All-optical logic NXOR based on semiconductor optical amplifiers with the effect of amplified spontaneous emission

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The performance of all-optical logic NXOR gate based on semiconductor optical amplifiers Mach-Zehnder interferometer (SOAs-MZI) is simulated. The effects of amplified spontaneous emission (ASE) and the input pulse energy on the system's quality factor are studied. For the parameters used, the all-optical logic gates using SOAs are capable of operating at speed of 80 Gbit/s.
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In future high-speed communication systems, optical logic gates are expected to play an important role in switching, signal regeneration, addressing, header recognition, data encoding and encryption, etc[1]. In recent years, optical logic gates based on several different schemes have been demonstrated and reported, including that based on dual semiconductor optical amplifiers Mach-Zehnder interferometer (SOAs-MZI)[2,3], semiconductor laser amplifier loop mirror (SLALM)[4], ultrafast nonlinear interferometers (UNFs)[5], four-wave mixing (FWM) process in SOA[6] and cross-gain modulation (XGM) or cross-phase modulation (XPM) in nonlinear devices[7]. Design of an all-optical NOT XOR gate based on cross-polarization modulation in an SOA is demonstrated[8]. Effect of amplified spontaneous emission (ASE) on SOA-based all-optical logic gates is reported[9]. Among these schemes, the SOA based on MZI has the advantage of being relatively stable, simple and compact.

In our previous work, we have studied the effect of ASE on bulk SOA based all-optical logic XOR, AND, OR, NOR and NAND gates at 80 Gbit/s[9]. In this paper, we complete our previous work. NXOR using SOAs-MZI is simulated. The simulation is performed under a repetition rate of 80 Gbit/s. The effects of ASE and input pulse energy on the system's quality factor (*Q*-factor) are studied. The device used in the paper is an MZI, each arm of which has an SOA. The primary noise in this calculation, which lowers the quality factor, in the absence of ASE noise is pattern effect resulting from long recovery time of gain and the gain-induced phase change. The ASE causes additional output noise through spontaneous-spontaneous beat noise and signal-spontaneous beat noise. In addition, if one wants to measure the error rate of the gate output, the dark current of the photodiode, shot noise and thermal noise need to be considered. The analysis of all these noise terms is given in Chapter 6 of Ref.[1] when the SOA is used as a pre-amplifier. The ASE-related noise depends on the spontaneous emission factor (N_{sp}) of the amplifier.

SOAs incorporated into MZI are used for wavelength conversion and to demultiplex high-speed time division multiplexed (TDM) optical signals. The schematic diagram of the device is shown in Fig.1, where BPF means band pass filter.

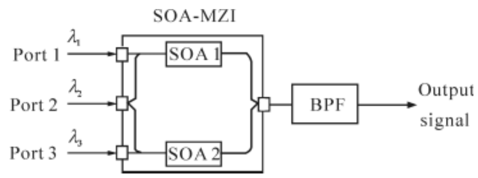

Fig.1 Schematic diagram of an MZI with integrated SOA

The operation of SOA-MZI can be studied using a rate equation model. The carrier heating results from a thermalization of carriers in the entire energy band following the pulse. This is a fast process occurring in time scale from 0.1 ps to 0.7 ps. The injected pulse reduces the gain of the photon energy of this pulse, i.e., in the gain spectrum it burns a hole. The process is known as spectral hole burning. By taking

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both carrier heating and spectral hole burning effects into consideration, the time-dependent gain for each SOA is given by[1]

$$\frac{\mathrm{d}h_1(t)}{\mathrm{d}t}=\frac{h_0-h_1(t)}{\tau_C}-\{\exp[h_1(t)+h_{CH}(t)+h_{SHB}(t)]-1\}S(t,0) \ , \tag{1}$$

$$\frac{\mathrm{d}h_{CH}(t)}{\mathrm{d}t}=-\frac{h_{CH}(t)}{\tau_{CH}}-\frac{\varepsilon_{CH}}{\tau_{CH}}\{\exp[h_1(t)+h_{CH}(t)+h_{SHB}(t)]-1\}S(t,0) \ , \tag{2}$$

$$\frac{\mathrm{d}h_{SHB}(t)}{\mathrm{d}t}=-\frac{h_{SHB}(t)}{\tau_{SHB}}-\frac{\varepsilon_{SHB}}{\tau_{SHB}}\{\exp[h_1(t)+h_{CH}(t)+h_{SHB}(t)]-1\}S(t,0)-\frac{\mathrm{d}h_1(t)}{\mathrm{d}t}-\frac{\mathrm{d}h_{CH}(t)}{\mathrm{d}t} \ . \tag{3}$$

