2011 International Conference on Network and Electronics Engineering
IPCSIT vol.11 (2011) © (2011) IACSIT Press, Singapore

Optical and Logic Gate Implementation using Four Wave Mixing in Semiconductor Optical Amplifier for High Speed Optical Communication Systems

Arez Nosratpour[1+], Mohammad Razaghi[2]

[1] Department of Electrical Engineering, Arak Branch, Islamic Azad University, Arak, Iran

[2] Department of Electrical and Computer Engineering, University of Kurdistan, Sanandaj, Iran

Abstract. A simple scheme for an all-optical AND gate, based on four-wave mixing (FWM) in semiconductor optical amplifier (SOA) is studied. In our proposed scheme an SOA and an optical filter are used, while an additional continuous-wave signal is absent. We have numerically studied four-wave mixing in semiconductor optical amplifier by the finite-difference beam propagation method (FD-BPM). We used the nonlinear propagation equation taking into account gain spectrum dynamic gain saturation which depends on carrier depletion (CD), carrier heating (CH), spectral hole burning (SHB), group velocity dispersion (GVD), self-phase modulation (SPM), and two photon absorption (TPA). The pattern effect in this scheme has been fully reviewed.

Keywords: Semiconductor optical amplifier, Four wave mixing, Nonlinear effects, Optical logic gate, pattern effect

1. Introduction

All-optical AND gate is an important logic unit for optical communication. All-optical logic gates are based on the nonlinear effects in semiconductor optical amplifier (SOA), such as cross gain modulation (XGM), cross-phase modulation (XPM), four-wave mixing (FWM), and cross-polarization modulation (XPolM).

Various schemes for optical AND gate are proposed, by using cross gain modulation (XGM) [1], AND gate by using cross polarization modulation [2], AND gate using a semiconductor optical amplifier (SOA) based on Mach-Zehnder interferometer (SOA-MZI) [3], AND gate by four-wane mixing (FWM) with polarization- shift-keying (PolSK) modulated signals [4], AND gate using an SOA assisted by optical filter [5], and AND gate based on four-wane mixing (FWM) [6].

In this paper, we propose and theoretical demonstrate an all- optical AND gate by utilizing FWM in an SOA with considering all nonlinear parameters in SOA including carrier depletion (CD), carrier heating (CH), spectral hole burning (SHB), group velocity dispersion (GVD), self-phase modulation (SPM), and two photon absorption (TPA). Modified nonlinear Schrödinger equations for modelling wave propagation in an SOA is used [7]-[8]. This equation is solved by finite difference beam propagation method (FD-BPM) [8], [9]. The BPM is widely used for the analysis of the field distribution in optical waveguides and optical pulse propagation in fibers [10]. Based on the simulation time and results, we used the FD-BPM, because of short convergence time and excellent accuracy of the results [9-11].

The paper is organized as follows; sect. 1 is introduction, sect. 2 is optical logic gate configuration, sect. 3 is theory of the model, the equations which govern the dynamics of the amplification process, sect. 4 is simulation results and discussion and finally conclusions in sect. 5

+ Corresponding author. Tel.: + (988717282791); fax: +(988716667445).
E-mail address: (arez_nosrat@yahoo.com).

2. Optical logic gate configuration

As shown in figure. 1, an AND gate operates on two serial optical return-to-zero (RZ) signals (Data1 and Data2).Data1 and Data2 are pump and probe signals, respectively. When two data streams at different central frequencies of f_p (pump) and f_q(probe) are injected into SOA simultaneously, the FWM signal is generated in the SOA at the frequency of $2f_p - f_q$, that is equivalent to the logic AND operation between the two input signals. As it can be seen in Table 1, only if both input signals are present the FWM occur (which is equal to logic one), and in other modes FWM does not occur (which is equal to logic zero).

