All-Optical Logic Circuits Based on the Non-linear Properties of the Semiconductor Optical Amplifier

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Abstract

This work shows the importance of utilizing the non-linear properties of the semiconductor optical amplifier SOA in constructing optical logic gates, half and full adders, flip-flops, counters and registers. Consequently, SOA may be considered as a promising component for building all-optical digital computer.

By using the SOASIM software, this paper shows how the optical buffer, inverter, unit- step pulse and falling/rising clock edges can be generated.

KEYWORDS: *SOA, SOASIM, OPTICAL LOGIC GATES.*

1. Introduction

First of all, to have wide-bandwidth communications, the switching technologies must be improved. Electronics technology no longer will be adequate where the speed of conventional computers is achieved by miniaturizing electronic components to a very small micron-size scale so that those electrons need to travel only very short distances within a very short time. The goal of improving on computer speed has resulted in the development of the VLSI technology with smaller device dimensions and greater complexity. But VLSI technology is approaching its fundamental limits in the sub-micron miniaturization process. Further miniaturization of lithography introduces several problems such as dielectric breakdown, hot carriers, and short channel effects. All of these factors lead to a seriously degrade device reliability. Therefore, a dramatic solution to the problem is needed [1].

Light is immune to electromagnetic interference because of its ability of traveling at speed of 186,000 miles/sec without charging or interacting of its photons with each other (as electrons). Consequently, light beams can pass through one another in a full-duplex operation with wavelengths in order of 1 micron. A higher bandwidth capacity and a transmission of a massive amount of information over a beam are obtained [1].

Optical data processing can be done much easier and less expensive in parallel than can be done in electronics. Parallelism is the capability of the system to execute more than one operation simultaneously. Then the parallelism associated with fast switching speeds would result in staggering computational power. A computation that might take more than eleven years by the conventional electronic computer could be performed by an optical computer in only one single hour [1].

Thus the optical-switching technology and the development of optical logic gates are required to eliminate the optical/electronic conversion. Their operation can scale with the data rate and they have further properties of data regeneration, gain, cascade-ability and implementing more complex operations than possible with a simple switch.

As a trend of developing optical logic gates to be used in building all-optical computers, this paper focuses on the importance of utilizing the nonlinear properties of SOA.

Section 2 of this paper will give a description of the physical mechanism of nonlinear optics. Section 3 shows the materials that can be used as nonlinear elements, especially SOA. Three different mechanisms used with nonlinear SOA as cross-phase modulation XPM, cross-magnitude modulation XGM and four-wave mixing FWM are discussed in sections 4, 5 and 6 respectively. Section 7 gives some applications to computer devices based on the three mechanisms discussed. The analysis of SOA-model and the circuit used in our work are given in section 8. Simulation results and discussion are given in sections 9 and 10 respectively.

2. Physical Mechanism of Nonlinear Optics

Much architecture that can be used to implement optical computers have been proposed such as laser logic gates, shadow casting logic, logic by symbolic substitution, optical interconnections and threshold logic using nonlinear optics [2].

Non linear optics become an important field of activity in 1960's with the advent of high power laser sources such as: Co_2 at 10.6μm, YAG: Nd^3 at 10.06μm, Ruby at 6943 Å and Argon at 5145Å [3]. The significant point of nonlinear optics is that, when electromagnetic fields become strong enough, the dielectric function becomes dependent on the electric field $\bar{E}$. Electric field of magnitude $|\bar{E}| \sim 10^6$ V/cm is required to have the nonlinear effects, which is already available for high power laser sources. Nonlinear phenomenon is used in all-optical data processing devices and gives an ultra fast switching response [3].

The physical mechanism of the nonlinearity as in [4]: consider a simple neural atom with a positive nucleus and negative electron as shown in figure (1-a). If the applied electric field to the atom is high, the atom can be excited to a higher-energy state leading to absorption of energy. Otherwise, the applied electric field polarizes the atom and it becomes an electric dipole oscillating at the same frequency of the applied field as in figure (1-b).

(a) (b)

Figure (1): Dipole creation when applying electric field.