The gain $G(t)$ is given by:

$$G(t,z) = \exp[h_1(t) + h_{CH}(t) + h_{SHB}(t)] = \exp\,(h_{total}) \ , \tag{4}$$

where $h(t)$ is an integral of optical gain per unit length over the length of SOA, and h_{total} equals the sum of h_1, h_{CH} and h_{SHB}.τ_c is the carrier lifetime, and $G_0=\exp(h_0)$ is the unsaturated power gain. $S(t,\ 0)$ is the instantaneous input optical intensity inside the SOA, and h_1, h_{CH} and h_{SHB} are the h-factor values for carrier recombination, carrier heating and spectral hole burning, respectively. τ_{CH} and τ_{SHB} are the temperature relaxation rate and the carrier-carrier scattering rate, respectively. ε_{CH} and ε_{SHB} are the nonlinear gain suppression factors due to carrier heating and spectral hole burning, respectively. The carrier density induced phase change is given by

$$\Phi(t) = -0.5\ [\alpha h_1(t) + \alpha_{CH} h_{CH}(t)] \ , \tag{5}$$

where α is the traditional linewidth enhancement factor, α_{CH} is the carrier heating alpha factor, and α_{SHB} is the spectral hole burning alpha factor which is about 0[9].

We assume the data stream pulse to be a Gaussian pulse as

$$P_{A,B}(t)=\sum_{n=-\infty}^{n=+\infty}a_{nA,B}\frac{2\sqrt{\ln(2)}P_0}{\sqrt{\pi}\tau_{FWHM}}\exp\left(-\frac{4\ln(2)(t-nT)^2}{\tau_{FWHM}^2}\right), \tag{6}$$

where $a_{nA,B}$ represents the nth data in data streams A and B, which equals 1 or 0. P_0 is the input pulse energy, and T is the bit period. τ_{FWHM} is the pulse width (full width at half maximum).

In this paper, NXOR is demonstrated by a series combination of XOR and INVERT operations. For XOR operation, two data signals A and B are injected into the two arms in ports 1 and 3 in Fig.1, respectively. A clock stream of continuous series of "1" or a continuous wave (CW) beam is injected in port 2. The data signals A (wavelength λ_1) and B (wavelength λ_3) can induce a phase shift in the CW or clock signal (wavelength λ_2) via cross-phase modulation in the SOA. The clock or CW signal carries the result of the XOR operation of the data signals (A and B) at the output. The wavelength λ_2 must be chosen so that it is different from λ_1 and λ_3, and λ_1 and λ_3 need not be different. Initially the MZI is unbalanced, i.e., when $A = 0$ and $B = 0$, the signals traveling through the two arms of the SOA acquire a phase difference of π when it recombines at the output port, thus the output is "0". When $A = 1$, $B = 0$, the signal traveling through the arm with signal A acquires a phase change due to the cross phase modulation (XPM) between the pulse train A and signal, and the signal traveling through the lower arm does not have this additional phase change. This results in an output "1". The same phenomenon happens if $A = 0$ and $B = 1$. However, when $A = 1$ and $B = 1$, the phase changes for the signals traveling in both arms are equal, hence the output is "0". The INVERT operation is similar to XOR if one of the inputs is a clock signal. Thus the effect of ASE on NXOR is due to both XOR and INVERT operations. The schematic diagram of an NXOR logic gate using two MZIs in series combination is shown in Fig.2.

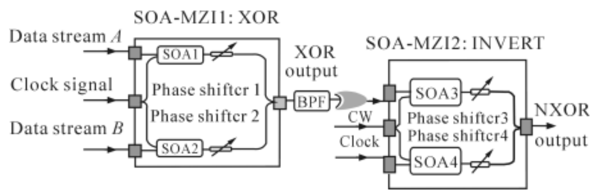

Fig.2 Schematic diagram of an NXOR logic gate using two MZIs in series combination

The modulated clock signals (probe) from the two arms of MZI interfere obeying the XOR formula

$$P_{XOR}(t)=\frac{P_C}{4}\{G_1(t)+G_2(t)-2\sqrt{G_1(t)G_2(t)}\times\cos[\Phi_1(t)-\Phi_2(t)]\} \ , \tag{7}$$

where P_C is the input probe power. For fast all-optical logic operations, the carrier lifetime (τ_c) must be small. Parameters used in this simulation are: P_0 = 0.05 pJ, τ_{FWHM} = 2 ps, τ_c= 5 ps, τ_{CH} = 0.3 ps, τ_{SHB} = 0.1 ps, $\varepsilon_{CH}=\varepsilon_{SHB}$ = 0.08 ps, α = 3, α_{CH} = 1, α_{SHB} = 0 and P_{sat} = 30 mW.

The instantaneous optical intensity inside each SOA for XOR gate is defined as

$$P_1(t) = P_A(t) + P_C \ , \tag{8}$$

$$P_2(t) = P_C + P_B(t) \ . \tag{9}$$

Fig.3(a) illustrates the simulation results of NXOR gate operation with the patterns of signal *A* and signal *B*. The middle trace shows the XOR output, and the bottom trace shows the NXOR output after SOAs-MZI. The eye diagram of an NXOR bit for pseudo-random streams of *A* and *B* bits is shown in Fig.3(b). The primary reason for noise in this calculations, which lowers the quality factor, in the absence of ASE noise is pattern effect resulting from long recovery time of gain and the gain-induced phase change.