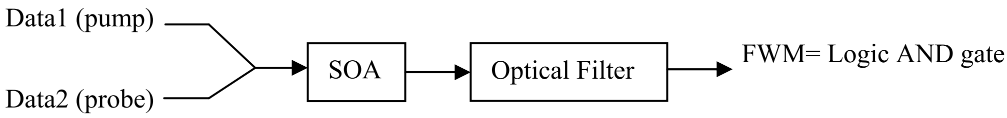


Fig. 1: Schematic diagram of AND gate

Table 1: AND logic operation

Data1(pump)	Data2(probe)	AND (FWM)
0	0	0
0	1	0
1	0	0
1	1	1

3. Theory of the model

The model we have used for simulation of SOA and obtain the logic gate is based on modified nonlinear Schrödinger equation (MNLSE) which explains the propagation of optical pulse in the SOA [8].

$$\left[\frac{\partial}{\partial z} - \frac{i}{2}\beta_2\frac{\partial^2}{\partial\tau^2} + \frac{\alpha_{int}}{2} + \left(\frac{\gamma_{2p}}{2} + ib_2\right)|A(\tau,z)^2|\right]A(\tau,z)$$
$$= \left\{\frac{1}{2}g_N(\tau)\left[\frac{1}{f(\tau)} + i\alpha_N\right] + \frac{1}{2}\Delta g_T(\tau)(1 + i\alpha_T)\right.$$
$$\left. -i\frac{1}{2}\frac{\partial_g(\tau,\omega)}{\partial\omega}\bigg|_{\omega_0}\frac{\partial}{\partial\tau} - \frac{1}{4}\frac{\partial^2 g(\tau,\omega)}{\partial\omega^2}\bigg|_{\omega_0}\frac{\partial^2}{\partial\tau^2}\right\}A(\tau,z) \tag{1}$$

Where, $A(z,\tau)$ is the complex envelope function of an optical pulse. and here:

$$g_N(\tau) = exp\left(-\frac{1}{E_{sat}}\int_{-\infty}^{\tau} e^{-s/\tau_s}|A(s)|^2 ds\right) \tag{2}$$

$$f(\tau) = 1 + \frac{1}{\tau_{shb}P_{shb}} \times \int_{-\infty}^{+\infty} u(s)e^{-s/\tau_{shb}}|A(\tau - s)|^2 ds \tag{3}$$

$$\Delta g_T(\tau) = -h_1\int_{-\infty}^{+\infty} u(s)e^{-s/\tau_{ch}} \times \left(1 - e^{-s/\tau_{shb}}\right)|A(\tau - s)|^2 ds$$
$$-h_2\int_{-\infty}^{+\infty} u(s)e^{-s/\tau_{ch}} \times \left(1 - e^{-s/\tau_{shb}}\right)|A(\tau - s)|^4 ds \tag{4}$$

$$\frac{\partial g(\tau,\omega)}{\partial\omega}\bigg|_{\omega_0} = A_1 + B_1[g_0 - g(\tau,\omega_0)] \tag{5}$$

$$\frac{\partial^2 g(\tau,\omega)}{\partial\omega^2}\bigg|_{\omega_0} = A_2 + B_2[g_0 - g(\tau,\omega_0)] \tag{6}$$

$$g(\tau,\omega_0) = \frac{g_N(\tau,\omega_0)}{f(\tau)} + \Delta g_T(\tau,\omega_0). \tag{7}$$

where, τ is the frame of local time which propagates with the group velocity v_g at the center frequency of an optical pulse. The slowly varying envelope function approximation is used in

Eq.(1),where the temporal change of the complex envelope function is very slow compared with the cycle of an optical field. $|A(z,\tau)|^2$is the optical power of an optical pulse, β_2 is the group velocity dispersion (GVD) coefficient, α_{int} is the linear loss, γ_{2p} is the two-photon absorption (TPA) coefficient, b_2 is the instantaneous self-phase modulation (SPM) term due to the instantaneous nonlinear refractive index (Kerr effect). $g_N(t)$ is the saturated gain due to carrier depletion, g_0 is the linear gain , E_{sat} is the saturated energy, τ_s is the carrier lifetime, $f_T(t)$ is the spectral hole-burning (SHB) function, P_{SHB} is the SHB saturation power, τ_{SHB} is the spectral hole-burning relaxation time, and α_N and α_T are the line-width enhancement factors associated with the gain change due to carrier depletion and carrier heating (CH), respectively. $\Delta g_T(t)$ is the resulting gain change due to the CH and TPA. $u(s)$ is the unit step function, τ_{CH} is the CH relaxation time, h_1 is the contribution of stimulated emission and free-carrier absorption to CH gain reduction, and h_2 is the contribution of TPA. Finally, A_1 and A_2 are the slope and curvature of linear gain at ω_0, respectively. While B_1 and B_2 are constant describing changes in these quantities with saturation [8-12].