In case of weak electric field E, the dielectric polarization can be expressed as:

$$P(t)=\varepsilon_0\,\chi^1\,E(t) \quad (1)$$

Where χ^1 is the first order susceptibility, *P (t)* and *E (t)* are vectors. If the dipole moment is strong enough, they will interact with each other and the dielectric polarization is expressed as:

$$P(t)=\varepsilon_0\,(\chi^1\,E(t)+\chi^2\,E(t)+\chi^3\,E(t)+....) \qquad (2)$$

Where $E\ (t)$ = ($A\ (t)$ $e^{j\omega t}$ + c.c), $A\ (t)$ is the slowly varying amplitude of the field, ω is the optical frequency, c.c is the complex conjugate of the field, χ^2 is the second order nonlinear susceptibility and χ^3 is the dominant nonlinear susceptibility. The nonlinear part of polarization can be expressed as:

$$P_{NL}=\varepsilon_0\gamma^3E(t) \quad (3)$$

The optical non-linearity based on the third nonlinear susceptibility is promising to demonstrate optical computer gates, adders, flip-flops and counters. They are relying on mechanisms such as XPM, XGM and FWM.

3. Nonlinear Elements

The nonlinear elements may be optical fibers, organic polymers or semiconductors where they interact with light in a way that the light changes the properties of the materials that in turns changes the properties of light [4].

The use of the optical fibers as nonlinear elements in switching devices gives some attracting features such as the possibility of having a very high speed operation since the nonlinear response of the fiber is extremely fast and the possibility of creating a rectangular switching by using a dispersive walk-off between the data and the control pulse but the nonlinear coefficient is usually very small in conventional fibers [4].

Organic and polymeric materials can have very large and very fast ($\sim 10^{-15}$ sec) nonlinear optical responses, which are critical for applications in many devices. Nonlinear optical organic compounds as phthalocyanines and polydiacetylenes are promising for optical thin films and waveguides but their losses are still very high [4].

Semiconductors have many effects that may be utilized for switching. SOA can be used as a nonlinear element where the nonlinear responses in semiconductors may arise due to carrier depletion or from gain saturation [4]. Although SOA gives slow recovery time which limits the performance of some applications but ways as delay-differential techniques can be used to get rid of the slow carrier density. The delay-differential techniques are based on the phase difference between the arms of the interferometer and two control pulses that determine the interferometer output [5]. The saturation energy of SOA is $E_{sat} = Ah\gamma/\Gamma g$, where A is the cross-sectional area of the active wave-guide, Γ is the confinement factor, g is the differential gain, and hγ is the photon energy. For a highly nonlinear device, E_{sat} should be low while in a linear device it should be high [6]. This paper uses the nonlinear effects of the third susceptibility of SOA.

4. The Mechanism of XPM in SOA

Optical switching using a nonlinear interferometer makes it possible for one optical signal to control and switch another optical signal through the nonlinear interaction in a nonlinear element as SOA. The input signal to be switched is split between the arms of the interferometer. The interferometer is balanced so that, in the absence of a control signal, the input signal emerges from an output port. The presence of a strong control pulse changes the refractive index of the medium. A change in the index adds a phase shift between the two arms of the interferometer, so that the input signal is switched over to the second output port [7]. This switching method based on XPM is schematically shown in figure (2).

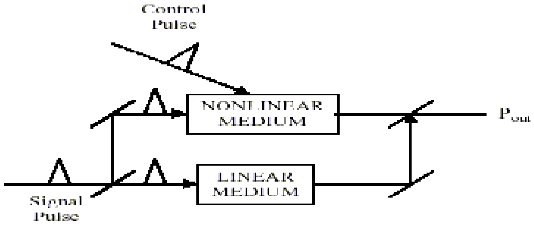

Figure (2): All-optical switching using XPM in a nonlinear interferometer

The most famous switching applications that based on XPM in SOA are terahertz optical asymmetric amplifier TOAD, Mach-Zender interferometer MZI and ultra fast nonlinear interferometer UNI.

5. The Mechanism of XGM in SOA

If SOA is injected by CW probe signal of wavelength λ_1 and pump signal of wavelength λ_2 as in figure (3). The high power of pump signal causes carrier depletion in SOA leading to gain saturation as in figure (4).The probe signal experiences the same changes of SOA and the shape of probe signal will be the reversal of pump signal .Then SOA works as NOT gate as in figure (5).