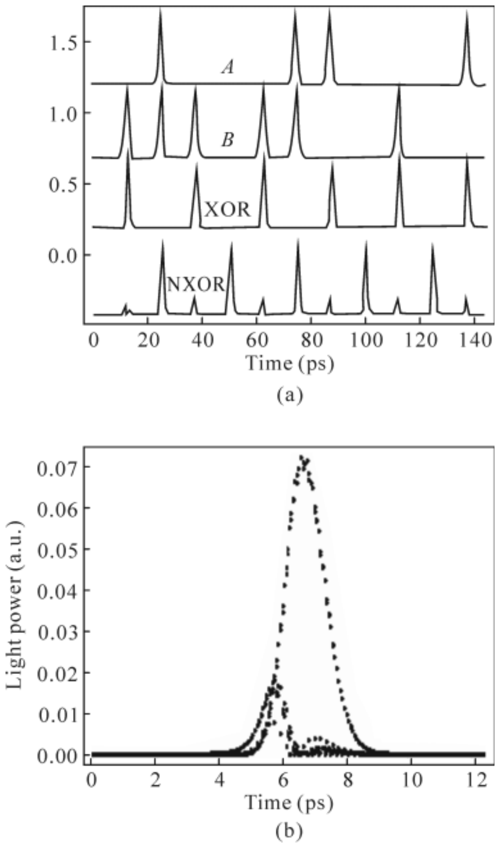

Fig.3 (a) Simulated results of NXOR gate operation; (b) Eye diagram for NXOR

To investigate the quality of NXOR operation by simulation, *Q*-factor of the NXOR output signal is calculated. *Q*-factor gives the information of the optical signal to noise ratio in digital transmission. *Q*-factor is given by $Q=(S_1-S_0)/(\sigma_1+\sigma_2)$, where S_1, S_0 are the average intensities of the expected "1" and "0", and σ_1, σ_2 are standard deviations of those intensities. *Q*-factor increases with decreasing the carrier lifetime (τ_c), and drops with increasing the input pulse energy (P_0). We investigate the effect of ASE power. The ASE power is related to N_{SP} by the relation:

$$P_{ASE}=N_{SP}(G-1)\,h\upsilon B_0\,, \tag{10}$$

where G is the maximum gain, h is Plank's constant, υ is the frequency, and B_0 is the bandwidth. The ASE noise is added numerically into the input signals using Eq.(10) on the pattern effect noise to obtain the *Q*-factor. The *Q*-factor versus N_{SP} for NXOR operation is shown in Fig.4.

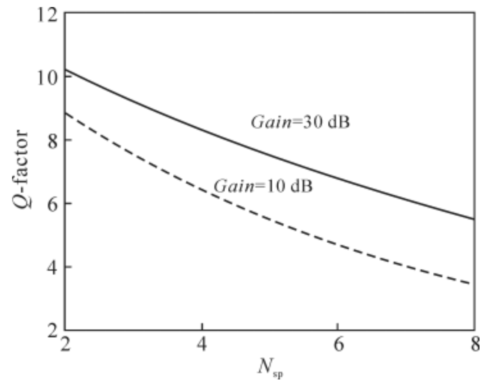

Fig.4 *Q*-factor versus N_{SP} for NXOR operation with data rate of 80 Gbit/s, pulse width of 2 ps, pulse peak power of 3.75 mW and bandwidth of 3 nm

To obtain further information on the NXOR gate performance, the *Q*-factors for different input single-pulse energies at 80 Gbit/s are calculated as shown in Fig.5. The increase of input pulse energy can make the SOAs easier to saturate, which results in the decrease of the *Q*-factor.

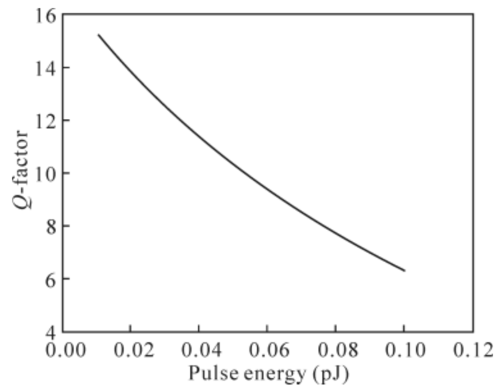

Fig.5 *Q*-factor versus pulse energy

The performance of all-optical logic NXOR gate based on SOAs is presented. Results show that SOA can perform logic NXOR at high bit-rate up to 80 Gbit/s. The effects of ASE and the input pulse energy (P_0) on the output *Q*-factor for all-optical logic NXOR gate are studied. ASE is calculated as a function of the spontaneous emission factor (N_{sp}). A decrease in quality factor is predicted for high N_{sp} and high P_0. The effect of ASE can be experimentally verified by adding wideband (a few nanometers) optical unmodulated signal to the data and measuring the *Q*-factor as a function of the intensity and bandwidth of this signal. ASE effects are important for cascaded logic operations.

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