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Amplitude noise suppression by intracavity phase modulation in a harmonically mode-locked laser

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ABSTRACT

A fiber coupled semiconductor ring laser that employs both an amplitude and a phase modulator was built and actively harmonic mode-locked at a repetition rate of 10 GHz. The phase modulator was driven at the cavity fundamental frequency and its effects on the optical spectrum and the optical pulse train were analyzed. The intracavity phase modulation at the cavity fundamental frequency resulted in 40% lower optical pulse amplitude fluctuations and improved the stability of the optical spectrum.

High repetition rate optical pulses and optical combs with low noise have several applications such as analog-to-digital conversion [1], arbitrary waveform generation [2,3], photonic radar [4], and high-speed communication [5]. Depending on the application requirements, certain properties of the pulse train, like timing jitter, amplitude fluctuation, optical bandwidth, pulse energy, or repetition rate, limit the system performance. Actively mode-locked lasers with amplitude only modulation can provide very low timing jitter and amplitude fluctuations at high optical pulse repetition rates [6]. Haus et. al. have theoretically proposed that intracavity phase modulation, in certain cases, may reduce the phase noise of an optical pulse train even further in an actively mode-locked laser [7]. Later, Ozharar et al. have experimentally verified this by reducing the timing jitter of a 10 GHz optical pulse train by 50% integrated from 1 Hz to the Nyquist frequency of 5 GHz [8]. Similar work was done by Vasseur et al. where they have realized multi-harmonic phase modulation and realized a small improvement in timing jitter and a 3 dB improvement in sensitivity [9]. However, the intracavity phase modulation in all these previous works was done at the same or very similar frequencies to the pulse repetition rate. In this work, we analyze the intracavity amplitude modulation at a high harmonic and phase modulation at the cavity fundamental frequency which is usually much smaller than the pulse repetition rate for harmonically mode-locked lasers. This approach reduces the amplitude fluctuations in both the time and spectral domains without having any phase/timing fluctuation penalty.

In this experimental work, an actively harmonic mode-locked, fiber-coupled, semiconductor laser was built using off-the-shelf components, and its layout is shown in Fig. 1. The fiberized ring laser is designed such that it employs both an amplitude modulator and a phase modulator. The gain medium is chosen as a fiber-coupled semiconductor optical amplifier (SOA). The diode temperature is stabilized to the thermistor value of 10 kΩ which corresponds to the room temperature. The fiber optic isolator (Iso.) ensures unidirectional operation of the laser and was placed before the gain medium to minimize backwards travelling amplified spontaneous emission (ASE) into the laser components. A 90/10 fiber splitter is used as the 10% output coupler after the SOA to maximize the output power. The laser cavity also includes a 100-m fiber delay (FD) to increase the cavity Q-parameter, but this also reduces the cavity fundamental frequency and increases the intracavity dispersion. Since all the intracavity elements except the output coupler and the fiber isolator, are polarization dependent, there are three fiberized manual polarization controllers (PC) as part of the cavity as well. The manual PC's are adjusted to maximize the output power of the laser.

First, the laser is operated at continuous wave (CW) regime and the resulting L-I curve is shown in Fig. 2. The efficiency of the laser is 1.7% W/A, and the threshold current is approximately 100 mA. In the following experimental work, the bias current was set to 550 mA resulting an output power of 8 mW. The output power was identical for CW and mode-locked regime.

The cavity fundamental frequency was measured to be 1.63 MHz which corresponds to a total cavity length of approximately 123 m. The laser is actively harmonic mode-locked by driving the amplitude modulator at 10 GHz (9.999167 GHz exactly) by an external synthesizer operating at the 6134th harmonic of the laser cavity. The DC bias to the amplitude modulator was also adjusted to a value of 2.4 Volts where the signal to noise ratio of the photo-detected optical pulse train was maximized. The resulting

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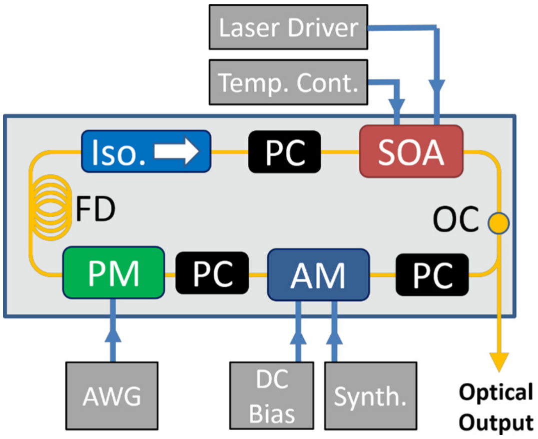

Fig. 1. The layout of the actively harmonic mode-locked laser. (AWG: arbitrary waveform generator, PM: phase modulator, AM: amplitude modulator).

