Jitter Reduction of Mode-Locked Hybrid Silicon Laser With Intra Cavity Filter

Mohammad Shekarpour[1], Mohammad Hasan Yavari[1]

[1] Department of electronic, Shahed University, Tehran, Iran

***Abstract*— We study the influence of the intra-cavity ring on dynamics, phase noise and timing jitter of a long-ring -cavity colliding pulse mode-locked laser using a delay differential equation (DDE) model. The results of dynamic show that the intra-cavity filter can suppress harmonics of 2 GHz cavity. We also find a reduction of phase noise and timing jitter compared to the fundamental 20 GHz ring laser, which is in good agreement with experimental result.**

***Keywords*— intra-cavity, dynamic, phase noise, timing jitter, long-ring-cavity mode-locked laser**

I. Introduction

Research on passively mode-locked semiconductor lasers has a long tradition. In the past several decades, These types of optical pulse sources have played an important role in the high bit-rate communication systems, optical clocking, arbitrary waveform generation, optically sampled analog to digital converters (ADCs), and frequency metrology [1]. Large noise figures are restricting applications of semiconductor mode-locked lasers (MLLs) such as ADCs and optical clocking in reaching higher sample rate and repetition frequency, respectively [2]. Several ways to overcome these problems that have been investigated, include optical injection, hybrid mode-locking, optical feedback, and harmonic mode-locking of long cavity lasers. External modulation is used in hybrid mode locking method reducing phase noise, the frequency of external modulation must be adjusted within certain range of the repetition rate of the pulse trains. This requires stable frequency represents high costs [3]. Optical injection requires continuous wave laser with narrow bandwidth, making the technique expensive thus this method suffers from the same disadvantage associated with the hybrid mode-locking. The optical feedback, without the need for external source, by adding a long delay line can achieved low phase noise [4]. high quality factor of the long cavity is useful for a low-noise operation. Of course, harmonic mode-locking is required to obtain high repetition rates in a long cavity[5]. This method, like the optical feedback, does not require an external source.

Hybrid silicon MLLs in a ring (long cavity) and linear (with and without optical feedback) configurations, are demonstrated [1,5]. The structures consist of the long low-loss silicon waveguides to reduce the phase noise. Integration of such mode-locked lasers on a silicon photonics platform is also promising for the integration of these devices with other optical components as complex high-speed photonic circuits [6].

We apply the delay differential equation (DDE) model to investigate the dynamics of the repetition rate with and without intra-cavity filter. The RF-power of the tenth harmonic is compared for the two configurations. Subsequently, phase noise and timing jitter of 20 GHz harmonically and fundamentally are investigated.

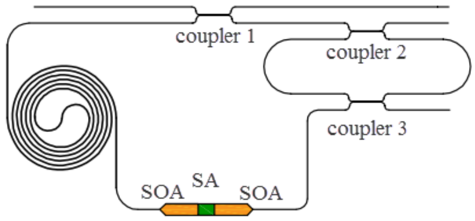

Fig. 1. Schematic of Mode-Locked hybrid silicon laser with intracavity Filter. Black lines indicate passive Si waveguides [1,5]. SOA—Semiconductor optical amplifier, SA—saturable absorber

II. Delay differential equation model

Based on the model proposed in [7], in this paper we extend the DDE model to study harmonic mode-locking of the long cavity lasers (see Fig. 1). Equations (1) and (2) describe the slowly varying field amplitude ε in long cavity without and with intra-cavity filter. In (2), intra-cavity filter is introduced by coupling the laser cavity to the passive cavity. The final set of three coupled DDEs (without intra-cavity (1),(3) and (4) - with intra-cavity (2),(3) and (4)) for the slowly varying field amplitude ε, the saturable gain G and the saturable loss Q is

$$\gamma^{-1}\dot{\varepsilon}(t) = -\varepsilon(t) + R_0(t-T)e^{-i\Delta\Omega T}\varepsilon(t-T) + D\xi(t) \tag{1}$$

