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Effect of various parameters on working of all-optical Schmitt trigger

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ABSTRACT

Schmitt triggers (ST) are well known and very widely used in the field of communications and signal processing techniques. It is robust, less sensitive to noise and is a building block in analog to digital converters. This work concentrates on all-optical Schmitt trigger for the purpose of using it in the field of optical modulation and signal processing. As the size of ring lasers is small these devices are best to use on a single integrated photonic chip. In this paper various dynamic effects of a binary Schmitt trigger is simulated and discussed. Control on various properties such as size of the ring, gain of SOA of a Schmitt trigger enables one to use it in developing all-optical devices.

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1. Introduction

Micro-ring lasers attracted a lot of research work to develop integrated photonic devices as the size was reduced to micrometer level [1–3]. A various all-optical devices using ring lasers such as Flip-flops, filters, reflectors have been proposed [4–6]. In line with this an all optical Schmitt trigger was also proposed and designed [7]. As the output of conventional Schmitt trigger is bipolar (1, –1), it is almost not possible to use for optical purposes. Taking the difference of the phase values of light is also a current day challenge which was been attempted before. Binary Schmitt trigger can be applied and used for optical purposes such as analog to digital converters as it has to deal with only positive signals (0, 1). In our previous work [7], an all-optical Schmitt trigger was designed and simulated using ring lasers of 12 μm diameter. The advantages involve low power consumption and small size of the devices to be mounted on a single photonic integrated chip. Phenomenon of injection locking was used for the purpose of building Schmitt trigger. In this phenomenon, a strong light beam from the master laser is injected into a slave laser. If this injected light is close to the resonant peak of the slave laser, injection locking occurs which means that light emits at the frequency of master laser. In order to extinguish lasing of any laser, an external light with frequency other than lasing frequency of the slave laser should be injected in the cavity of ring laser [8–10]. As the process of coupling is used to inject light in the cavity, study on coupling characteristics and switching behavior of the semicon-

ductor ring lasers [11–13] was very useful in designing of all-optical devices.

Through reduction of switching times and having control on coupling between lasers many devices can be designed and developed. Role of various parameters such as gain of Semiconductor Optical Amplifier (SOA), size of the ring, carrier life-time is very essential in order the Schmitt trigger to be used in ADCs and other all optical devices. Also, to boost up the performance of Schmitt trigger, it is important to know the impact of factors effecting the working of it, so that they can be controlled. Therefore in this work the effect of process parameters and external factors on the working of schmitt trigger is studied and simulation results of the same are presented.

2. Design and simulation of Schmitt trigger

A schematic of Schmitt trigger employed with two coupled ring lasers is shown in Fig. 1. Two ring lasers, ring A and ring B each contain a single mode laser beam in uni-direction. This can be achieved by placing a directional isolator inside the passive part of ring laser. Let the single mode in ring A be denoted by S_A and in ring B by S_B where S is a notation of photon numbers. The electric field associated with the modes inside the rings E_0 is normalized with the photon numbers S as $E_0^2 = S$.

2.1. Operation

By definition, when the input to the Schmitt trigger is higher than a threshold value, the output will be at a maximum value and if the input is less than another lower threshold value the output jumps to a minimum value. In terms of two ring lasers coupled with

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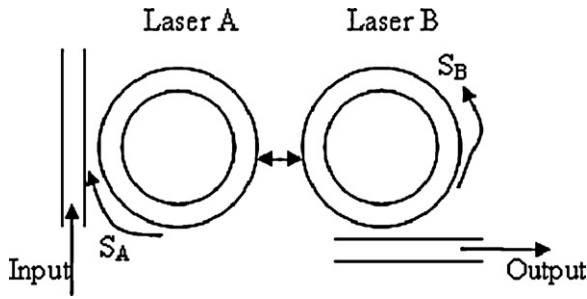


Fig. 1. All-optical Schmitt trigger using two ring lasers.

Table 1
Symbol and its significance.

Symbol	Explanation	
S	Photon numbers	
γ	Phase associated with E field V_g	Group velocity (8.57e9 cm/s)
τ_e	Carrier lifetime	
τ_p	Photon lifetime	
N_A, N_B	Number of carriers in laser	
G_A, G_B	Gain of the SOA	
I_A, I_B	Injection currents	
q	Charge of electron (1.6e-19 C)	
a	Differential gain	
ε	Non linear gain suppression factor (6.3e-7)	
N_o	No. of carriers at transparency (9.05e6)	
η_i	Internal quantum efficiency	
V_p	Photon reservoir volume (3e-11 cm ³)	

input reaches another threshold value of 4.2×10^5 photon numbers at which the output jumps back to the low state.

