Experimental analysis of absolute phase noise of a harmonically mode-locked semiconductor laser

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In this work, we have designed and experimentally characterized the absolute phase noise of a fiber coupled semiconductor ring laser at 1550 nm, actively mode-locked at 10 GHz by an external RF oscillator. The dependency of mode-locked laser phase noise to the external RF oscillator phase noise and laser cavity length is investigated using different RF sources and cavity lengths. A timing jitter of 14.6 fs (1 kHz to 1 MHz) has been measured at 10 GHz with a total cavity length of 315 meters.

(Received August 11, 2017; accepted April 5, 2018)

Keywords: Mode-locked laser, Phase noise, Semiconductor laser

1. Introduction

Short optical pulses at high repetition rates have various applications in photonic ADC's [1,2], optical communication [3], and arbitrary waveform generation [4]. Among several optical pulse generation methods, actively mode-locked lasers step forward owing to the low phase noise and high repetition rate of the generated pulse train. One of the important parameters that limit the use of an optical pulse train for certain applications is its phase noise (i.e. timing jitter) [5]. Therefore, the need for optical sources with lower phase noise is ever increasing [6]. However, one should differentiate between relative phase noise and absolute phase noise of a pulsed optical source [7,8]. Relative phase noise is a measure of how much the optical pulse train fluctuates relative to the oscillator (i.e. the master clock) driving the laser, whereas the absolute phase noise is a measure of how much the pulse train fluctuates relative to a hypothetical perfect clock with zero phase noise (i.e. timing jitter). If the generated optical pulse train is to be used in part of a network employing a master clock, a low relative phase noise is crucial. However, if the optical source is to be used as an independent source or as the master clock of a network, then the absolute phase noise is the important parameter. Also, a low relative phase noise will not guarantee a low absolute phase noise and vice versa, since the laser cavity may act as a high Q phase noise filter [8]. Generally, it is easier to measure the relative phase noise of a mode-locked laser, since the timing of the optical pulses are compared to the synthesizer acting as the master clock; the absolute phase noise measurement requires a more complex approach as there is no master clock for comparison. In this work, we are experimentally measuring and analysing the absolute phase noise of a harmonically mode-locked semiconductor laser when it is driven by different synthesizers and has different cavity lengths. For this aim, we have designed and built a fiber coupled semiconductor ring laser, harmonically mode-locked at 10 GHz. In order to minimize the absolute phase noise, the amplitude modulator, used as the mode-locker, is driven by different synthesizers. The cavity length is also increased by adding a 300-meter-long optical fiber to the cavity, in order to improve the cavity Q-parameter and its effects on the absolute phase noise is investigated. The absolute phase noise of the output pulse trains for different configurations are compared and the lowest timing jitter of 14.6 fs (1 kHz to 1 MHz) has been obtained where the driving synthesizer has a timing jitter of 14.9 fs in the same range.

2. Experimental details

The layout of the fiberized harmonically mode-locked laser is chosen to have a ring cavity as shown in Fig. 1. A commercially available fiber coupled semiconductor optical amplifier (SOA) at 1550 nm is used as the gain medium. The SOA diode temperature is stabilized to a thermistor value of 10 kΩ which corresponds to the room temperature. An inline fiber optical isolator ensures the unidirectional operation in the ring cavity preventing the undesired interference between clockwise and counter-clockwise propagating pulses and amplified spontaneous emission. A lithium-niobate based interferometric amplitude modulator is driven by a synthesizer at around 10 GHz to actively mode-lock the laser cavity, the DC bias to the amplitude modulator is externally controlled and optimized for maximum output power in CW mode, and for minimum phase noise in the pulsed mode. The ring cavity has a 10% fiberized output coupler. The cavity fundamental frequency was measured to be 13.6 MHz which corresponds to a total optical cavity length of 15.2 meters.

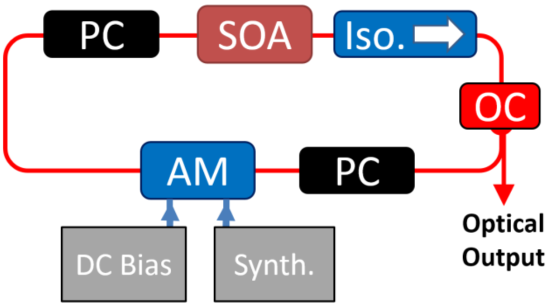

Fig. 1. The setup of the harmonically mode-locked fiber coupled semiconductor laser

When operated in CW mode, the laser has an efficiency of 1.55% W/A, and a threshold current of around 75 mA as shown in Fig. 2. At 600 mA, an output power of 8 mW has been obtained, further increase in the bias current was not tested due to the limitations of the commercial SOA.

