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RF injection locked 18 GHz regeneratively mode-locked semiconductor laser

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Abstract: In this manuscript, a semiconductor based fiber ring cavity mode-locked laser regeneratively driven at 18 GHz is presented. The optical spectrum of the laser is centered at 1578 nm. The laser is RF injection locked via an external source at 18 GHz. The phase noise of the mode-locked laser is measured and the integrated timing jitter was found to be 10.8 fs (from 100 Hz to 20 MHz) and 13.3 fs (from 100 Hz to Nyquist frequency). The integrated amplitude fluctuation (from 100 Hz to 20 MHz) was less than 0.02%. The laser phase and amplitude noise responses to various injected RF power levels were also investigated. The injection RF power has significant effect on the phase noise and the best jitter value is around 40 dB lower than the cavity regenerated RF power.

OCIS codes: (140.4050) Mode-locked lasers; (060.5625) Radio frequency photonics.

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1. Introduction

High frequency and low jitter sources have applications in photonic analog to digital conversion [1], high speed RF waveform generation [2] and RADAR systems [3]. Mode-locked lasers have the potential to provide jitter values down to atto-second levels [4]. Since lasers with longer optical cavities have a higher Q-parameter, they can generate optical pulse

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trains with lower phase noise [5]. However, a longer cavity also means that the cavity fundamental frequency will be low as well. Therefore, to obtain high repetition rate and low phase noise simultaneously, harmonic mode-locking is needed [6]. To achieve harmonic mode-locking, lasers are generally actively driven for loss modulation by an external RF signal. In this case, the phase noise of this external RF source may become a limiting factor for the performance of the output pulse train. Excellent optical pulse train phase noise values are presented with this method using a very low jitter external source [7]. The other method of achieving mode-locking is by regenerating the RF signal of the mode-locked laser and then feeding it back to the laser cavity itself [8–10]. This method is also called coupled opto-electronic oscillators [5,11]. Even though the laser cavity itself is very similar in both cases, the focus of a coupled opto-electronic oscillator is the low phase noise of the generated RF signal, whereas the regeneratively mode-locked lasers are also focused on the time and optical domain properties such as optical combs. The timing jitter value of the previous works was 260 fs [8] and 140 fs [9], which are nearly an order of magnitude higher than the values reported in this work.

In this work, an 18 GHz semiconductor based fiber ring cavity laser was regeneratively harmonic mode-locked, and RF injection by an external source was implemented to improve the close-in phase noise. The resulting optical pulse train has a timing jitter of 10.8 fs and amplitude fluctuations less than 0.02% (integrated from 100 Hz to 20 MHz). The laser phase noise and the amplitude noise responses to various RF injection power levels are also investigated and presented. The paper is organized as follows: first the experimental setup of the laser is explained, then the experimental results are presented for continuous wave, free running mode-locked and RF injection locked mode-locked operation cases. After the analysis and discussion of injection power effects on the phase noise, the paper is concluded.

2. Mode-locked laser design and experimental setup

The experimental setup of the laser is shown in Fig. 1.

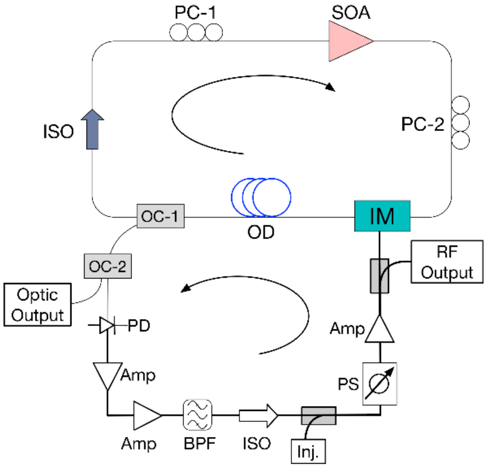

Fig. 1. The setup of the regeneratively mode-locked laser. (SOA: semiconductor optical amplifier, ISO: isolator, OC: optical coupler, IM: intensity modulator, OD: optical delay, Amp: RF amplifier, BPF: band pass filter, Inj: injected RF signal, PS: RF phase shifter)