3. Effect of various parameters on the performance of Schmitt trigger

In designing all optical devices employing ring lasers it is essential to know the operation and effects of a variety of parameters. In this section effect of parameters such as gain, injection current, frequency of external input, carrier lifetime, size of the ring laser, and group velocity on the Schmitt trigger is discussed.

3.1. Effect of differential gain (a)

The relation between the differential gain of the ring lasers and the hysteresis loop of Schmitt trigger is presented in this section. Initially the gain of the ring laser was set at 10^{-5} . The output photon numbers of the ST is plotted with respect to input photon numbers at different gains viz. gain being twice (black) and then for halved (red) (for interpretation of the references to color in the text, the reader is referred to the web version of the article) the initial gain. It is observed from Fig. 3, when the differential gain is increased

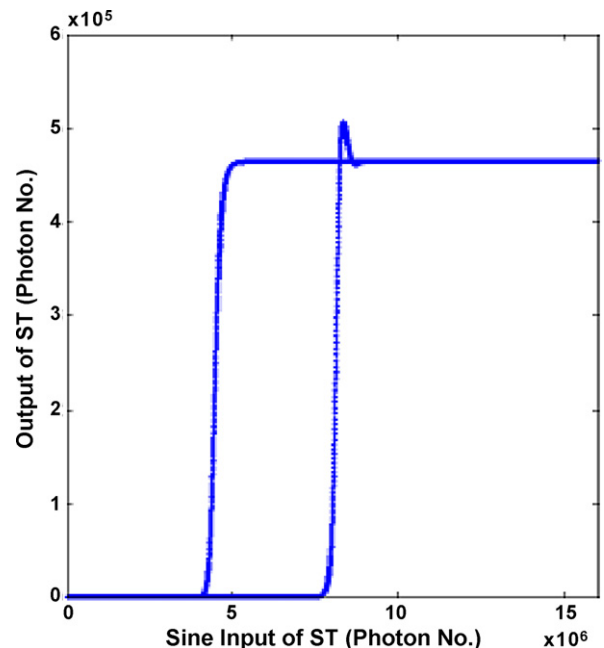


Fig. 2. Transfer function of Schmitt trigger showing hysteresis.

each other the operation of Schmitt trigger is as follows. Initially, the injection current of laser A is kept higher than that of laser B so that laser A is master and laser B is slave. With no input or zero input, the master laser A suppresses the slave laser B so that the Schmitt trigger output is low (at a minimum value). When an input is given to master laser or injected into master laser, the mode inside it gradually reduces and finally extinguishes. If the power of master laser suppressing the slave laser B reduces and becomes less than that of slave laser, then laser B starts lasing and the output jumps to a maximum value. Similarly as the input injected into laser A starts reducing (as in sinusoidal signal) and reaches below a lower threshold value, master laser starts to lase and suppress back the slave laser, hence the output of Schmitt trigger will be low again. Rate equations of the Schmitt trigger with a single mode in one direction are given below.

$$\dot{N}_A = \frac{\eta_i I_A}{q} - \frac{N_A}{\tau_e} - V_g G_A (S_A + S_B + S_{input}) \quad (1)$$

$$G_A = \frac{(a/V_p)(N_A - VN_o)}{1 + (\varepsilon/V_p)(S_A + S_B + S_{input})} \quad (2)$$

$$\dot{S}_A = \left(V_g G_A - \frac{1}{\tau_p} \right) S_A + \frac{1}{\tau_p} \quad (3)$$

$$\dot{\gamma}_A = -\frac{\alpha}{2} \left(V_g G_A - \frac{1}{\tau_p} \right) \quad (4)$$

$$\dot{N}_B = \frac{\eta_i I_B}{q} - \frac{N_B}{\tau_e} - V_g G_B (S_A + S_B) \quad (5)$$

$$G_B = \frac{(a/V_p)(N_B - VN_o)}{1 + (\varepsilon/V_p)(S_A + S_B)} \quad (6)$$

$$\dot{S}_B = \left(V_g G_B - \frac{1}{\tau_p} \right) S_B + \frac{1}{\tau_p} \quad (7)$$

$$\dot{\gamma}_B = -\frac{\alpha}{2} \left(V_g G_B - \frac{1}{\tau_p} \right) \quad (8)$$

The explanations of symbols and values used in the above rate equations are explained in Table 1. The device parameters selected are realistic using which fabrication and theoretical study is done [14].

