Effect of Nonlinearities on Directed Optical Logic Gates Using Integrated Semiconductor Ring Lasers

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***Abstract*—Nonlinearities in the semiconductor ring laser (SRL) are incorporated in the analysis of directed optical logic gates and their effects on the output are studied. The paper discusses the effects of gain medium linewidth, internal quantum efficiency and self and cross gain saturation on the output of directed optical NOT gate implemented using SRLs.**

I. Introduction

As logic gates are the fundamental elements of data processing and storage, a miniaturized, simple and ultrafast design of all-optical logic gates is needed to implement complex all-optical data processing circuits. There have been several implementations of all-optical logic gates using microring resonators [1], spatial soliton interactions [2], parallel SOA-MZI structure [3] etc. The author has demonstrated a simple design of all-optical NOT and XOR gates using semiconductor ring lasers (SRL) in previous publication [4]. SRLs have very rich nonlinear properties which have been harnessed for variety of applications. These nonlinearities such as laser linewidth, self and cross gain saturation and internal quantum efficiency degrade the performance of logic gates. In this paper, the effect of above mentioned nonlinearities on the operation of directed logic NOT gate is analyzed. Such an analysis helps in identifying parameters that critically affect the performance of logic gates and other optical computing elements made out of them.

II. Proposed Design and Simulation Method

The proposed design of directed logic all-optical NOT gate is as shown in Fig. 1 and its detailed working is explained in our previous publication [4].

In order to analyze the effect of nonlinearities, the SRLs can be modeled using phenomenological rate equations describing the evolution of electric fields inside the ring cavity as [5]

$$\frac{dE_{cw}}{dt} = i(\omega - \Omega)E_{cw} + 0.5v_g[\Gamma g_g(n-n_0)(1-\epsilon_s|E_{cw}|^2 - \epsilon_c|E_{ccw}|^2) - \alpha_{int}]E_{cw} - (k_d + ik_c)E_{ccw} \quad (1)$$

$$\frac{dE_{ccw}}{dt} = i(\omega - \Omega)E_{ccw} + 0.5v_g[\Gamma g_g(n-n_0)(1-\epsilon_s|E_{ccw}|^2 - \epsilon_c|E_{cw}|^2) - \alpha_{int}]E_{ccw} - (k_d + ik_c)E_{cw} \quad (2)$$

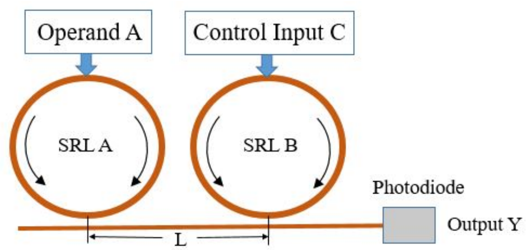

Fig. 1: Schematic design of directed logic optical NOT gate

$$\frac{dn}{dt} = \frac{\eta_i I}{q} - n(c_1 + c_2 n + c_3 n^2) - v_g \Gamma g_g(n-n_0)[(1-\epsilon_s|E_{cw}|^2 - \epsilon_c|E_{ccw}|^2)|E_{cw}|^2 + (1-\epsilon_s|E_{ccw}|^2 - \epsilon_c|E_{cw}|^2)|E_{ccw}^2|] \quad (3)$$

where E_{cw}, E_{ccw} are electric field propagating in the clockwise (CW) and counterclockwise (CCW) directions inside the SRL and n is the carrier concentration inside the SRL active medium while detailed description of other parameters are given in [5]. The outputs of SRLs are the corresponding E_{cw} and E_{ccw} which are coupled into the bus waveguide and the final output of logic gate is given by the photodiode output which is proportional to optical intensity i.e. $|E_{ccw}|^2$.

III. Simulation Results and Conclusions

A. Gain Bandwidth

Bandwidth of the semiconductor gain medium ($\Delta\nu$) affects the gain of SRL as [6]

$$g_g(\nu) = \frac{g_g(\Delta\nu/2)^2}{(\nu-\nu_0)^2 + (\Delta\nu/2)^2} \quad (4)$$

where ν_0 is the peak gain frequency and ν is the operating frequency. Thus, gain at the operating frequency ($g_g(\nu)$) increases with increase in the bandwidth. On the other hand, reduction in the bandwidth causes distortion in the output of SRL and consequently the output of logic gates, as shown in Fig. 2 (a). For efficient operation of logic gates, higher bandwidths of SRL are desired. As the proposed design consists of two SRLs in cascade, higher bandwidth can be easily achieved by designing both SRLs of different lengths [7]. But such a design will result in different optical power at