The laser has two main parts, the all-optical-loop and the opto-electronic loop. The all optical loop consists of a fiber-coupled semiconductor optical amplifier (Thorlabs BOA1004S) as the gain element, a lithium-niobate Mach-Zehnder intensity modulator for loss modulation (20 GHz bandwidth, EO Space), a fiber optical delay of 50 meters of a standard single mode fiber (SMF-28) in order to increase the cavity length for lower phase noise [11], an optical isolator for unidirectional lasing, 10/90 output coupler and two polarization controllers in order to align the polarization of light before entering the optical amplifier and intensity modulator. The laser light from the all optical cavity tapped out from the first output coupler and sent to the second output coupler, where 30% of the power is taken out as the optical output and 70% is sent to the opto-electronic loop. The optical signal is converted to the RF domain using a 20 GHz photodiode (Discovery Semiconductor DSC30S) and then amplified by two cascaded low phase noise amplifiers with 15 dB gain. The amplified signal passes through a band pass filter centered at 18 GHz, defining the pulse repetition rate, and an RF isolator to prevent any back reflection. A 10 dB RF coupler is used to inject an external RF signal and an RF phase shifter is used to overlap the supported modes of all optical loop and opto-electronic loop. A third RF amplifier is used to drive the intensity modulator. Another 10 dB RF coupler is used to take out 10% of the RF power as the RF output and the 90% of the power is sent to the intensity modulator. The experiment is held in a controlled environment but no vibration damping optical table is used.

3. Experimental Results

3.1 Without mode-locking

The laser is first driven at continuous wave mode without mode-locking. The output optical power versus the bias current graph is shown in Fig. 2(a). The laser threshold current is 70 mA and the maximum optical power at 590 mA is 4.7 mW. The output optical power is measured right after the first output coupler (OC-2 was not connected). The polarization controllers in the laser cavity are aligned by maximizing the output power when the intensity modulator is in 100% transmission mode. Throughout the experiments the semiconductor optical amplifier is driven at 590 mA. After the output of the all-optical-loop is connected to the second output coupler (OC-2), the RF output trace is obtained using an RF spectrum analyzer (Rohde & Schwarz FSU 20 Hz-43 GHz). The RF output of the laser without mode-locking is shown in Fig. 2(b). The mode-locking is prevented by misaligning the supported modes in the opto-electronic loop and the all optical loop. The RF spectrum shows the RF supported modes which are also responsible for the supermode noise spurs in the phase noise plots. The mode separation of the supported modes is found to be 3 MHz (cavity fundamental frequency) which corresponds to a cavity length of ~66 meters.

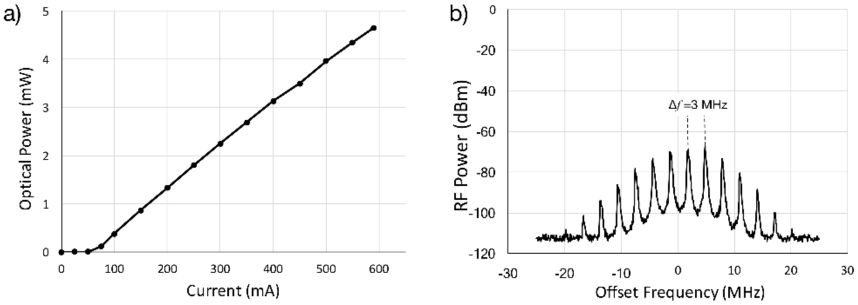

Fig. 2. (a) The output power versus applied current graph. (b) The RF spectrum trace of RF modes in the laser cavity (The center frequency is around 18 GHz).

3.2 Mode-locked but no injection locked

After the all-optical-loop alignment is completed, the RF phase shifter is tuned until the mode-locking is achieved. The polarization controllers also tuned slightly as any temperature changes may have an impact on the polarization. Optical and RF properties of the free running mode-locked laser is analyzed using an optical spectrum analyzer (Yokogawa AQ6370C) and the RF spectrum analyzer. The optical spectrum is shown in Fig. 3(a). The optical comb lines of the mode locked laser have a separation of ~0.14 nm which corresponds to 18 GHz frequency separation as expected. The visibility of the comb lines is 20 dB, limited by the resolution of the spectrum analyzer. The RF spectrum trace of the RF output is shown in Fig. 3(b). The repetition rate of the optical pulse train is measured as 18.006 GHz and the RF tone has 130 dBc/Hz signal-to-noise ratio for offset frequencies larger than 10 MHz. The supermode noise spurs cannot be observed with 30 kHz resolution bandwidth or in the dynamic range of the spectrum analyzer.

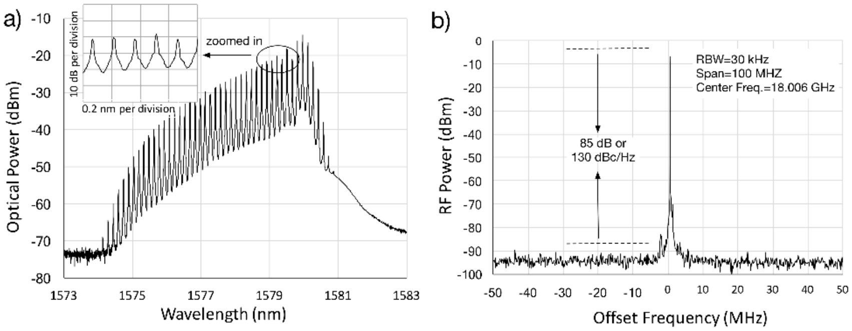

Fig. 3. (a) The optical spectrum analyzer. (b) RF spectrum analyzer.