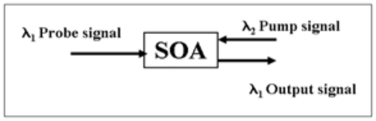

Figure (3): XGM in a SOA

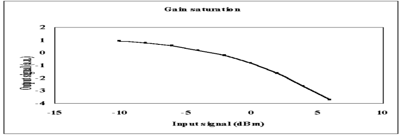

Figure (4): Static characteristics of SOA

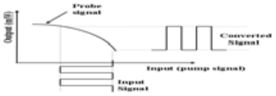

Figure (5): SOA as a NOT gate.

6. The Mechanism of FWM in SOA

FWM shown in figure 6 is the third-order nonlinear process in which a polarization is created in a medium that depends on the product of three electric fields. The induced polarization leads to the creation of new frequency components of the electric field. In a typical FWM experiment, a strong pump wave at frequency ω_p and a probe wave at frequency ω_q are combined and coupled to the waveguide modes of SOA, which is a traveling wave amplifier. Dynamic gain and index gratings are formed due to the beating of the pump and probe waves, at a detuning frequency given by $\Omega = \omega_q - \omega_p$. The pump and the probe waves are subsequently scattered by these gratings that give rise to the FWM sidebands [7].

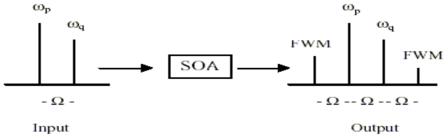

Figure (6): Generation of the FWM sidebands in a SOA

7. Logic Devices Based SOA Nonlinearity

TOAD offered many contributions to construct optical computer devices as OR, AND, XOR, binary half adder, full adder and binary counter [8, 9, 10].

MZI is used to construct all-optical XOR and XNOR gates [11, 12, 13]. Also two coupled MZIs that contain SOA in their arms have been used to build all-optical flip-flop [14].

Some researchers utilized UNI in implementing all-optical AND/NAND gates, and as a circulating shift register with an inverter [15, 16].

SOA contributes also in constructing all optical flip-flop based on optical bistability in an integrated SOA [17] and it was used with wavelength dependent mirrors to form laser diode and implementing all optical flip-flop based on coupled laser diode [18].

All-optical three-bit adder based on FWM in SOA has been proposed in [7]. All-optical AND gate based on XPM in SOA has been demonstrated [19] All-optical NOT gate and XOR gate based on XGM in SOA have been built [19, 20], and half adder based on XGM/XPM in SOA have been proposed [21].

8. The Gain Controlled SOA model

SOASIM is a C^{++} software written by Cristeano et al. [22] to simulate the circuit in figure (7).

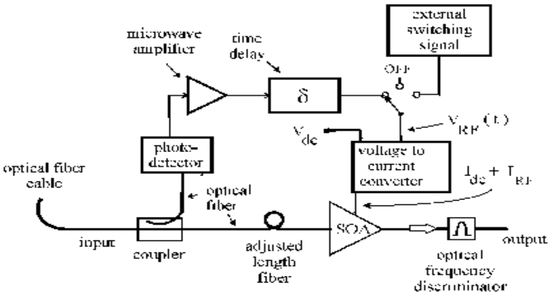

Figure (7): Block diagram of the feed forward gain controlled SOA with chirp controlled filtering.

When the input signal is considered in *x-axis* polarized plane wave, the electric field inside the SOA active region can be expressed as:

$$\overline{E}(x,y,z,t) = \hat{x}.\frac{1}{2}\{F(x,y).A(z,t)e^{j(k_o z - \omega t)} \qquad (4)$$

Where $\hat{x}$ is the unit vector in the x direction, *A(z, t)* is the slowly time varying optical carrier envelope of the pseudo-random binary sequence, *F(x, y)* is the field transversal distribution in the active region, k_0 is the wave number, and ω is the optical angular frequency. It is assumed that *F (x, y)* is time independent and that the wave polarization is preserved for ring propagation in the SOA active region. Therefore, the time variation is included only in *A (z, t).* The integral in the x and y directions can be done and the envelope equation in the active region can be expressed as:

$$\frac{\partial A(z,t)}{\partial z} + \frac{1}{v_g}\frac{\partial A(z,t)}{\partial t} = \frac{1}{2}(1 + jb_c)g(z,t)A(z,t) \qquad (5)$$