$$\gamma^{-1}\dot{\varepsilon}(t) = -\varepsilon(t) + R_1(t-T_1)e^{-i\Delta\Omega T_1}\varepsilon(t-T_1) + \sum_{l=1}^{\infty} K_l e^{-ilC} R_2(t-T_1-lT_2)e^{-i\Delta\Omega(T_1+lT_2)}\varepsilon(t-T_1-T_2) + D\xi(t) \tag{2}$$

$$\dot{G}(t) = J_g - \gamma_g G(t) - e^{-Q(t)}(e^{G(t)}-1)|\varepsilon(t)|^2 \tag{3}$$

$$\dot{Q}(t) = J_q - \gamma_q Q(t) - r_s e^{-Q(t)}(e^{G(t)}-1)|\varepsilon(t)|^2 \tag{4}$$

$$R_i(t) = \sqrt{k_i}\, e^{1/2(1-i\alpha_g)G(t) - 1/2(1-i\alpha_q)Q(t)}$$

J_g is unsaturated gain and J_q is unsaturated absorption. The carrier lifetimes in the gain and absorber sections are given by $1/\gamma_g$ and $1/\gamma_q$, respectively. The factor r_s is proportional to the ratio of the saturation energies in the gain and absorber sections. $T \equiv v/L_0$ and $T_1 \equiv v/L_1$ are the cold

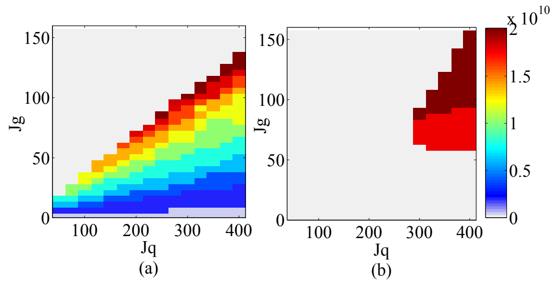

Fig. 2. Dynamic of repetition frequency for without-intracavity (a) and with-intracavity long ring laser (b).

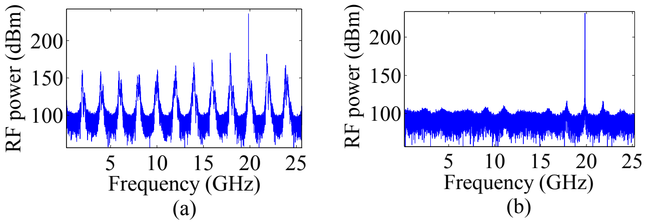

Fig. 3. Electrical spectrum (RBW—1 MHz) of tenth harmonic of without-intracavity (a) and with-intracavity long ring laser (b).

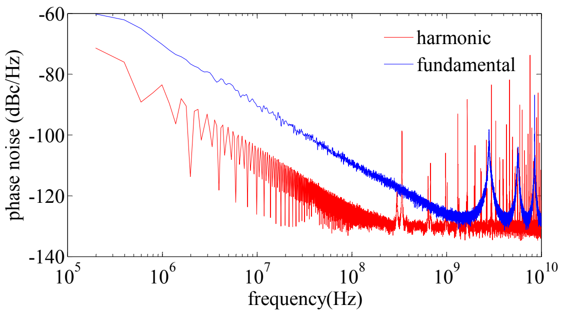

Fig. 4. The single side-band phase noise of the fundamental(20GHz) ring laser and the tenth harmonic of intracavity long ring laser .

cavity roundtrips time for the configuration without and with intra-cavity filters, respectively. $T_2 \equiv v/L_2$ is the cold cavity roundtrip time for intra-cavity filter. L_i is the length of the cavity in different configurations. The bandwidth of the laser is taken into account by a Lorentzian-shaped filter function with full-width at half maximum γ. Here l is the number of roundtrips in the intra-cavity filter, K_l is the roundtrip-dependent intra-cavity filter strength and C is the phase of the light due to one roundtrip in the intra-cavity filter. Spontaneous emission is modeled in (1) and (2) by a complex Gaussian white-noise term $\xi(t)$ with strength D. $R_i(t)$ describes the amplification and losses of the electric field during one round trip in the ring cavity. Internal and out-coupling losses are taken into account in the attenuation factor ki and the linewidth enhancement factor (α factor) in the gain and absorber sections are denoted αg and αq, respectively.