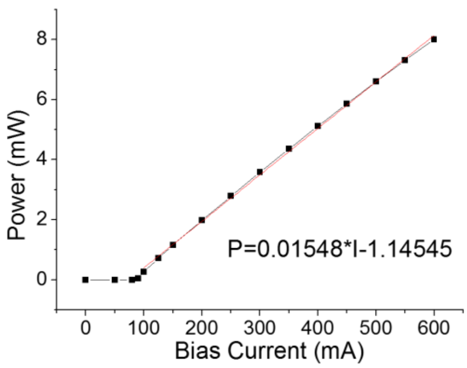

Fig. 2. Power efficiency of the laser in CW mode together with a linear fit to the experimental data. The curve shows an efficiency of 1.55% W/A

3. Mode-locking and absolute phase noise measurements

To harmonically mode-lock the laser, the amplitude modulator is first driven by an Anritsu MG37022A synthesizer at a frequency of around 10 GHz (approximately 735th harmonic). The generated optical spectrum around 1585 nm having a -10 dB bandwidth of 4 nm is shown in Fig. 3a. The pulse train is photo-detected and the absolute phase noise of the 10 GHz signal is measured using an Agilent E5053A microwave downconverter in conjunction with an Agilent E5052B signal source analyser. The absolute phase noise of the laser pulse train together with the absolute phase noise of the synthesizer driving the laser are compared in Fig. 3b. As seen in the phase noise graph, the laser phase noise closely follows the synthesizer up to an offset frequency of 1 MHz, and then realizes a slope of -30 dB per decade while the synthesizer phase noise drops 20 dB per decade. This result shows that after the offset frequency of 1 MHz the laser starts to filter out the phase noise of the synthesizer but at lower offset frequencies the absolute phase noise of the laser is limited by the phase noise of the synthesizer.

This means that, the laser phase noise is limited by, and less than the phase noise of the synthesizer driving the laser. To further lower the absolute phase noise of the mode-locked laser, the synthesizer was replaced with an Agilent E8257D synthesizer. The Agilent E8257D has around 10 dB lower phase noise for low offset frequencies than the Anritsu MG37022A. Using this low phase noise synthesizer, a slightly broader optical spectrum having a -10 dB bandwidth of 5 nm and centred around 1593 nm is realized as shown in Fig. 4a. Even though the general characteristics of the optical power spectrum did not change, the absolute phase noise of the laser, shown in Fig. 4b, is reduced dramatically. In this case, the phase noise plateau of the laser extends up to the offset frequency of 100 kHz, and follows the phase noise of the synthesizer very closely. Also, there is a large phase noise spur at 3 MHz due to unknown laser or electronics dynamics. However, as seen in Fig. 4b, the absolute phase noise of the laser was still limited by the synthesizer and a choice of another synthesizer with an even lower phase noise would reduce the absolute phase noise of the laser.

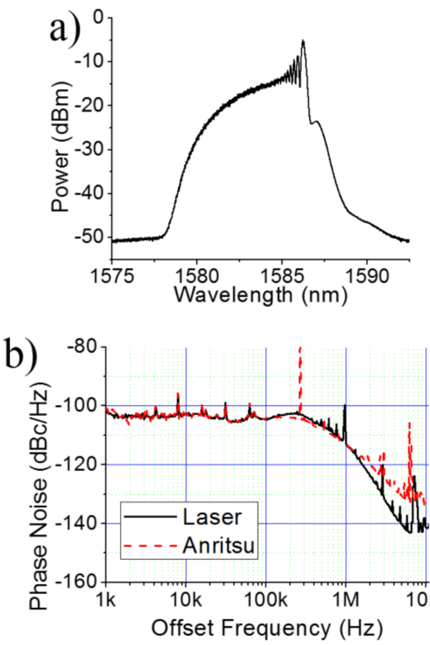

Fig. 3. (a) Optical spectrum of the 15.2-meter-long laser cavity driven with an Anritsu (MG37022A) synthesizer. The resolution is 0.02 nm. (b) The absolute phase noise of the laser together with the absolute phase noise of the synthesizer

Since an ultra-low-phase noise oscillator, such as a sapphire loaded cavity oscillator, was not available to drive the laser; to further reduce the absolute phase noise of the harmonically mode-locked laser, the cavity length was increased to improve the cavity Q-parameter, so that the cavity itself will filter out the phase noise of the synthesizer. A 300-meter-long fiber delay line is added to the optical cavity, increasing the total cavity length by almost 21 times, decreasing the cavity fundamental frequency from 13.6 MHz to 658 kHz. The additional fiber delay line also increases the total the intracavity dispersion, which results in a narrower optical spectrum (shown in Fig. 5a), down to a -10dB bandwidth of only 1 nm, however well resolved optical comb lines with a visibility of 20 dB are obtained, measured with an optical resolution of 0.02 nm. Optical frequency combs become visible when the cavity length is increased from 15 meters to 315 meters. We believe this is due to the higher Q factor of the laser cavity and hence less noise. The harmonic optical mode sets cannot produce a dominant mode set when the noise is high which results in lasing of all the modes. The optical spectrum analyser cannot resolve the closely separated optical tones. However when the noise is low, one of the harmonic optical modes can be dominant and suppress the other ones, which leaves only one mode set with 10 GHz separation.