For solving Eq. 1, the SOA cavity is divided to M equal sections. By using a central-difference approximation in time domain and trapezoidal integration over spatial section and applying an iterative procedure, a set of MNLSEs can be solved with high precision in few seconds [9].

4. Results and discussions

The parameters that we used in our simulations are listed in Table2 [8]. In this simulation the form of input pulses are sech^2.the full width at half maximum (FWHM) of the input pulses are 3.4ps . the central frequencies of pump, probe, and FWM pulses are 349 THz, 348 THz, 350 THz, respectively. The return-to-zero (RZ) bit sequences have been used for two input signal at bit rates of 50 Gb/s. The input energies for pump and probe are equal. Pattern effect (PE) defined as the ratio of the maximum peak power (P_{max}) to the minimum peak power $(P_{\min})$ that for FWM signal is as follow [13]:

$$PE_{FWM} = 10\, log_{10}\left(\frac{P_{max,FWM}}{P_{min,FWM}}\right) \tag{8}$$

Due to the gain recovery phenomena in the SOA pattern effect between output FWM signals is occurred. Therefore the first logic 1 bit which happen after the long zero bit sequence has the maximum energy because the SOA gain is fully recovered. On the other hand in the worst case when the long bit sequence of logic 1 occur, SOA's gain cannot recover to its initial value and remain constant for rest of the bits and therefore the FWM peak power is not changed.

Figure 2 illustrates the increases of pattern effect in SOA versus increases of input energies of pump and probe signals. In figure 3, we analyze the energies of input pulses on the peak power of pump signal at the output of SOA for serial data streams. As it can be seen with increasing input signal energies, difference between minimum and maximum peak power of signals become greater. This is due to the saturation effect of the SOA.

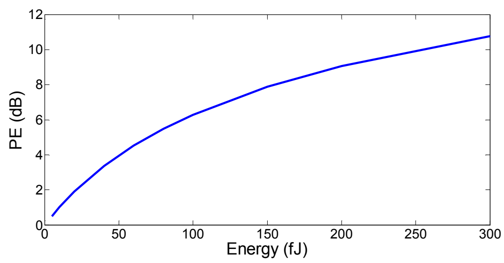


Fig. 2: Pattern effect in SOA versus input energies of pump and probe signals.

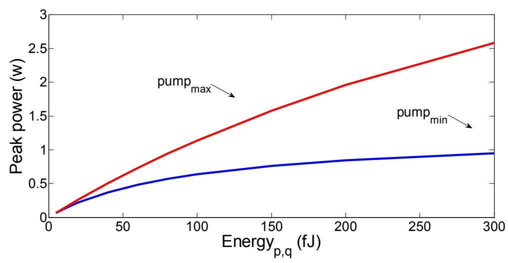


Fig. 3: Influence of input energies on the output peak power of pump and probe signal.

Table 2: The parameters that we used in our simulations [8]