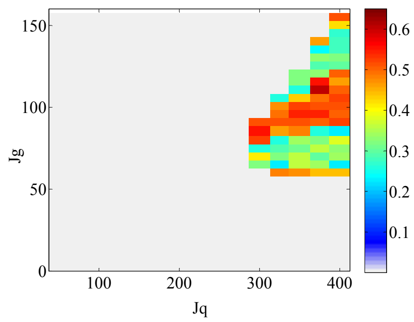

Fig. 5. The rms-timing jitter of intra-cavity long ring laser that is normalized to the rms-timing jitter of the fundamental(20GHz) ring laser.

III. Simulation Results

In fig. 2(a), dynamic of the repetition frequency for the configuration without intra-cavity long ring laser shows that all of the harmonics H_1 to H_{10} can be obtained. However, dynamic of the intra-cavity long ring laser exhibits only H_9 and H_{10} and the region of continuous wave increases (see Fig.2b). The advantage of this configuration is a significant increase in H_{10} region.

Indeed, intra-cavity filter suppresses intermediate harmonics. We investigate this influence of the intra-cavity filter by applying discrete fourier transform to the field power For both configurations in tenth harmonic (see fig. 3). From the power spectrum in Fig. 3(b), only tenth harmonic component can be observed in the configuration with intra-cavity long ring laser, while in the other configuration all the harmonic components appear(see Fig. 3(a)) which cause amplitude distortions in the time domain.

The phase noise and timing jitter of the harmonically MLL with an intra-cavity filter by (2)–(4) is simulated with a noise strength of D. The rms-timing jitter is obtained by integrating the phase noise spectrum over the frequency range from νlow = .5 MHz to νhigh = 5 GHz. The single side-band phase noise of the fundamental and the tenth harmonic are plotted in Fig. 4 that shows up 10 dB improvement in phase noise. The rms-timing jitter of intra-cavity long ring laser that normalized to the rms-timing jitter of fundamental (20GHz) ring laser as a function of J_q and J_g, is depicted in Fig. 5. The reduction of phase noise and timing jitter are in good agreement with the experimental results of [1] and [5].

IV. Conclusion

The influence of intra-cavity filter on dynamics, phase noise and timing jitter has been numerically investigated. We find the intra-cavity filter suppressed intermediate harmonics. Results from phase noise and timing jitter showed the reduction of this in intra-cavity filter mode locking laser compared to the fundamental 20 Ghz ring laser.

References

[1] S. Srinivasan, et al., "Low phase noise hybrid silicon mode-locked lasers," Front. Optoelectron., vol 39, no. 3, pp. 265-276, 2014.

[2] S. Gee, et al., "Simultaneous Optical Comb Frequency Stabilization and Super-Mode Noise Suppression of Harmonically Mode-Locked Semiconductor Ring Laser Using an Intracavity Etalon," IEEE Photonics Technology Letters, vol 17, no. 1, pp. 199-201, 2004.

[3] M. kuntz, et al., "High-Speed Mode-Locked Quantum-Dot Lasers and Optical Amplifiers," Proceedings of the IEEE, vol 95, no. 9, pp. 1767-1778, 2007.

[4] L. Jaurigue, et al., "Dynamics of a passively mode-locked semiconductor laser subject to dual-cavity optical feedback," Physical Review E, vol 93, no. 2, pp. 022205, 2016.

[5] S. Srinivasan, et al., "Harmonically Mode-Locked Hybrid Silicon Laser With Intra-Cavity Filter to Suppress Supermode Noise," IEEE Journal of Selected Topics in Quantum Electronicsvol 20, no. 4, pp. 8-15, 2014.

[6] S. Keyvaninia, et al., "Narrow-linewidth short-pulse III-V-on-silicon mode-locked lasers based on a linear and ring cavity geometry," Optics express, vol 23, no. 3, pp. 3221-3229, 2015.

[7] A. G. Vladimirov, "Model for passive mode locking in semiconductor lasers," Physical Review A, vol 72, no. 3, pp. 033808, 2005.