Design and Modeling of 1 Gbps Directed Optical XOR/OR Gates Using Integrated Semiconductor Ring Lasers

Arpit Khandelwal
Department of Electrical Engineering, Indian Institute of Technology Jodhpur
Email: arpitkhandelwal@iitj.ac.in

***Abstract*—A novel design of optical XOR/OR gate operating at 1 Gbps and implemented by directed logic using integrated semiconductor ring lasers is presented. The proposed design is simple to implement with no optical non-linearities required for switching operation. Modeling of proposed logic gates is performed using the rate equations for counter-propagating electric fields inside the ring lasers.**

I. Introduction

There has been considerable research in the field of optical logic gates and numerous designs have been presented based on microring resonators [1], spatial soliton interaction [2], parallel SOA-MZI structure [3], silicon nanowires etc. Out of these, logic gates made using microring resonators are simple and compact which can be easily fabricated on a Photonic Integrated Circuit (PIC). Most of the designs involving microring resonators use optical nonlinear effects such as two photon absorption, four wave mixing, cross phase modulation [3] or injection locking [4] to perform logical operations on optical signals. Although very high switching speed has been reported using these devices, they use optical operands and are highly dependent on the nonlinear effects.

In this paper, a novel and simple optical gate design has been presented using semiconductor ring lasers (SRL) which performs logical operation on electrical input signals and gives corresponding output in electrical domain. Such a design can be used to complement the highly developed electronic signal processing and speed-up the critical computations. As none of the optical nonlinear processes are used for logical operations, no special modification in the ring laser structure is required. Theoretical simulations show switching speed of 1 Gbps which is comparable to that achieved using complex electronics.

II. Proposed Design and Operation Principle

The design of proposed optical XOR and OR gate uses two electrically pumped SRLs (SRL A and SRL B) with same radius as shown in Fig 1. The electrical signals on which logic operations are to be performed are used as pumping sources for both the SRLs which are coupled to a single straight bus waveguide extracting useful optical signals. A reverse biased photodiode fabricated at the end of bus waveguide acts as an output element giving an electrical signal equivalent to the XOR/OR of inputs.

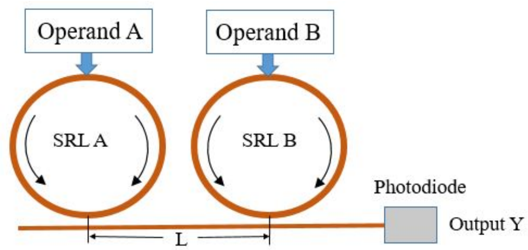

Fig. 1: Schematic design of directed logic optical XOR/OR gate

When both the inputs are at logic '0' i.e. A=B=0, both the SRLs are not pumped and hence no lasing is observed. Thus, the output of photodiode Y=0. When either of the inputs are at logic '1', i.e. A=1 or B=1, one of the SRLs starts lasing and the photodiode output will be constant DC signal proportional to the intensity of the lasing SRL, i.e. Y=1. When both the inputs are at logic '1', the output of photodiode will depend upon the resultant intensity of the interference of optical signals from SRL A and SRL B. As both the SRLs have same radius, their lasing frequencies will be same and hence the resultant intensity will be dependent only on the phase difference due to different path length of the two optical signals. If intensities of both optical signals are equal and separation 'L' between SRL A and SRL B is an integer multiple of $\lambda/2$, where λ being the lasing wavelength of SRLs, complete destructive interference will occur between the optical signals. Thus, the resultant intensity will be zero and output of photodiode will also be zero i.e. Y=0. Thus, the design with $L = n\lambda/2$ mimics the function of an XOR gate.

When the separation between SRL A and SRL B is an integer multiple of $2\lambda/3$, the corresponding phase shift between their output optical signals will be 240^0. Thus, the resultant intensity when A=1, B=1 will be equal to the intensity of single optical signal and the corresponding output of photodiode will again be proportional to intensity of single optical signal i.e. Y=1. Thus, for $L = 2n\lambda/3$, output of photodiode will be high when both the inputs are high, behaving as a OR gate.