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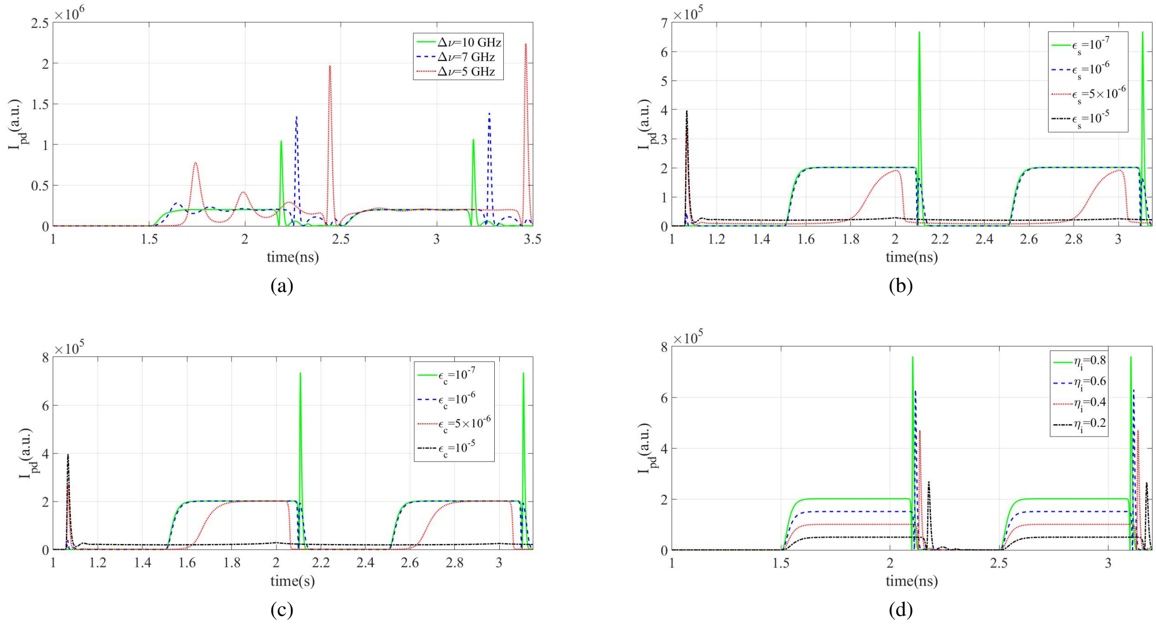

Fig. 2: Variations in the output of all-optical directed logic NOT gate caused by (a) gain medium linewidth (b) self gain saturation, (c) cross gain saturation and (d) internal quantum efficiency of SRL respectively.

the output of each SRL, thus causing the 0-level of the output to increase.

B. Gain Saturation

The self and cross gain saturation coefficients affect the steady state values of optical intensity (I_0) and charge carrier concentration (N_0) of SRL as given by [8]

$$I_0 = \frac{2(N_0 - 1 + k_d)}{(\epsilon_s + \epsilon_c)N_0} \tag{5}$$

$$N_0 = \frac{1}{1 + I_0 - (\epsilon_s + \epsilon_c)I_0^2} \tag{6}$$

Thus an increase in the self and cross gain saturation coefficients causes a decrease in the optical intensity of SRL and also decreases the pulse width of the output signal as shown in Fig. 2 (b) and Fig. 2 (c) respectively.

C. Internal Quantum Efficiency

Internal quantum efficiency (η_i) denotes the fraction of injection current that generates photons in the active region. It is associated with the loss of charge carriers that recombine in the regions other than the active medium. Thus, a lower value of η_i implies lower electrical to optical conversion efficiency leading to lower intensity at the output of SRL. This causes a reduction in the magnitude of 1-level of the NOT gate output and corresponding lowering of eye opening as shown in Fig. 2 (d).

In conclusion, it is demonstrated through simulations that nonlinearities in SRL such as linewidth, self and cross gain saturation and internal quantum efficiency degrade the performance of all-optical directed logic NOT gate. The performance degradation manifests itself through lowering of logic ’1’ level and reduction in the pulse width of the output pulses.

References

[1] Q. Xu and M. Lipson, “All-optical logic based on silicon micro-ring resonators,” *Optics express*, vol. 15, no. 3, pp. 924–929, 2007.

[2] A. Ghadi and S. Sohrabfar, “All-optical multiple logic gates based on spatial optical soliton interactions,” *IEEE Photonics Technology Letters*, vol. 30, no. 6, pp. 569–572, 2018.

[3] Y.-D. Wu, T.-T. Shih, and M.-H. Chen, “New all-optical logic gates based on the local nonlinear mach-zehnder interferometer,” *Optics Express*, vol. 16, no. 1, pp. 248–257, 2008.

[4] A. Khandelwal, “Design and modeling of 1 gbps directed optical xor/or gates using integrated semiconductor ring lasers,” in *2019 International Conference on Numerical Simulation of Optoelectronic Devices (NUSOD)*. IEEE, 2019, pp. 129–130.

[5] M. Sorel, G. Giuliani, A. Scire, R. Miglierina, S. Donati, and P. Laybourn, “Operating regimes of gaas-algaas semiconductor ring lasers: experiment and model,” *IEEE Journal of Quantum Electronics*, vol. 39, no. 10, pp. 1187–1195, 2003.

[6] B. E. Saleh, M. C. Teich, and B. E. Saleh, *Fundamentals of photonics*. Wiley New York, 1991, vol. 22.

[7] A. Matsumoto, K. Kuwata, A. Matsushita, K. Akahane, and K. Utaka, “Numerical analysis of ultrafast performances of all-optical logic-gate devices integrated with inas qd-soa and ring resonators,” *IEEE Journal of Quantum Electronics*, vol. 49, no. 1, pp. 51–58, 2013.

[8] M. Sorel, P. Laybourn, A. Scirè, S. Balle, G. Giuliani, R. Miglierina, and S. Donati, “Alternate oscillations in semiconductor ring lasers,” *Optics letters*, vol. 27, no. 22, pp. 1992–1994, 2002.