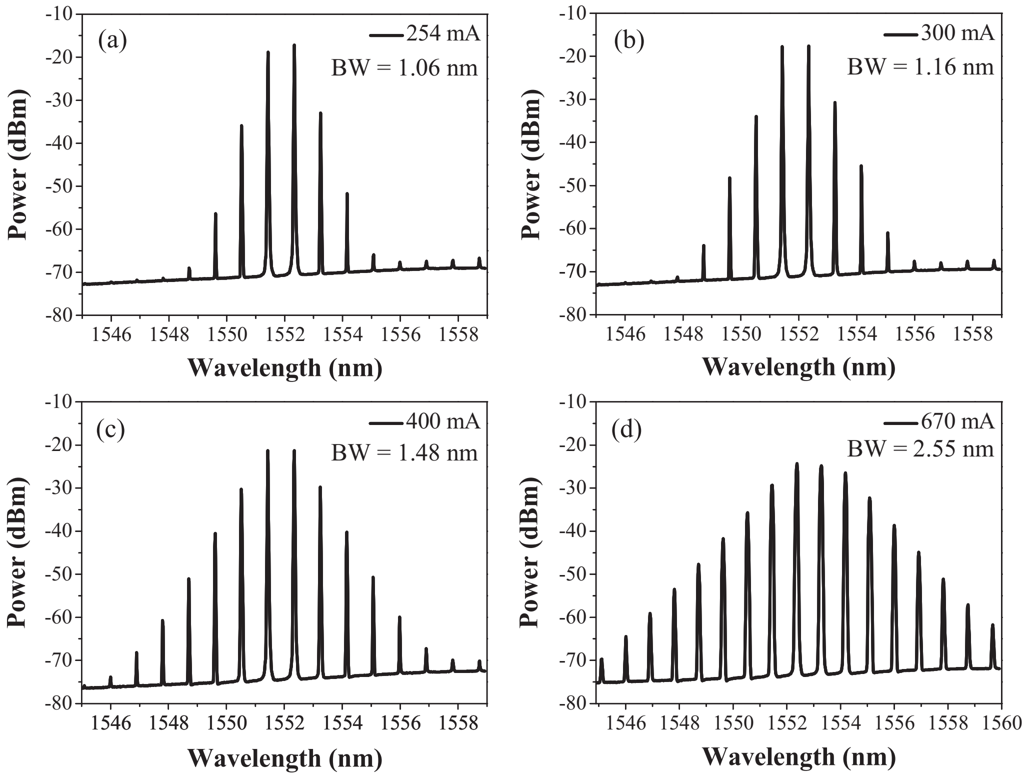

Figure 2. Optical spectra with different pump currents of 254, 300, 400 and 670 mA. The corresponding optical 3 dB bandwidth (BW) are 1.06, 1.16, 1.48 and 2.55 nm, respectively.

−2.5–4 μm in the x–z plane, the additional loss caused by the offset is less than 1 dB. Furthermore, the coupled optical mode through GCs was laterally tapered down to 500 nm through an adiabatic taper. Then, the light carried by straight silicon waveguide couples into the SMRR via the evanescent side coupling. The width and height of the straight silicon waveguide are 500 nm and 220 nm, respectively. For the SMRR, the length of the straight coupling region and the circumference of the ring are 6 μm and 674 μm, respectively. The gap between the SMRR and the SNW is 200 nm. The optical 3 dB filtering bandwidth and the Q of the SMRR are 0.038 nm and 4×10^4, respectively, at the resonant wavelength of 1550 nm. The Q supports the resonant modes in a circulating time ($\boldsymbol{\tau}$) of 5.79×10^{-8} s that is calculated by $\tau = (Q/2\pi f_r)$, where Q and f_r represent quality factor and resonant frequency, respectively. The resonant frequency is 110 GHz, equal to the FSR of 0.88 nm.