III. Simulation Method

The SRLs can be modeled using rate equations describing the evolution of electric fields inside the ring cavity as [5]

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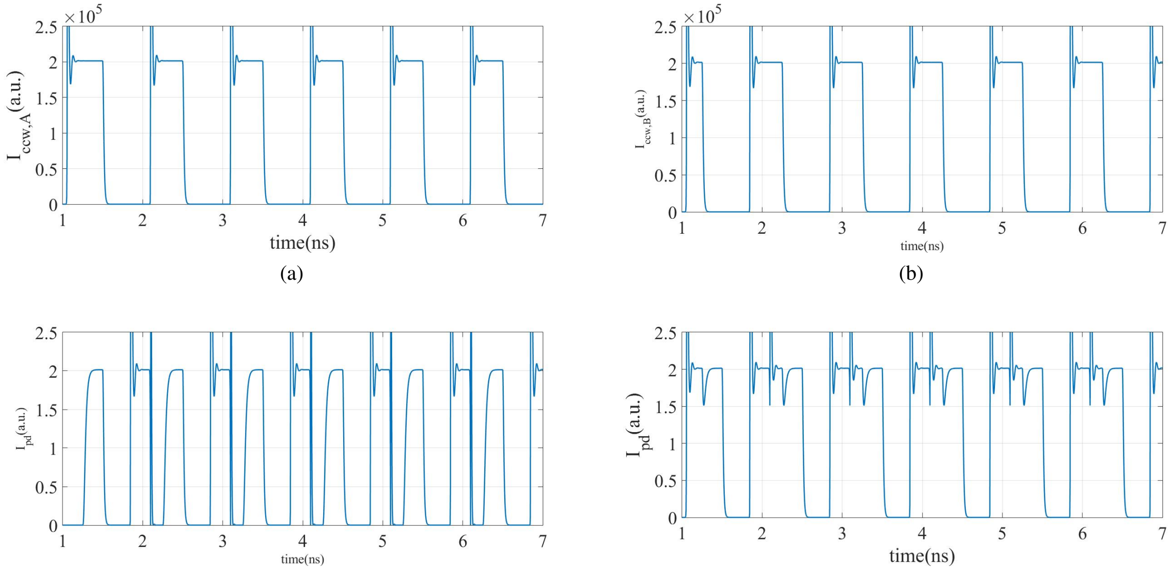

(a) (b) (c) (d)

Fig. 2: Output intensity of (a) SRL A, (b) SRL B and (c) output of photodiode corresponding to XOR and (d) OR operation.

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

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

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

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. $|E_{ccw}|^2$.

IV. Simulation Results and Conclusions

The rate equations (1), (2) and (3) are solved simultaneously for SRL A and B using standard values of all the relevant parameters [6]. The input injection current (I) to both the SRLs is a square wave electrical signal of 1 GHz frequency which act as operand. The corresponding SRL output intensity (calculated as $|E_{ccw}|^2$) also follows the same square wave pattern as shown in Fig. 2(a) and (b). The resultant intensity, depending on the separation (L) between the two SRLs, is converted into equivalent electrical signal by the photodiode. The output current of photodiode (I_{pd}) in case of XOR gate and OR gate is shown in Fig. 2(c) and Fig. 2(d) respectively.

In conclusion, a novel design for directed optical logic gates (XOR/OR) operating at 1 Gbps using integrated semiconductor ring lasers is presented in this paper. The design is simple and does not involve any optical nonlinear process for performing logical operations. Moreover, as the input and outputs are in electrical domain, the proposed design can be used as an interface between conventional electronic circuits to speed up the computation process. The complete qualitative and quantitative description of SRL nonlinearities on the performance of proposed logic gates will be the topic of further study.

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