The absolute phase noise of this elongated cavity with higher cavity Q (long laser cavity) is compared to the absolute phase noise of its shorter version (short laser cavity) in Fig. 5b with both lasers driven by the low phase noise RF oscillator. The noise filtering function of a mode-locked laser can be taken as a Lorentzian function in the form of $\Gamma^2/(\omega^2+\Gamma^2)$, where Γ is the knee frequency, and ω is the offset frequency as shown in the phase noise plots [9].

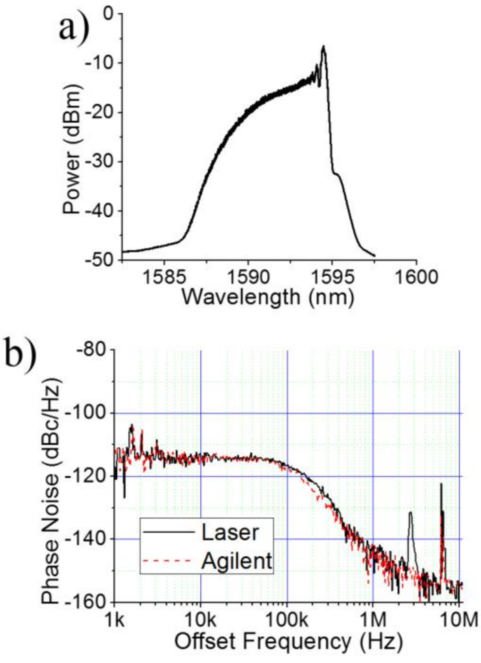

Fig. 4. (a) Optical spectrum of the 15.2-meter-long laser cavity driven with a low phase noise synthesizer (Agilent E8257D). The resolution is 0.02 nm. (b) The absolute phase noise of the laser together with the absolute phase noise of the synthesizer

As the cavity length has increased, the noise filtering knee frequency has been shifted towards a lower frequency value as expected and the laser phase noise starts to deviate from the synthesizer noise at around 50 kHz. However, note that the supermode noise spurs [10] at the cavity harmonics of 658 kHz can be observed on the phase noise plot, and at the higher offset frequencies the laser phase noise level of the long cavity is approximately 5 dB higher.

The root-mean-squared (RMS) timing jitter of a pulse train (σ_J) is given by the equation:

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

where f_{ML} is repetition rate of the pulse train and $L(f)$ is the phase noise of the signal in units of dBc/Hz. Using Eq.1, the integrated RMS timing jitters of the short and long cavities are calculated. It is found that the short cavity timing jitter is 16.4 fs (1 kHz to 1 MHz) and 18 fs (1 kHz to 10 MHz); while the long cavity has a timing jitter of 14.6 fs (1 kHz to 1 MHz) and 15.8 fs (1 kHz to 10 MHz) respectively. For comparison, the timing jitter of the Agilent synthesizer is 14.9 fs (1 kHz to 1 MHz) and 15.1 fs (1 kHz to 10 MHz). One major factor responsible for the small deviation from the synthesizer jitter is the phase noise spur at the 3 MHz frequency offset at a value of around -135 dBc/Hz.

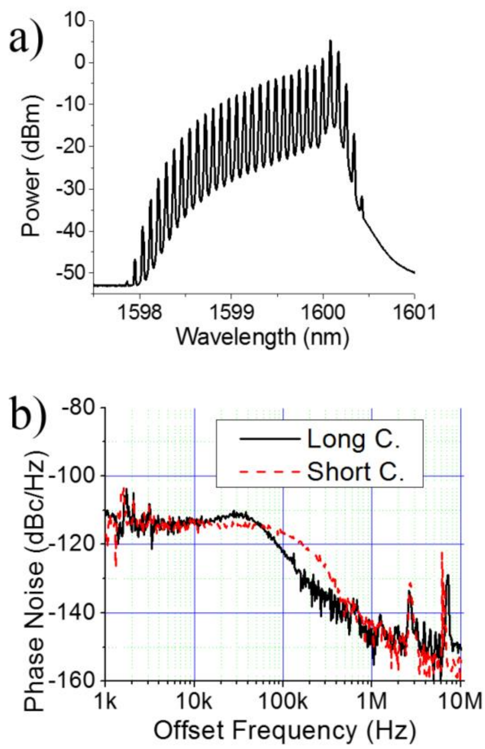

Fig. 5. (a) Optical spectrum of the 315-meter-long laser cavity driven with lower noise synthesizer. The resolution is 0.02 nm. (b) The absolute phase noise graphs of the long and short laser cavities

4. Conclusion

As seen from these results, even though some supermode noise spurs are generated, still the integrated jitter of the laser has been reduced with the increasing cavity length in all integration ranges. However, as the cavity gets longer the emerging supermode spurs and other spurs due to certain intracavity dynamics, may increase the absolute phase noise at high frequency offset values, which suggests that the cavity length may be optimized to minimize the absolute phase noise of the laser. The lowest integrated timing jitter of 14.6 fs shows that, even a standard cavity laser without the use of active frequency stabilization or supermode suppression, may act as a high Q filter and reduce the absolute phase noise of the synthesizer driving it.

Acknowledgments

This work is supported by The Scientific and Technological Research Council of Turkey (TUBITAK) project number 115F468.

The authors also thank to Tubitak Bilgem for the phase noise measurements.

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