2.2. Working

A sinusoidal input at frequency 300 MHz is applied to the Schmitt trigger and the transfer function is observed which is shown in Fig. 2. Hysteresis occurs as expected which shows that the two coupled ring lasers are operating as Schmitt trigger. The transfer function shows that as input increases, output (S_B) is at its low state until the input reaches a threshold value of 8×10^5 photon numbers at which the output jumps to the high state. As the injected input decreases the output maintains at high state until the

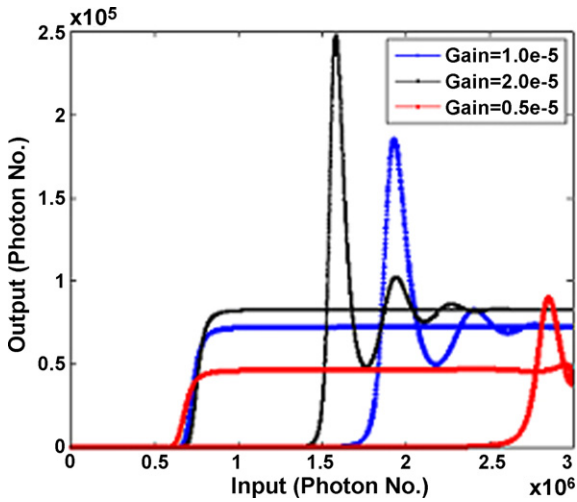


Fig. 3. Transfer function plot with varying SOA gains.

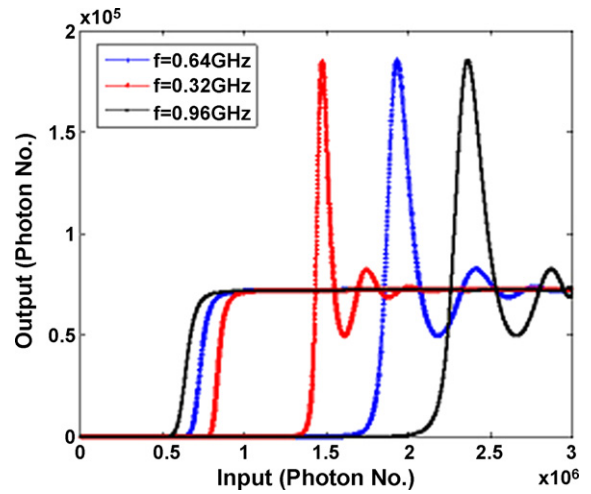


Fig. 5. Transfer function plot with varying input frequency.

(black), the hysteresis loop gets narrower, with a decrease in upper threshold value and increase in amplitude of the output. On the other hand, the upper threshold value of Schmitt trigger with low gain is at a higher value than that of high gain making the loop wider. There is no effect on lower threshold value in any case.

3.2. Effect of injection current

A comparison is made by varying the injection currents given to the ring lasers. The ratio of the injection currents between the ring lasers A and B is kept constant at 10. The injection currents given to lasers A and B are $I_A = 2.5I$ and $I_B = 0.25I$ respectively. Three cases are studied and presented viz. with $I = 60$ mA, 90 mA and 120 mA which is shown below in Fig. 4. The blue color graph is the transfer function with current at 90 mA. With increase in injection current to 120 mA, the hysteresis loop shifts towards right (black). The Schmitt trigger with higher value of injection current switches on and off later than that with a smaller value of injection current, shifting the hysteresis loop towards the right. In this case both upper and lower threshold values got affected.

3.3. Effect of frequency of the external input

The frequency of the external input also affects the hysteresis loop of the Schmitt trigger. In order to observe this effect, the fre-

quency of the signal injected into the Schmitt trigger is varied. As can be seen in Fig. 5, the increase in frequency, broadens the hysteresis loop. When the input sinusoidal wave frequency is 0.32 GHz, the hysteresis loop (red) starts later than that when the frequency is 0.96 GHz (black). At the lower frequency the upper threshold value is at a lower value than that at higher frequency making the loop narrower. This broadening of hysteresis loop is due to the delay in the ring lasers with respect to high frequency input signal. This effect helps to find the frequency limit of a Schmitt trigger.

3.4. Effect of carrier lifetime (τ_e)

The effect of Carrier lifetime, denoted by τ_e , on the performance of Schmitt trigger is shown in Fig. 6. As the value of τ_e increases (black) the upper threshold value decreases but the lower threshold value remains same. With decrease of τ_e value (red), the amplitude of the output decreases and the upper threshold value changes to a higher value. The effect of the carrier lifetime is looks similar to the effect of differential gain.

