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Comparative study of all-optical INVERTER and BUFFER gates using MZI structure

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Abstract: In the paper, one input optical gates i.e., INVERTER and BUFFER have been designed using some basic assumption to analyze with the help of Semiconductor Optical Amplifier based Mach–Zehnder Interferometer structure. The results are optimized by iterative process. The proposed design of optical gates presents low complexity, high scalability and more feasible to evaluate through digital Boolean analyzation. The digital Boolean analyzation is analyzed by some basic Boolean rules and assumptions which makes the design more digital so that it can be compatible for more than one input optical gates also. Optical Gate is designed to get constructive and destructive interference for pump and probe as they are injected into SOA simultaneously. The phase modulation is converted into intensity modulation which gives a Boolean result. The paper is optimized by Eye diagram, Q factor, wavelength spectrum and frequency chirp for both the gates. The comparative results of extinction ratio for both the gates have also been discussed. The design is supported by theoretical analysis, simulation tool (Optsim) and Boolean explanation. The proposed designs are constructed with same pattern which supports the same Boolean analysis.

Keywords: clock wave laser (CLL); cross gain modulation (XGM); cross phase modulation (XPM); Mach–Zehnder interferometer (MZI); mode lock laser (MLL); semiconductor optical amplifier (SOA).

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1 Introduction

An optical fiber communication system is similar to any other communication system. The commercial demand for higher capacity transmission is needed to introduce a new information service and broadband service. The increase demand of bandwidth and cost are interconnected. Optical technology has succeeded in reducing the cost of bandwidth to improve the novel set of applications of bandwidth, making it more useful in behavioral pattern. The survival and improvement of optical fiber communication is based on the development of laser, amplifiers, photo detectors, switches, optical gates, optical circuits and optical devices etc. Last few decades, the research is going on to provide optical signal processing which include optical logic gates, memory elements, power limiters and pulse shapers, differential amplifiers, and A/D converters etc. All-optical logic gates are in category of ultra-fast switching device that can perform a Boolean operation in compact integration circuit [1–3]. Moreover, all optical logic gates response to light in non-linear manner to perform an optical computing where one optical data stream controls another data stream. In optical communication systems, an optical logic operation plays an essential roll to perform the optical signal processing. Now days, most of the research are diverted in the area for growing high speed optical networks. Therefore, it is essential to design an all-optical gate to avoid power consumption in opto-electronics conversion. The research is going in the field of optical logic gates is to demonstrate, ultra-high-speed optical signal processing. Many approaches have been implemented to design an optical logic gates by introducing SOA [4, 5] in waveguide, either in line or in design of MZI to produce phase modulation. Design of optical logic gates in which SOA is used, has advantage of simple implementation with large bandwidth and high-power efficiency. SOA is a single mode waveguide structure with small size, so it is easy to integrate to produce subsequent systems which are essential in optical communication [6]. For optical logic operation, a nonlinear effect is required which is introduced by SOA, making it as an excellent choice for optical switches. At low power level switching speed of SOA depends on driving power that offers potential for fast switching in picoseconds using pico-joules energy. Recent optical digital system operation is also based on digital logic design [7]. Now, to setup this technology it is important to develop basic Boolean function such as optical gates which can operate at high speed. These logic elements include the traditional Boolean logic functions operating optically such as INVERTER, BUFFER, OR, AND, NOR, XOR, NAND etc. [8, 9] and circuits such as parity checker, all-optical adder, shift registers and memory elements [10–13].

Many research papers have investigated one input NOT gate with the help of different schemes [14–16]. In the paper, we have done comparative study of one input gates i.e., BUFFER and INVERTER [17, 18] with the help of two SOAs in MZI structure that made it possible to use its nonlinearity for gates. The study is also analyzed by the new optical Boolean synthesis. The switching operation of INVERTER helps to construct two inputs NOR gate as well as n-input NOR gate. Same as switching operation of Buffer helps to construct two inputs OR gate as well as n-input OR gate. The design result and analysis was supported by the opti-sim simulator and theoretical analysis.

2 Proposed model and principle

The proposed model of INVERTER/BUFFER gates, as in Figure 1 consists of a symmetrical Mach–Zehnder Interferometer (MZI) where the two SOAs are placed in series with multiplexer at the upper and lower arm of MZI. In the simulated design, the optical data (0100000 1001000001001) and string of (11111111111111111111)/(00000000000000000000) which is pump signal are fed in the upper and lower arms of multiplexers through CW laser to perform Boolean INVERTER/BUFFER operation. Mode lock laser (MLL) is used to generate a string of (11111111111111111111)/(01000001001000001001) which acts as a probe signal is fed into the upper arm of first 3 dB coupler. The phase shift of π/2 is produced between upper and lower arm of probe pulse traveling through it, as it is fed into the first 3 dB coupler. Pump and probe at different wavelengths are injected into SOA, so that it may operate under the gain saturated condition. As XGM occurs in SOA, available optical gain will be distributed between pump and probe wavelengths according to their photon densities. Thereby, the probe is compressed, giving the inverse effect on the gain, available to the pump wavelength. Therefore, the outputs of SOA1 and SOA2 for INVERTER/BUFFER gates with respect to the probe signal are (10111110110111110110)/(00000000000000000000) and (00000000000000000000)/(01000001001000001001) respectively. After passing through SOAs these saturated signals are fed into the second 3dB coupler, again the phase shift of π/2 is created on the probe pulse. Due to the phase modulation in MZI structure with second 3dB couplers, the total phase shift i.e., π/2 (introducer by first coupler) added to π/2 (introduced by second coupler) equals to π (at T-port) for probe signal. Therefore, if outputs of SOAs are same, it is canceled, and no pulse appears at the T-port. If it is different, then it still appears as T-port giving the INVERTER/BUFFER operation as (01000001001000001001)/(01000001001000001001).