Where v_g is the group velocity, b_c the line width enhancement factor and *g(z, t)* is the active region distributed gain, which is governed by:

$$\frac{\partial g(z,t)}{\partial t} = \frac{g_o - g(z,t)}{t_c} - \frac{g(z,t)P(z,t)}{E_s} \qquad (6)$$

Where E_s is the active region saturation energy, t_c is the carrier lifetime, *P* is the optical power level in the active region and g_o is a small-signal gain which is expressed as:

$$g_o = Gs_g n_t [I_o - I_t) - 1] \qquad (7)$$

Where G is the guide confinement factor, s_g the active region transversal gain, n_t the carrier concentration at transparency, I_0 the SOA bias current and I_t the current to achieve transparency. Taking A (t) as follows:

$$A(z,t) = P(z,t)e^{jf(z,t)} \qquad (8)$$

And by using adequate variable transformation, equation (5) can be rewritten as:

$$\frac{\partial P(z,t)}{\partial z} = g(z,t)P(z,t) \qquad (9)$$

$$\frac{\partial f(z,t)}{\partial z} = -\frac{1}{2p}b_c g(z,t) \qquad (10)$$

To obtain the output signal amplitude, equation (9) is integrated over 0 £ z £ L, so**:**

$$\ln[\frac{P_{out}}{P_{in}}] = h(t) \Rightarrow P_{out}(t) = P_{in}(t).e^{h(t)} \qquad (11)$$

$$h(t) = \int_0^L g(z,t)dz \qquad (12)$$

Where *h (t)* is the SOA gain factor, *L* is the active region length, and P_{out} and P_{in} are the SOA input and output optical power levels, respectively. Therefore, the SOA total gain factor can be expressed as:

$$\frac{\partial h(t)}{\partial t} = \frac{g_o L - h(t)}{t_c} - \frac{P_{in}(t)}{E_s}(e^{h(t)} - 1) \qquad (13)$$

To implement the semiconductor attenuation, a term is introduced in equation (11) to give the final SOA output power:

$$P_{out}(t) = P_{in}(t).e^{h(t) - aL} \qquad (14)$$

$$I(t) = I_{dc} + I_{RF} = I_{dc} + VG_{RF} \qquad (15)$$

The SOA injected current has a dc level and a time varying RF component. It is given by**:**

Where I_{dc} is the continuous part of the current, I_{RF} is the alternate current, *G* is the trans-conductance of the voltage-to-current converter, and V_{RF} is the RF voltage.

The dependence with the carrier concentration can be expressed as:

$$t_c = 1/(A + Bn + Cn^2) \qquad (16)$$

Where *A*, *B* and *C* are, respectively, trapping, spontaneous and Auger recombination coefficients, and *n* is the carrier density in the SOA active region. A linear relation between the SOA gain and the carrier population was assumed and it can be expressed as:

$$N = \frac{gV}{Gs_g} + N_t \qquad (17)$$

Where *N* is the active region carrier population, *V* is the active region volume, and N_t is the carrier population at transparency.

9. Simulation results

By injecting SOA by 33mA DC current, input pulse's wavelength of 1.55um, transmission rate of 100MHz, super Gaussian form of 30, and using parameters in table 1, positive and negative edges in figure 8 are obtained.

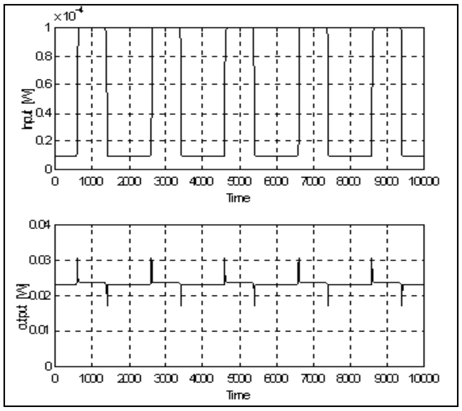

Figure (8): Input and output versus time for falling/rising clock edges

Table (1): SOA parameters for falling/rising clock edges

Parameter	Value
Width	0.2 um
Height	0.05 um
Length	30 um
Volume	0.3 um^3
Carrier Density N_0	$2*10^{18}/cm^3$
Transversal Section Gain	$2*10^{-16}.cm^2$
Attenuation Coefficient	20 /cm

Facet Reflection	0.0001
Line-width-Enhancement Factor	5
Effective Refractive Index	0.118077
Confinement Factor	0.4
Total insertion Loss	5 dB
Carrier Lifetime at N_0	750 ps
Transparency Current	0.128mA
Small-signal Gain	535.355 dB
Cavity Loss	0.260577dB
Saturation Energy	0.160403pJ
Photon Lifetime	0.0012737ps

By setting SOA parameters as in table 2, injecting SOA by 63mA DC current, input pulse wavelength of 1.55 um and transmission rate of 5000 MHZ, the positive edge trigger in figure 9 is obtained.