3.5. Effect of size of the ring lasers

As the diameter of the ring laser increases the hysteresis loop shifts to the right with increase in amplitude. This effect is shown in Fig. 7. With increase in size, the lower and upper threshold

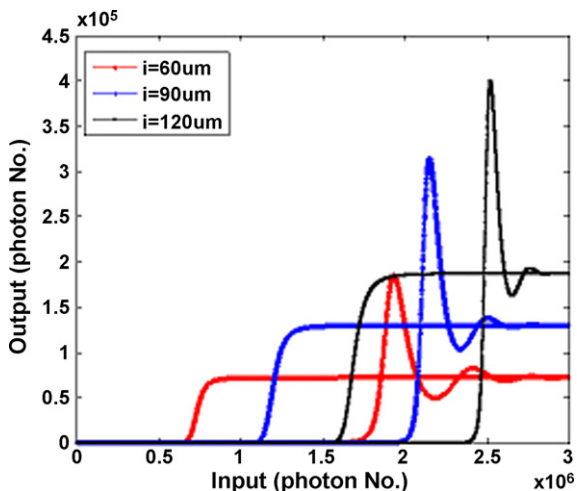


Fig. 4. Transfer function plot with varying injection currents.

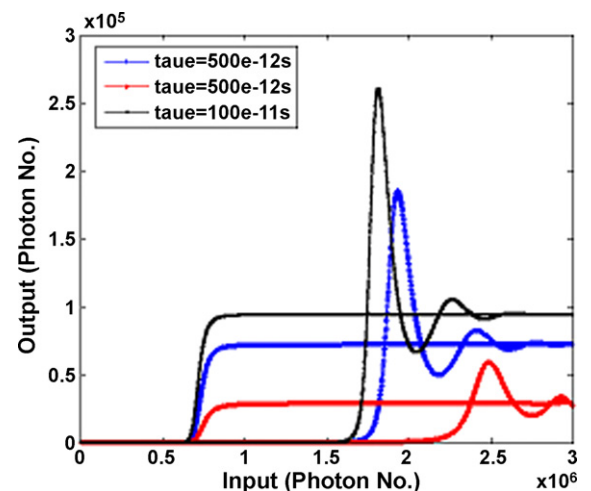


Fig. 6. Transfer function plot with varying carrier life-times.

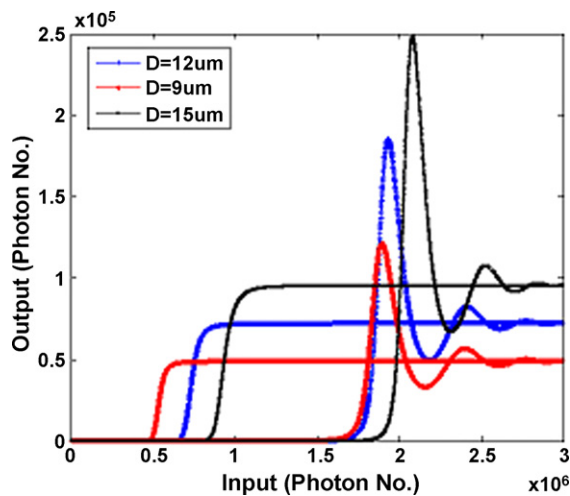


Fig. 7. Transfer function plot with varying ring diameters.

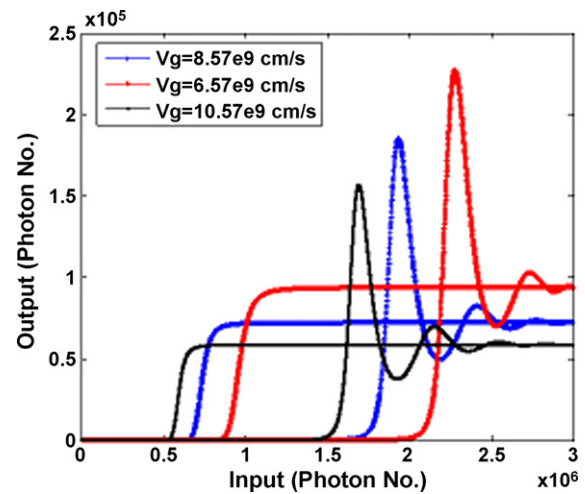


Fig. 9. Transfer function plot with varying group velocities.