3. Results and discussion

To evaluate the nonlinear FWM effect inside the laser cavity, the pump currents to the EDFA are set at 254, 300, 400 and 670 mA, respectively. The optical modes were monitored by an OSA and the optical spectra at different EDFA pumping currents are shown in figures 2(*a*)–(*d*). When the EDFA pump current is 254 mA, the optical spectrum shows 6 optical modes and the 3 dB bandwidth of the optical spectral profile is 1.06 nm. In the measurement this is the threshold pump current to achieve mode-locking. Then, when the pump current is increased to 300 mA, 8 optical modes build up due to a higher FWM effect and the 3 dB bandwidth of the optical spectral profile is 1.16 nm. At the pump current of 670 mA, the 3 dB optical spectral profile has 16 modes and the 3 dB bandwidth is 2.55 nm.

The autocorrelation trace at the pumping current of 670 mA is shown in figure 3. The measured period of the optical pulses is 9 ps, corresponding to the repetition rate of 110 GHz. In order to estimate the optical pulse-width, the Fourier series expansion based on optical spectral measurement results with some added dispersion value is used to fit the autocorrelation trace. The black solid line is the measured SHG autocorrelation trace and the red dashed line is the fitting curve. Hence, the curve-fitting pulse-widths are 4.6 ps, 3.7 ps, 2.6 ps and 2.93 ps at the pump currents of 254 mA, 300 mA, 400 mA and 670 mA, respectively. The TBPs are 0.6, 0.473, 0.455 and 0.934, as shown in figure 4.

In order to look for the reason for the increase in TBP from 0.455 to 0.934 when the pump current increases from 400 to 670 mA, the RIN of the proposed 110 GHz mode-locked laser is measured. Figure 5 shows the measured RIN at different pump currents. When the pump current is at 254 and 300 mA, the RIN at 100 kHz is < -100 dB Hz^{-1}. However, when the current is at 350 and 400 mA, the RIN is increased to -82 dB Hz^{-1}. It is also observed that the RIN significantly increases when the pump current is at 670 mA. We think this growth of RIN is due to the relaxation oscillation of the fiber laser. This is supported by the experimental evidence that the peak of the spectral noise shifts to higher frequencies when the pump current is increased. In principle, the laser noise performance can be further improved by enhancing the noise suppression mechanism from the combined effects of self-phase

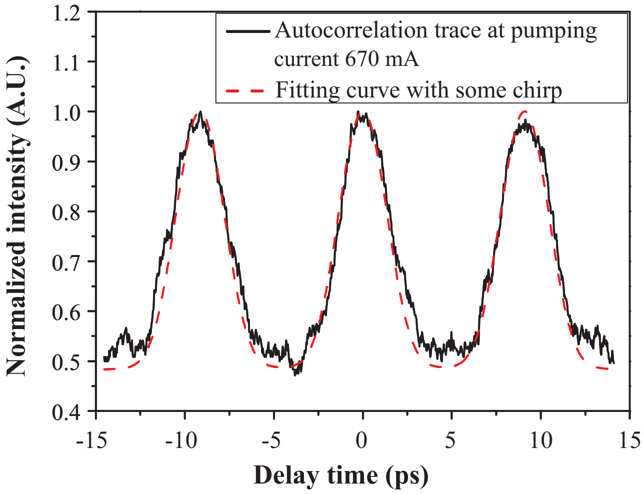

Figure 3. The autocorrelation trace of the 110 GHz mode-locked optical pulse train at pump current of 670 mA. The pulse-width is about 2.93 ps.