The RF properties of the photo-detected pulse train is further investigated using a signal source analyzer (Agilent Technologies E5052 B) and a microwave down converter (Agilent Technologies E5053 A). The absolute phase noise of the free running regeneratively mode-locked laser is shown in Fig. 4(a). The phase noise decreases 30 dB per decade from 100 Hz to 10 kHz offset frequencies; and 20 dB per decade from 10 kHz to 10 MHz. The phase noise reaches to −161 dBc/Hz noise floor after 10 MHz. The first and second super mode spurs can be seen at 3 MHz and 6 MHz offset frequencies. The third spur mode noise spur is barely visible around 9 MHz. The first super mode noise spur is suppressed to −134 dBc/Hz level. The amplitude noise property of the mode-locked laser is also measured using the same signal source analyzer and shown in Fig. 4(b). The amplitude noise has around −110 dBc/Hz at 100 Hz offset frequency and goes down to −155 dBc/Hz for offset frequencies higher than 10 MHz. The first super mode noise can again be seen at 3 MHz and suppressed down to −140 dBc/Hz. The spurs at 300 kHz and 600 kHz are believed to be resulting from unknown external sources.

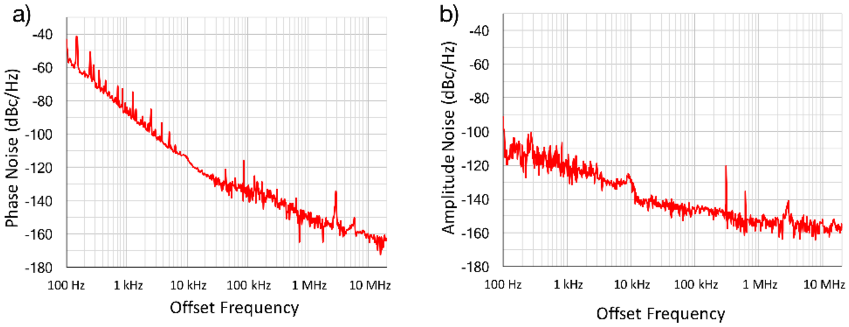

Fig. 4. (a) The absolute phase noise and (b) amplitude noise of the mode-locked laser.

3.3 Mode-locked and RF injection locked

The laser was then RF injection locked to decrease the close in phase noise and improve the long-term stability. The RF signal is injected to the opto-electronic loop through the first RF coupler. The injected RF signal power is tuned and the lowest phase noise graph is obtained. The phase noise and the amplitude noise plots are shown in Figs. 5(a) and 5(b) respectively together with their free-running versions for easier comparison. The phase noise starts from -

88 dBc/Hz at 100 Hz offset frequency and decreases with a 15 dB/decade average up to 1 MHz. The phase noise reaches to −162 dBc/Hz level at 1 MHz offset which is a few dB higher than the shot noise limit. The 1 Hz bandwidth phase noise associated with shot noise can be expressed as $q\Re P_{opt}R/P_{RF}$, where q is the electron charge, $\Re$ is the detector responsivity, P_{opt} is the average optical power, R is the system impedance and P_{RF} is the RF signal power. In our system, the average output optical power is 4.5 mW and the RF output power is –2 dBm (after compensating the 5 dB cable loss) which corresponds to a shot noise phase noise floor of −163 dBc/Hz. The first super mode noise spur can be seen at 3 MHz offset frequency. The first super mode noise floor is suppressed to – 138 dBc/Hz level. The second supermode noise spur can also be seen at 6 MHz offset frequency and suppressed below −155 dBc/Hz level. The higher harmonics are suppressed below the phase noise floor. The integrated RMS (root mean square) timing jitter is calculated by the following formula [12]:

$$\sigma_j = \frac{1}{2\pi f_{ML}}\sqrt{2\int L(f)df} \tag{1}$$

where f_{ML} is the pulse repetition rate and $L(f)$ is the phase noise. The integrated timing jitter from the 100 Hz to 20 MHz is calculated to be 10.8 fs. The jitter calculated by extrapolating the noise floor and integrating up to the Nyquist frequency of 9 GHz is estimated to be ~13.3 fs. When the integrated timing jitter of the free-running laser is calculated for the same integration ranges, ~379 and ~381 fs are found respectively. The amplitude noise properties of the optical pulse train start with ~-110 dBc/Hz at 100 kHz offset frequency and reaches to ~-155 dBc/Hz at 10 MHz. The integrated amplitude fluctuation from 100 Hz to 20 MHz is below 0.02%. As seen from Fig. 5(b), RF injection has limited effect on the amplitude noise.