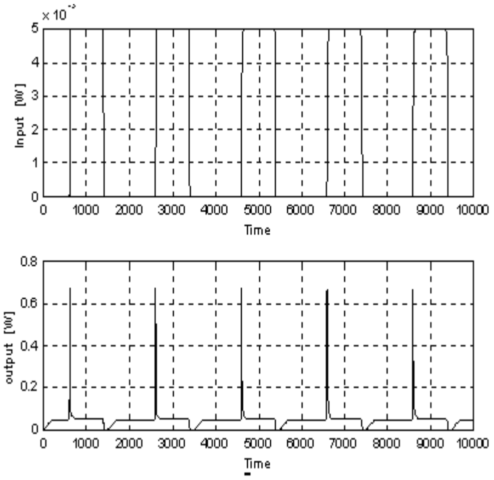

Figure (9): Input and output versus time for rising clock edge.

Table (2): SOA parameters for rising clock edge

Parameter	Value
Width	0.2 um
Height	0.05 um
Length	30 um
Volume	0.3 um^3
Carrier Density N_0	2 10^{18}/cm^3
Transversal Section Gain	2 10^{-16}.cm^2
Attenuation Coefficient	20 /cm
Facet Reflection	0.0001
Line-width-Enhancement Factor	5
Effective Refractive Index	0.0484918
Confinement Factor	0.4
Total insertion Loss	5 dB
Carrier Lifetime at N0	750 ps
Transparency Current	0.128mA
Small-signal Gain	1023.94 dB
Cavity Loss	0.260577 dB
Saturation Energy	0.160403 pJ
Photon Lifetime	0.000523086ps

By setting SOA parameters as in table 3, injecting SOA by input current of 100mA DC, input pulse of wavelength 1.55 um, and transmission rate of 100 MHz, a unit step (logic ‘1’) is obtained. A buffer is also obtained by injecting SOA by 50mA DC current and 50mA modulated current. NOT-gate is obtained by injecting SOA with 50mA DC current, 50mA modulated current and phase shift of 190^0. Results are shown in figure 10.

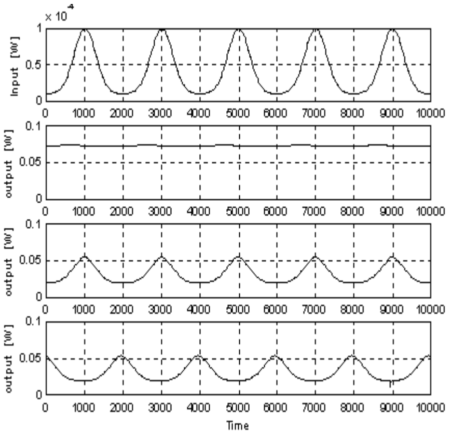

Figure (10): Input and output versus time for logic '1', buffer and NOT gates.

Table (3): SOA parameters for logic '1', buffer and NOT gates

Parameter	Value
Width	0.2 um
Height	0.05 um
Length	30 um
Volume	0.3 um^3
Carrier Density N_0	2 10^18/cm^3
Transversal Section Gain	2 10^{-16}.cm^2
Attenuation Coefficient	20 /cm
Facet Reflection	0.0001
Line-width-Enhancement Factor	5
Effective Refractive Index	0.0780646
Confinement Factor	0.4
Total insertion Loss	5 dB
Carrier Lifetime at N0	750 ps
Transparency Current	0.128mA
Small-signal Gain	1626.52 dB
Cavity Loss	0.260577 dB
Saturation Energy	0.160403 pJ
Photon Lifetime	0.000842089ps

Conclusion

In this paper, we could utilize the nonlinear SOA in obtaining all-optical logic devices as NOT, buffer, positive and negative edges that may be used in triggering flip-flops and positive impulses. This work focuses on how much SOA is promising material in building all-optical computer.

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