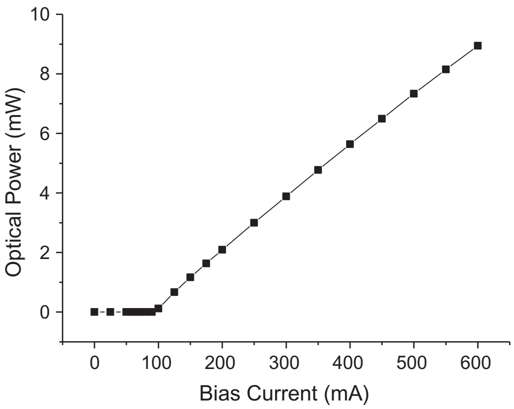

Fig. 2. The L-I curve of the laser when operated in CW mode.

mode-locked optical spectrum, as shown in Fig. 3, has its maximum peak at 1585.3 nm, and is not very stable such that the comb-like structure is continuously varying in time in terms of wavelength, amplitude, and visibility. This is mainly due to the intentional exposure of the laser structure to external mechanical noise sources (open laser enclosure, no vibration isolated table, sharing the same table with some electronic equipment with operational cooling fans, etc.).

However, when the intracavity phase modulator is driven by a sinusoidal signal at the cavity fundamental frequency of 1.63 MHz, the optical spectrum becomes much more stable as shown in Fig. 4. As seen in the figure, the variations among the comb-like structures are greatly reduced due to this intracavity phase modulation and the envelope of the optical spectrum is much smoother. This increase of the stability of the optical spectrum is also shown in the animation included in the digital version of this paper.

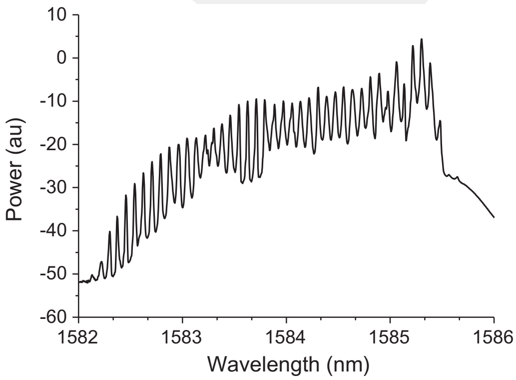

Fig. 3. Unstable mode-locked optical spectrum without the intracavity phase modulation.

To quantify the increase in the stability of the optical spectrum, both the phase noise and amplitude noise properties of the optical pulse train were measured with and without the intracavity phase modulation. The noise measurements are done by using an Agilent E5052B Signal Source Analyzer in conjunction with an Agilent E5053A Microwave Downconverter. The phase noise (i.e. the timing jitter) of the output pulses did not change whether the intracavity phase modulation is on or off as shown in Fig. 5. The root-mean-square (RMS) timing jitter is given by the formula:

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

where $L(f)$ is the phase noise of the photo-detected signal in units of dBc/Hz and f_{ML} is the repetition rate of the pulse train. Using Eq.1, the integrated (10 Hz–1 MHz) RMS timing jitter values for the two cases, where the PM is OFF and ON, are calculated to be 22.3 fs and 23 fs respectively. Even though this almost constant timing jitter looks contradictory to previous work at first, the reason for this constant timing jitter is that the intracavity phase modulation in our experiment was executed at the cavity fundamental frequency of 1.63 MHz while the pulse repetition rate was 10 GHz. Due to this large difference between the amplitude and the phase

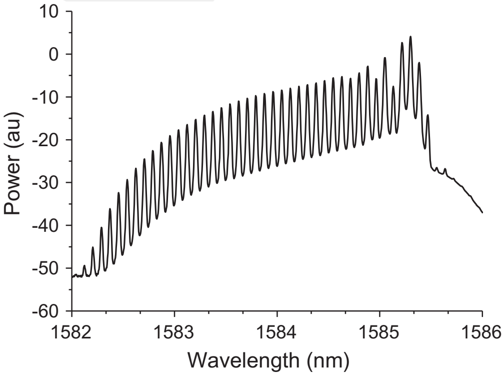

Fig. 4. Stable mode-locked optical spectrum with the intracavity phase modulation.