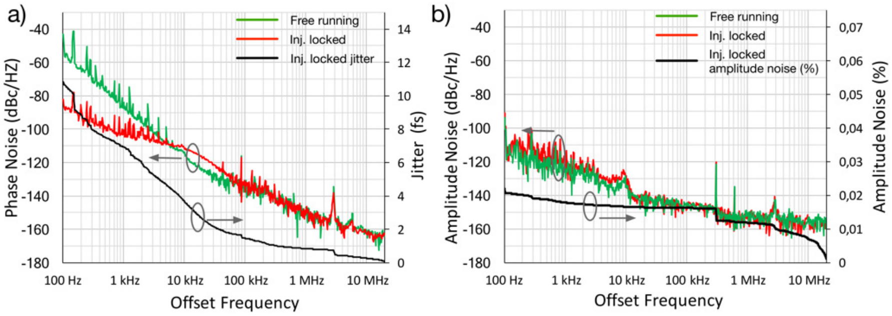

Fig. 5. (a) The absolute phase noise of injection locked regeneratively mode-locked laser, (b) Amplitude noise of the injection locked mode-locked laser.

4. Analysis and discussion

Our experiments further showed that the phase noise performance of the laser output, especially at low frequency offsets, are greatly dependent to the power level of the RF injection signal. Figure 6(a) shows the phase noise plots of free running laser and injection locked laser at different injection signal power. Figure 6(a) can be divided in to three sections according to injection power dependencies. The first section is from 100 Hz to 9 kHz where phase noise decreases with higher injection power; the second section is from 9 kHz to around 200 kHz where the phase noise increases with the higher injection power level and the last section is from 200 kHz to 20 MHz where the phase noise does not depend on the injection power and remains constant for different levels. The injection power levels shown in Fig. 6(a) are the relative RF powers with respect to the regenerated RF power at the injection point. For high injection powers a noise plateau with a knee structure emerges on the phase noise which originates from the phase noise of the RF injection signal. The knee frequency is getting lower for low injection powers, which means the phase noise filtering property of the mode locked laser is dominant for low injection powers. The change of knee frequency with respect to the relative injection power is shown in Fig. 6(b). One important parameter is the locking range of the mode-locked laser which changes with the injection power level as shown in Fig. 6(c). For very low injection powers the locking range can be as small as 10 kHz and it increases to hundreds of kHz with higher injection power levels which means a tighter lock. In our system, the best phase noise with the lowest timing jitter is observed when the relative injection power level is around – 40 dB. At this power level, the locking range was more than 50 kHz. In order to further improve the phase noise, the quality factor of the laser cavity needs to be improved which can be obtained by increasing the cavity length or decreasing the cavity losses.

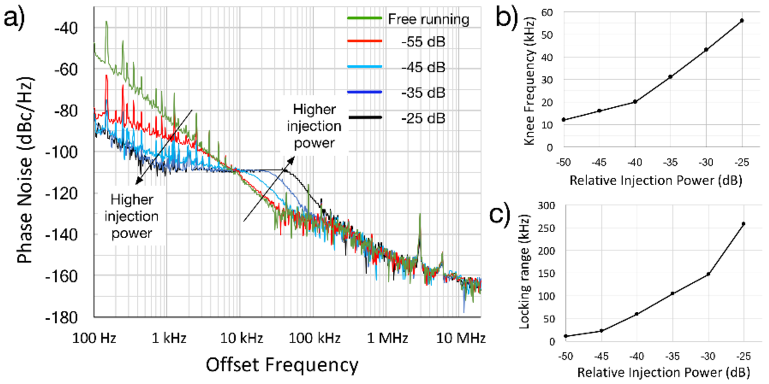

Fig. 6. (a) A comparison of phase noise for free running laser and different relative injection power levels. (b) The knee frequency and injection power. (c) The RF injection locking relative power and injection locking frequency.

5. Summary

In this work, we have demonstrated an 18 GHz semiconductor based fiber ring cavity mode-locked laser. The pulse repetition rate of the laser is RF injection locked to an external 18 GHz oscillator. The RF injection locked regeneratively mode-locked laser has a timing jitter of 10.8 fs and 13.3 fs (integrated from 100 Hz to 20 MHz and 100 Hz to Nyquist frequency) whereas the free-running operation has timing jitter values of 379 fs and 381 fs in the corresponding integration ranges respectively. The amplitude fluctuation of the pulse train is less than 0.02% (integrated from 100 Hz to 20 MHz) and is nearly independent from the RF injection since the RF injection only acts as a weak temporal filter and does not correct any pulse to pulse energy fluctuation. The effects of the RF injection power on the laser noise (both phase and amplitude) is investigated and it was found that as the RF injection power increases the low offset frequency phase noise (up to 9 kHz) decreases, but the intrinsic phase noise of the injection source starts to dominate the system.

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