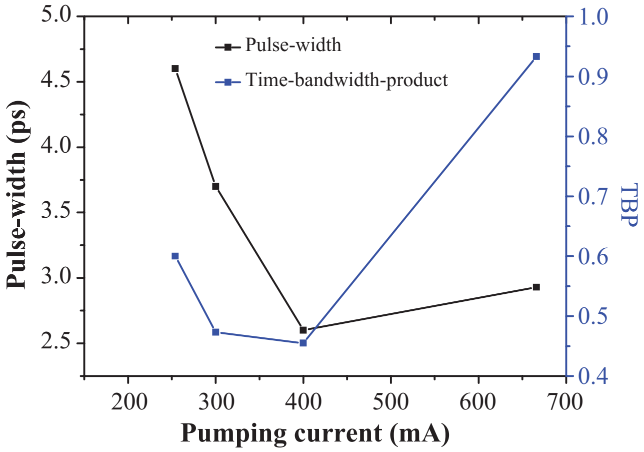

Figure 4. The pulse-width and TBP of the 110 GHz mode-locked optical pulse train at pump currents of 254, 300, 400 and 670 mA.

modulation (SPM) and optical bandpass filtering inside the laser cavity. Figure 5 also indicates that the mode spacing of the fiber ring cavity is 4 MHz. In addition, the SPM may also chirp the pulse and result in a large TBP. We measure that at the pump current of 670 mA, the EDFA output optical power is 308 mW before coupling into GC. However, the coupling power into the SMRR is only 61.69 mW owing to the coupling loss of the GC. The large coupling loss has caused the current fiber laser cavity to have a relatively low Q value, which will increase the RIN noise level in comparison to fiber laser cavities with higher Q values [22]. Thus, in principle, the performance of the current laser can be further improved by using a better optical confinement micro-ring with a higher Q [23] and a more efficient apodized GC [24].

We have also evaluated the laser's stability. As shown in figure 6, the laser can operate stably at the 110 GHz mode-locked state for more than an hour when the pump current is at 400 mA without using any active feedback mechanism. Figure 6 shows that the autocorrelation time trace remains stable and the pulse-width is unchanged during the monitoring time of an hour.

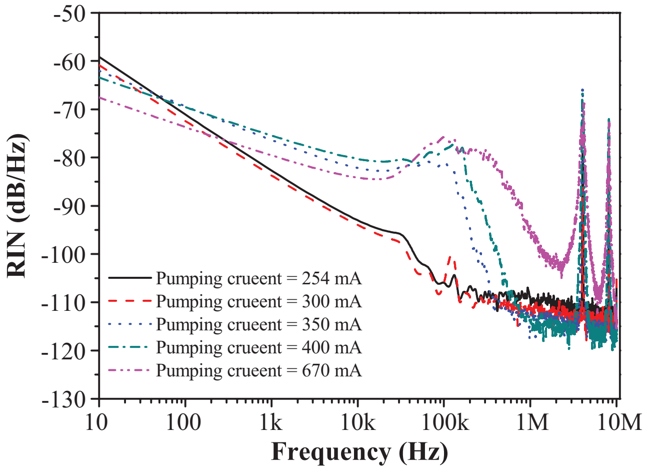

Figure 5. RIN at different pump currents from 254 to 670 mA.

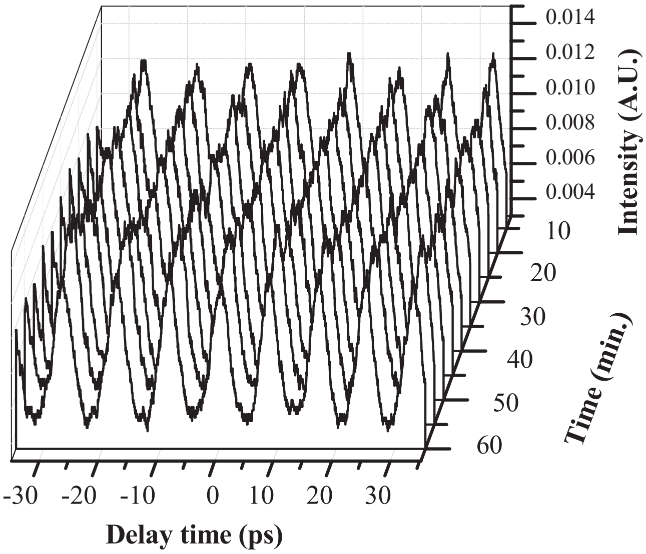

Figure 6. SHG autocorrelation traces at the pumping current of 400 mA, monitored for an hour.