parameter	Symbols	Values
SOA length	L	$500\mu m$
Effective area	A_r	$5\mu m^2$
Center frequency of the pulse	f_0	349 THz
Saturation energy	E_{sat}	80pJ
Linear gain	g_0	$92cm^{-1}$
Group velocity dispersion	β_2	$0.05ps^2cm^{-1}$
Line width enhancement factor due to the carrier depletion	α_N	3.1
Line width enhancement factor due to the carrier heating	α_{ch}	2.0
The contribution of stimulated emission and free carrier absorption to the carrier heating gain reduction	h_1	$0.13cm^{-1}pJ^{-1}$
The contribution of two-photon absorption	h_2	$126fscm^{-1}pJ^{-2}$
Carrier lifetime	τ_s	200ps
Carrier heating relaxation time	τ_{ch}	700ps
Spectral-hole burning relaxation time	τ_{shb}	60fs
Spectral-hole burning relaxation power	P_{shb}	28.3 W
Linear loss	α_{int}	$11.5\ cm^{-1}$
Instantaneous nonlinear Kerr effect	n_2	$-0.70\ cm^2TW^{-1}$
Two-photon absorption coefficient	γ_{2p}	$1.1\ cm^{-1}W^{-1}$
Parameters describing second-order Taylor expansion of the dynamically gain spectrum	A_1 B_1 A_2 B_2	$0.15fs\ \mu m^{-1}$ -80 fs $-60fs^2\ \mu m^{-1}$ $0\ fs^2$

In figure 4, we analyze the gain of the SOA. For this case we assume two inputs serial data with long sequence of logic 1 bit injected to SOA. In this figure, $Gain_{max}$ related to the SOA's gain for the first bit which decreases with the increase of input pulse energies. This is due to inclusion of nonlinear phenomenon in our equations which leads to saturation effects in SOA. $Gain_{min}$ is the SOA's gain after the long sequence of logic 1 bits. It can be seen as the gain cannot be recover to its initial value the SOA's gain gradually decreases. To obtain the optimum peak power and energies of the output FWM signal of SOA for logic 1 we have to analyze the pattern effect and the SOA's gain accurately. According to figures 2-4 for input energies less than 50 fJ desirable PE and SOA's gain are occur. Therefore, we consider 40 fJ input energies for pump and probe signals.

Figure 5 shows the simulated results for our proposed all-optical AND gate. Figures 5(a) and 5(b) are the data streams for data signal 1 and data signal 2, respectively. The corresponding RZ bit sequences are "1110101101101011" and "1010001011001110" for two input signals. The demodulated bit sequences in Figure 5(c) is "1010001001001010" that is equal to AND operation between the two input signals.

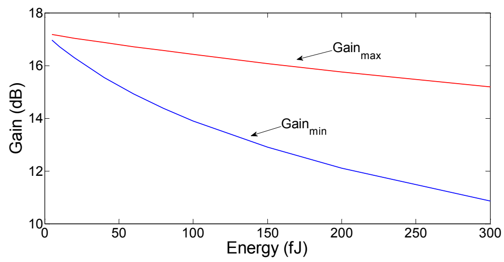
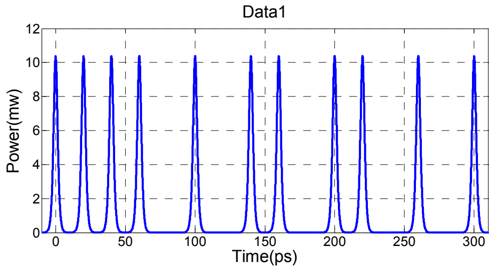


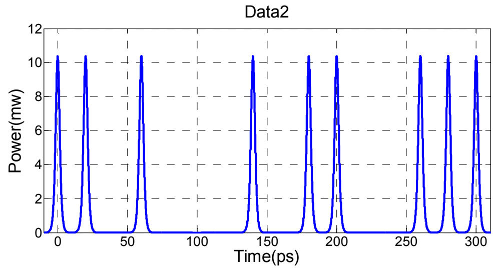
Fig. 4 : Demonstration of SOA's Gain versus input signal energies.

5. Conclusions

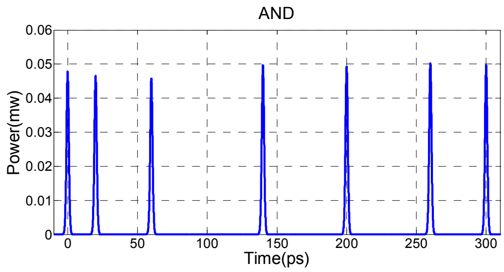
In this work, all-optical AND gate using FWM in SOA is numerical simulated by FD-BPM technique. For implementing the AND gate all nonlinear parameters such as CD, CH, SHB, GVD, SPM, and TPA are considered. It is shown that gain recovery phenomena play an essential role for optimizing the PE on FWM bit stream. It is depicted as the input pulse energies increases although the output FWM signal energy is also increases but PE increases too.



