Noise Suppression of Hybrid Silicon Mode-Locked Ring Laser Using Intracavity Reflectors

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***Abstract*— We have proposed harmonically hybrid silicon mode-locked ring laser using intracavity reflectors (ICR's) to suppress supermode noise. The dynamic and noise properties of ring laser for without-reflector structures (WOICRS) and proposed structure (PS) are investigated using a delay differential equation model (DDE).**

Keywords*— *intracavity reflector, phase noise, timing jitter, long-ring-cavity mode-locked laser

I. Introduction

The mode-locked laser (MLL) is a special class of laser that produces a time-domain series of short optical pulses at radio frequencies [1]. The major drawback of MLL is large timing jitter owing to the absence of an external reference clock [2]. Long cavity structures are used for generating low-noise pulse train due to their high quality factor. In long cavity lasers, the supermode noise caused by harmonically mode-locked operation is drawback of such structures [3]. Using low-loss silicon waveguides, on-chip long cavity structures can be implemented. In [4], by implementing intracavity filter, RF-linewidth is reduced to 52 KHz. Furthermore, tenth harmonic (H_{10}) regime can be significantly increased compared to without intracavity filter structure [5].

We have presented a modification of long ring MLL by using ICR's to produce harmonic mode-locking (HML). The DDE model is used to investigate the influence of ICR's on the dynamic behavior of passively mode-locked hybrid silicon laser. The timing jitter and phase noise of PS are simulated and compared with WOICRS.

II. Delay Differential Equation Model

Fig. 1 shows the mode-locked hybrid silicon ring laser. The structure has two gain section separated by saturable absorber (SA). A 10:90 directional coupler couples light from ring laser to bus waveguide. Two ICR's positioned on both sides of SA symmetrically, and consequently, the pulse train can be generated in clockwise and counter clockwise direction.

Based on the model proposed in in [5] and [6], in this paper we extend the DDE model to study HML of PS and WOICRS (Fig. 1 (b) and (c)). Noted that we define effective mirror to model the transient grating that is generated in saturable absorber. Equations (1) and (2) describe the slowly varying field amplitude E in WOICRS and PS, respectively. The final set of three coupled DDEs for the field amplitude E, the saturable gain G and the saturable loss Q are

$$\gamma^{-1}\dot{E}(t) = -E(t) + R_0(t-T_0)e^{-i\Delta\Omega T_0}E(t-T_0) + D\xi(t) \qquad (1)$$

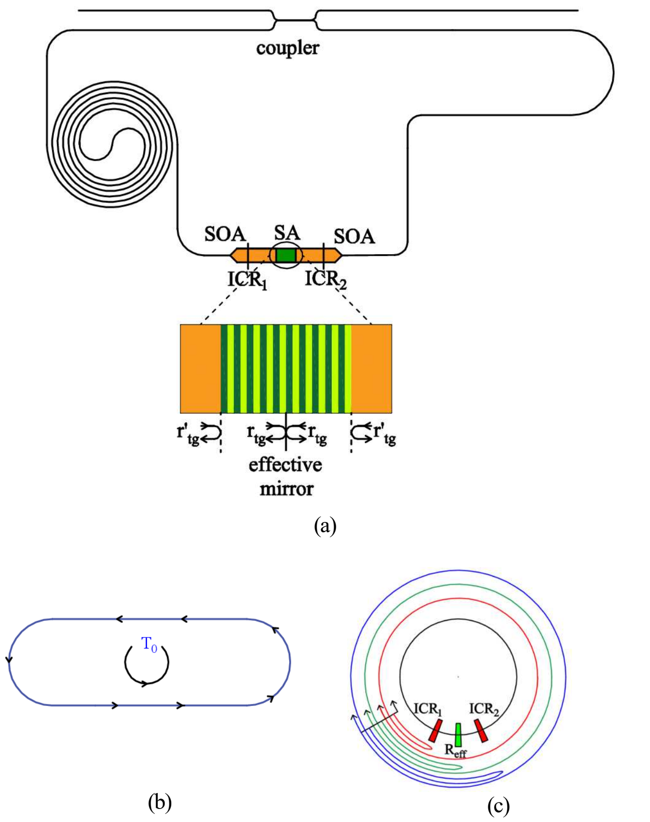


Fig. 1. (a) Schematic of proposed structure and corresponding paths for time delays used for derivation of DDE model in (b) WOICRS and (c) proposed structure.

$$\gamma^{-1}\dot{E}(t) = -E(t) + R_1(t-T_1)e^{-i\Delta\Omega T_1}E(t-T_1) + \sum_{l=1}^{\infty} e^{-ilc-i\Delta\Omega(T_1+l\tau)} \times R_2(t-T_1-l\tau)E(t-T_1-l\tau) + \sum_{l=1}^{\infty} e^{-i2lc-i\Delta\Omega(T_1+2l\tau)} \times R_3(t-T_1-l(2\tau))E(t-T_1-l(2\tau)) + D\xi(t) \qquad (2)$$