Finally, to further characterize the laser stability, a delayed heterodyne interferometer with a 80 km single mode fiber (SMF) delay-line is employed and the experimental results are shown in figure 7. In this measurement, one optical mode of the mode-locked laser is filtered and power divided by a 3 dB power splitter into two parts. One part is phase-modulated by a 1 GHz sinusoidal signal, and the other part propagates through 80 km SMF. Then the two parts are combined by another 3 dB power combiner. The beating RF spectrum at 1 GHz is measured by a 10 GHz photodetector after the delayed heterodyne interferometer output port. When the laser pumping current is tuned from 254 to 670 mA, the measurement line-width is 1 kHz. The inset of figure 7 shows the delayed heterodyne detection beating RF spectrum at the pump current of 670 mA. The delayed heterodyne detection, with an 80 km delay length (measurement resolution about 1 kHz), can avoid unwanted beating signals. Therefore, the real laser line-width could be narrower than 1 kHz. From the results, the optical modes from the proposed laser should have high spectral purity.

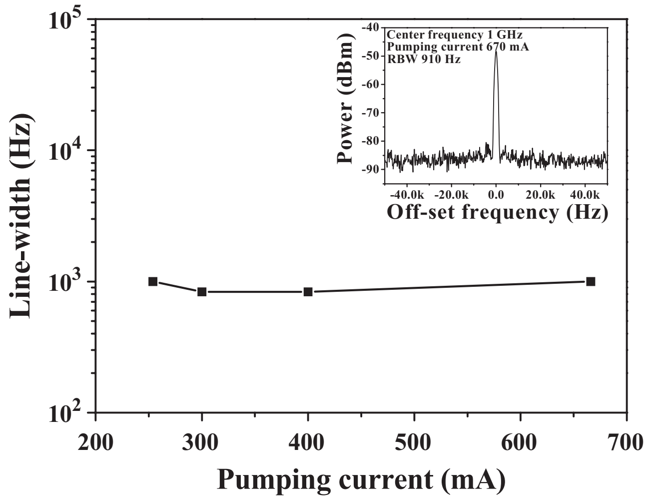

Figure 7. Line-width measurement with the delayed heterodyne detection at different pump currents. Inset: the delayed heterodyne beating RF spectrum at the pump current of 670 mA.

4. Conclusion

We fabricated a compact SMRR and demonstrated a 110 GHz high repetition rate mode-locked fiber laser based on the SMRR, which acted as the intra-cavity optical comb filter as well as an optical nonlinear element. It has a FSR of 0.88 nm and acts as an optical filter for enforcing mode-locking at the 110 GHz. The uniform tapered grating coupling technique with an off-vertical coupling angle (10°) was used to place the SMRR inside the fiber ring intra-cavity with tolerable insertion loss. The laser can be successfully mode-locked through the dissipative FWM mechanism. The pulse-widths were 4.6 ps, 3.7 ps, 2.6 ps and 2.93 ps, respectively, at pump currents of 254 mA, 300 mA, 400 mA and 670 mA. The TBP were 0.6, 0.473, 0.455 and 0.934 respectively. A delayed heterodyne interferometer with 80 km SMF delay-line was employed, and the measured line-width was 1 kHz. In addition, the autocorrelation time trace remained stable during the monitoring time of an hour, showing that the laser can stably operate without any additional feedback mechanism. The experimental results showed that the optical pulse train generated by the proposed SMRR-based mode-locked fiber laser had a 2.6 ps pulse-width (pump current at 400 mA) at a 110 GHz high repetition rate, narrow line-width (1 kHz), high stability (under observation of an hour), and nearly Gaussian transform-limited (TBP is 0.455). We expect the laser performance can be further enhanced by reducing the optical coupling losses between the SMF fiber and the SMMR, which will in turn increase the intra-cavity optical power and the intra-cavity optical nonlinearity. Finally, we believe this work opens up an opportunity of using a silicon-photonics integrated circuit to generate cost-effective sub-terahertz optical pulses.

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