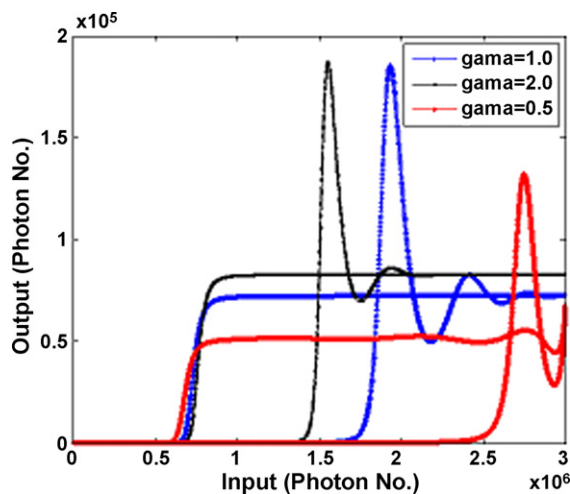


Fig. 8. Transfer function plot with varying confinement factors.

values occurs at higher values when compared to that of smaller size of ring laser, shifting the hysteresis loop (black) towards right. Whereas, the reduction in size reduces the amplitude of the output (red) with a slight shift towards left. This effect is similar to the effect of injection currents.

3.6. Effect of confinement factor (γ) and group velocity (v_g)

The ratio of volumes occupied by electrons to that of photons is known as confinement factor. As the confinement factor increases, the amplitude of the output of the Schmitt trigger (black) also increases as shown in Fig. 8. The upper threshold value of the hysteresis loop reduces whereas the lower threshold value remains same. Therefore it can be said that the hysteresis loop widens with decrease of confinement factor, an effect similar to that of differential gain.

The hysteresis loop of the Schmitt trigger shifts towards left and the amplitude of the output decreases with increase in group velocity as shown in Fig. 9.

4. Conclusion

The design of the Schmitt trigger which is a building block of ADCs along with its rate equations is presented. Effect of different parameters of ring laser on dynamics of Schmitt trigger is discussed which gives future designers a direction to design various all-optical devices.

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References

- [1] M.T. Hill, H.J.S. Dorren, T. de Vries, X.J.M. Leijtens, J.H. den Besten, B. Smalbrugge, Y.-S. Oei, H. Binsma, G.-D. Khoe, K.S. Meint, A fast low-power optical memory based on coupled micro-ring lasers, *Nature* 432 (2004) 206–209.
- [2] S.C. Hagness, D. Rafizadeh, S.T. Ho, A. Taflove, FDTD microcavity simulations: design and experimental realization of waveguide-coupled single-mode ring and whispering-gallery-mode disk resonator, *J. Lightwave Technol.* 15 (1997) 2154–2165.
- [3] Z. Wang, V. Guy, Y. Shu, G. Mezosi, M. Sorel, J. Danckaert, S. Yu, Integrated small-sized semiconductor ring laser with novel retro-reflector cavity, *IEEE Photonics Technol. Lett.* 20 (2008) 99–101.
- [4] M.T. Hill, H. de Waardt, G.D. Khoe, H.J.S. Dorren, All-optical flip-flop based on coupled laser diodes, *IEEE J. Quantum Electron.* 37 (2001) 405–413.
- [5] M.R. Sayeh, A. Siahmakon, All optical binary delta-sigma modulator, *SPIE* 5970 (2005), 0P1–0P7.
- [6] J.K.S. Poon, J. Scheuer, A. Yariv, Wavelength-selective reflector based on a circular array of coupled microring resonators, *IEEE Photonics Technol. Lett.* 16 (2004) 1331–1333.
- [7] A. Syed, M.R. Sayeh, Design and simulation of all-optical Schmitt trigger using semiconductor ring lasers, in: *Proc. Photonics*, New Delhi, India, 2008.
- [8] H. Yokoyama, S.D. Brorson, Rate equation analysis of microcavity lasers, *J. Appl. Phys.* 66 (1989) 4801–4805.
- [9] R. Lang, Injection locking properties of a semiconductor laser, *IEEE J. Quantum Electron.* QE-18 (1982) 976–983.
- [10] I. Petitbon, P. Gallion, G. Debarge, C. Chabran, Locking bandwidth relaxation oscillations of an injection-locked semiconductor laser, *IEEE J. Quantum Electron.* 24 (1988) 148–154.
- [11] A. Yariv, Critical coupling its control in optical waveguide-ring resonator systems, *IEEE Photonics Technol. Lett.* 14 (2002) 483–485.
- [12] V. Van, T.A. Ibrahim, K. Ritter, P.P. Absil, F.G. Johnson, R. Grover, J. Goldhar, P.T. Ho, All-optical nonlinear switching in GaAs-AlGaAs microring resonators, *IEEE Photonics Technol. Lett.* 14 (2002) 74–76.
- [13] J. Wang, M.K. Haldar, F.V.C. Mendis, Equivalent circuit model of injection-locked laser diodes, *Microw. Opt. Technol. Lett.* 18 (1998) 124–126.
- [14] L. Coldren, S. Corzine, *Diode Lasers and Photonic Integrated Circuits*, Wiley Series, 1995.