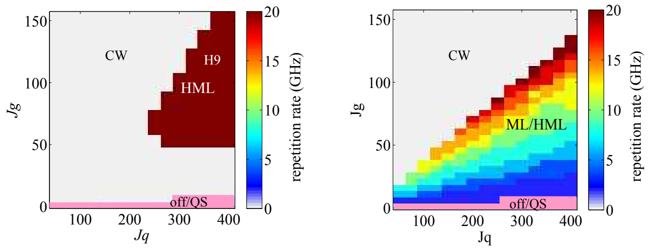
$$\dot{G}(t) = J_g - \gamma_g G(t) - e^{-Q(t)}(e^{G(t)}-1)\,|E(t)|^2 \qquad (3)$$

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

$$R_i(t) = \sqrt{k_i}\,e^{1/2(1-i\alpha_g)G(t)-1/2(1-i\alpha_q)Q(t)} \quad i = 0,1,2,3 \qquad (5)$$

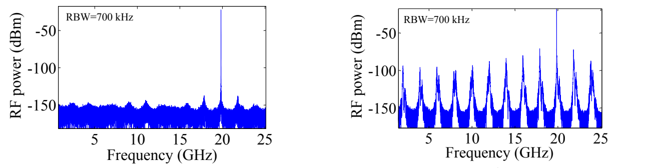
where equations (1), (3) and (4) model the WOICRS (Fig. 1(b)) and equations (2), (3) and (4) model the PS (Fig. 1(c)).

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. The delay time of WOICRS is T_0 and for PS, the DDE is based on three delay time T_1=0.9T_0, τ=0.1T_0 and 2τ. The bandwidth of the laser is taken into



(a) (b)

Fig. 2. Dynamic of repetition frequency for PS (a) WOICRS (b).



(a) (b)

Fig. 3. Electrical spectrum (RBW—700 KHz) of 20 GHz harmonic regime of PS (a) and WOICRS (b).

account by a Lorentzian-shaped filter function with full-width at half maximum (FWHM) γ.

Here l is the number of roundtrips between ICR and effective mirror, and C is the phase of the light due to one roundtrip. $\Delta\Omega$ accounts for a possible detuning between the frequency of the maximum of the gain spectrum and the frequency of the nearest cavity mode. The linewidth enhancement factor in the gain and absorber sections are denoted by α_g and α_q, respectively. Spontaneous emission is modeled in (1) and (2) by a complex Gaussian white-noise term $\xi(t)$ with strength D. In (5), $R_l(t)$ describes the amplification and losses of the electric field during one roundtrip in WOICRS and PS.

III. Simulation Results

Fig. 2 shows dynamic results of WOICRS and PS. 20 GHz harmonic regime can be achieved for WOICRS and PS in H_{10} and H_9, respectively. By using PS, only 20 GHz harmonic regime (H_9) can be produced however, employing WOICRS can generate all of the harmonics (H_1- H_{10}). 20 GHz harmonic regime of Ps, significantly increased and also it can be achieved in lower J_g and J_q compared to WOICRS. We investigate the influence of ICR's on intermediate harmonics by applying discrete fourier transform to the field power (Fig. 3). As shown in Fig. 3(a), ICR's can also suppress the intermediate harmonics, as the intracavity filter proposed in [4]. However in WOICRS, all the harmonic components will be appeared which leads to amplitude distortions in the time domain (Fig. 3(b)).

By considering spontaneous emission noise (D≠0), the fluctuations in arrival times of pulses are appeared. By using the procedure proposed in [7], these fluctuations can be quantified. Phase noise spectrum is obtained for a WOICRS and PS by averaging over M = 30 noise realizations. Subsequently, rms-timing jitter is obtained by integrating the phase noise spectrum over the frequency range from $\nu_{low} = 0.5$ MHz to $\nu_{high} = 5$ GHz. The single side-band phase noise of both WOICRS and PS are plotted in Fig. 4 that shows up 8 dB improvement. The rms-timing jitter of PS normalized to the rms-timing jitter of WOICRS as a function of J_g and J_q., is shown in Fig. 5. As can be seen, the rms-timing jitter of PS

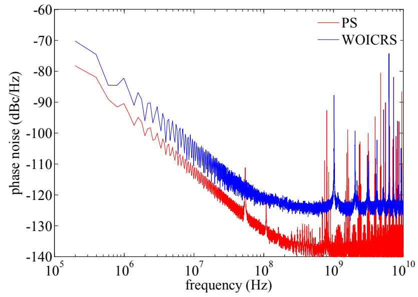


Fig. 4. The single side-band phase noise of PS and WOICRS.

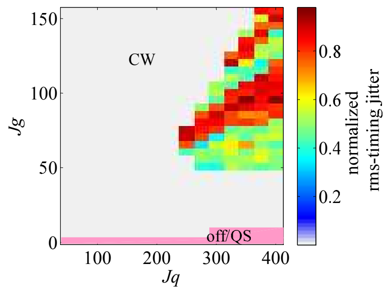


Fig. 5. The rms-timing jitter of PS that is normalized to the rms-timing jitter of WOICRS.

is decreased compared to WOICRS. Also, significant reduction of timing jitter is occurred, periodically.

IV. Conclusion

We have proposed harmonically long ring MLL by using ICR's. The influence of ICR's on dynamic, phase noise and timing jitter has been numerically investigated. In PS, only 20 GHz harmonic regime is produced. Also we find that ICR's can suppress intermediate harmonics. Results show that phase noise and timing jitter are considerably reduced in proposed structure compared to WOICRS.

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