(a)



(b)



(c)

Fig. 5: waveform for (a) the input serial data 1, (b) the input serial data 2, (c) the logic AND output.

6. References

[1] Sang H. Kim, *et al.*, "Design and Simulation of All-Optical AND Gate using XGM in Semiconductor Optical Amplifiers without Input Additional Beam," *NUSOD'06 Int. Conf.* , pp. 91-92, 2006.

[2] Han Liu-Yan, Wen He, Jiang Huan, Guo Yi-Li, Zhang Han-Yi "All-optical AND gate without input beam by utilizing cross polarization modulation effect," *Chin. Phys. Lett*., Vol.25, No.11, pp. 3901-3904, 2008.

[3] H. Dong, H. Sun, Q. Wang , N. K. Dutta and J. Jaques, "80 Gb/s All-optical logic AND operation using Mach-Zehnder interferometer with differential scheme," *Opt. Commun*., Vol. 265m No. 1, pp. 79-83 , 2006.

[4] Pei-li Li, De-xiu Huang, Xin-liang Zhang, and Guang-xi Zhu, "Ultrahigh-speed all-optical half adder based on four-wave mixing in semiconductor optical amplifier " *Opt. Express*, Vol. 14, No. 24, pp. 11839-11847, 2006

[5] Z. Li, *et al.*, "All-optical logic gates using semiconductor optical amplifier assisted by optical filter," *Electron. Lett*., Vol. 41, No. 25, pp. 1397-1399, 2005.

[6] S. Kumar and A. E. Willner, "Simultaneous four-wave mixing and cross-gain modulation for implementing an all-optical XNOR logic gate using a single SOA," *Opt. Express*, Vol. 14, No.12 , pp.5092-5097, 2006

[7] M. Y. Hong, Y. H. Chang, A. Dienes, J. P. Heritage, P. J. Delfyett, S. Dijaili, and F. G. Peterson, "Femtosecond self- and cross-phase modulation in semiconductor laser amplifiers," *IEEE J. Select. Topics Quantum Electron.*, Vol. 2, pp. 523–539, 1996.

[8] N. K. Das, Y. Yamayoshi and H.Kawaguchi, "Analysis of four wave mixing characteristics in a semiconductor optical amplifier by the finite-diffrence beam propagation method," *IEEE J. Quantum Electron.,* Vol. 36, pp.1184-1192 , 2000.

[9] M. Razaghi, V. Ahmadi and M. J. Connelly*,"* Comprehensive finite-Difference time-dependent beam propagation model of counterpropagating picosecond pulses in a semiconductor optical amplifier,*" IEEE J. of light wave technol.*, Vol. 27, No. 15, pp. 3162-3174, 2009.

[10] G. P. Agrawal, N. A. Olsson, "Self-Phase Modulation and Spectral Broadening of Optical Pulses in Semiconductor Laser Amplifiers," *IEEE Journal of Quantum Electronics*, Vol. 25, No.11, pp. 435-442, 1989.

[11] M. Razaghi, V. Ahmadi and M. J. Connelly*,"* Femtosecond pulse shaping using counter-propagating pulses in a semiconductor optical amplifier,*" Opt. Quantum Electron.*, Vol. 41, No. 7, pp. 513-523, 2009.

[12] M. Y. Hong, Y. H. Chang, A. Dienes, J. P. Heritage, P. J. Delfyett, S. Dijaili, and F. G. Peterson, "Femtosecond self- and cross-phase modulation in semiconductor laser amplifiers," *IEEE J. Select. Topics Quantum Electron.*, Vol. 2, pp. 523–539, 1996.

[13] Jing Xu, Xinliang Zhang, and Jesper Mørk, "Investigation of Patterning Effects in Ultrafast SOA-Based Optical Switches," *IEEE J. Quantum Electron*., Vol. 46, No. 1, pp. 87-94, 2010.