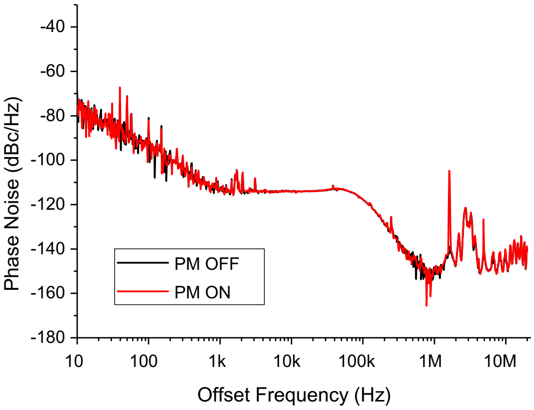

Fig. 5. Comparison of the phase noise of the output pulse trains with and without the intracavity phase modulation.

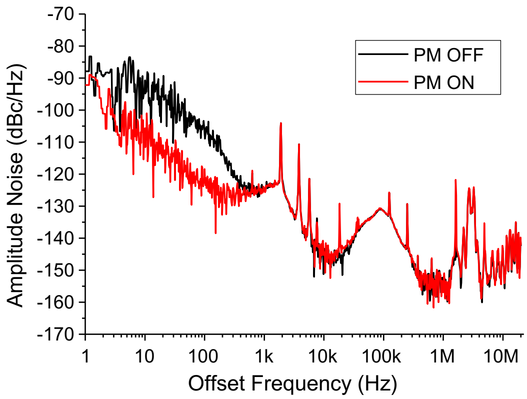

Fig. 6. Comparison of the amplitude noise of the output pulse trains with and without the intracavity phase modulation.

modulation frequencies, there are approximately 6134 optical pulses under one phase modulation cycle. This means that the phase modulation is temporally not fast enough to act as a restoring force on the individual pulses and unable to counteract their fluctuations in the time domain. In other words, the intracavity phase modulation at high frequency creates a restoring force for optical frequency components counteracting the temporal dispersion, similar to the effect of self phase modulation on solitons. However, at low frequency, each individual pulse experiences a phase modulation having a very small depth of modulation which does not improve the timing jitter.

However, when the amplitude noise of the optical pulse train is analyzed, the effect of the intracavity phase modulation is clearly evident as seen in Fig. 6.

When the phase modulator is turned on, the amplitude noise of the pulse train in the low-frequency range (below 1 kHz) is suppressed up to 25 dB near 100 Hz, but at the higher offset frequencies, the amplitude noise is the same. The integrated RMS amplitude fluctuation of the optical pulse train can be calculated, like timing jitter, by integrating the amplitude noise sidebands according to the following equation:

$$\frac{\Delta E}{E} = \sqrt{2\int M(f)df}, \tag{2}$$

where $M(f)$ is the amplitude noise of the signal in units of dBc/Hz and $\Delta E/E$ is the fractional fluctuation of the pulse energy. The integrated amplitude fluctuation (1 Hz–1 MHz) is calculated to be 0.028% when the intracavity phase modulation is off and it reduces to 0.017% when the phase modulation is turned on. In other words, the intracavity phase modulation reduced the amplitude fluctuations by almost 40%. The reason for this effect is that even though the intracavity phase modulation is much slower relative to the pulse repetition rate in the time domain, and does not affect the timing jitter, it still creates sidebands in the optical frequency domain exchanging energy among the supermode families. This energy exchange correlates the supermode spurs reducing their relative phase/amplitude jumps and therefore filters the pulse to pulse fluctuations up to an offset frequency of 1 kHz.

1. Conclusion and analysis

A fiber coupled semiconductor ring laser that has both an amplitude and a phase modulator was built and actively harmonic mode-locked at a repetition rate of 10 GHz. By introducing intracavity phase modulation at the cavity fundamental frequency, the changes in the noise properties of the optical spectrum and optical pulse train are analyzed. Our results show that even though the two optical spectra (shown in Figs. 3 and 4, and in the animation) display very different levels of stability on their comb-like structure in terms of wavelength and amplitude, both spectra result in the same timing jitter. These results bring a deeper understanding of the nature of phase noise and suggest that a more stable optical spectrum does not necessarily guarantee a lower timing jitter. Also, our results together with the previously reported results infer that the effects of intracavity phase modulation depend on the modulation frequency. The frequencies that are close to the pulse repetition rate may improve the phase noise whereas the low-frequency modulation improves amplitude fluctuations and has no impact on phase noise.

We also present a new and practical way to reduce the amplitude fluctuations of a high repetition rate pulse train through a low-frequency phase modulation. Using this novel approach, the amplitude fluctuation of the 10 GHz pulse train was reduced from 0.028% to 0.017%, while keeping the timing jitter constant.

Acknowledgments

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.optlastec.2018.02.033.

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