3 Theoretical analysis

In the proposed model, of the given design the path length (L) of two arms of interferometer is same and both signals present the same wavelength (λ). As θ_1 and θ_2 is a phase difference created by both the arms then, total phase difference created by both the arms of MZI is $\Delta\theta$ that can be described by

$$\theta_1 - \theta_2 = \Delta\theta$$
$$\left(\frac{2L\pi \quad (n_1 - n_2)}{\lambda}\right) \tag{1}$$

where, n_1 and n_2 are refractive index of both the arms of MZI. As in design, the first 3dB coupler of 50:50 coupling ratio for which $\epsilon = 0.5$can be calculated with the scattering matrix or propagation matrix as in [19] is given by

$$\begin{bmatrix} \sqrt{1-\epsilon} & j\sqrt{\epsilon} \\ j\sqrt{\epsilon} & \sqrt{1-\epsilon} \end{bmatrix} \tag{2}$$

If I_1 and I_2 are intensity of light at the input terminal of MZI, which is output of Mode lock laser and MUX_1 and MUX_2 is intensity of light after passing through first 3dB coupler then,

$$\begin{bmatrix} MUX_1 \\ MUX_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{2}} & j\frac{1}{\sqrt{2}} \\ j\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \tag{3}$$

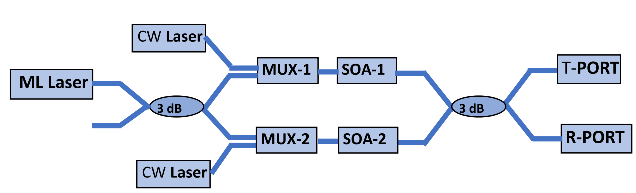

Figure 1: Schematic design of all-optical INVERTER/BUFFER gate.

After passing through SOA, due to XGM, the MLL pulse is compressed, giving the inverse effect on the gain, available to the CWL pulse. This will create the phase change in MLL pulse, so the propagation matrix is given as [20]

$$\begin{bmatrix} e^{j\frac{\Delta\theta}{2}} & 0 \\ 0 & e^{-j\frac{\Delta\theta}{2}} \end{bmatrix} \tag{4}$$

The transfer matrix of an MZI can be defined as

$$\begin{bmatrix} \frac{1}{\sqrt{2}} & j\frac{1}{\sqrt{2}} \\ j\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \cdot \begin{bmatrix} e^{j\frac{\Delta\theta}{2}} & 0 \\ 0 & e^{-j\frac{\Delta\theta}{2}} \end{bmatrix} \cdot \begin{bmatrix} \frac{1}{\sqrt{2}} & j\frac{1}{\sqrt{2}} \\ j\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

$$= \begin{pmatrix} \frac{1}{2}e^{j\frac{\Delta\theta}{2}} - \frac{1}{2}e^{-j\frac{\Delta\theta}{2}} & j\frac{1}{2}e^{j\frac{\Delta\theta}{2}} + j\frac{1}{2}e^{-j\frac{\Delta\theta}{2}} \\ j\frac{1}{2}e^{j\frac{\Delta\theta}{2}} + j\frac{1}{2}e^{-j\frac{\Delta\theta}{2}} & -\frac{1}{2}e^{j\frac{\Delta\theta}{2}} + \frac{1}{2}e^{-j\frac{\Delta\theta}{2}} \end{pmatrix} \tag{5}$$

Since the second 3 dB coupler has same coupling factor, so at the output of MZI can be calculated as

$$\begin{bmatrix} T_{\text{port}} \\ R_{\text{port}} \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{2}} & j\frac{1}{\sqrt{2}} \\ j\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} MUX_1 \\ MUX_2 \end{bmatrix} \tag{6}$$

As there is no signal in input 1 so, the output power at T-port and R-port is given as

$$P_{\text{T-port}} = T_{port} . T_{port*} = \sin^2\left(\frac{\Delta\theta}{2}\right) P_1 \tag{7}$$

$$P_{\text{R-port}} = R_{port} . R_{port*} = \cos^2\left(\frac{\Delta\theta}{2}\right) P_1 \tag{8}$$

where, P_1 is power at input terminal-1. From this equation we can conclude that,

At Δθ = 180° Power of T-port has maximum intensity of light and R-port has minimum. To create the optical logic gates with good performance, it is always required that for logic 0, we have to create a proper phase difference of π so that pulse is totally canceled and no power should occur at the output terminal.

4 Boolean analysis

As in digital gates, we expect the same output from the all-optical logic gates shown in Table 1. The proposed one input gates are based on XGM in SOA and XPM in MZI configuration. The design of two input gates with four case studies was mentioned in [21]

Table 1: Truth table of INVERTER and BUFFER gates.

	Input (I)	INVERTER(O)	BUFFER(O)
Case-1	0	1	0
Case-2	1	0	1

Boolean analysis for the proposed gates is given as

Condition-1- Due to cross gain modulation (XGM) in SOA.

There will be two Rules

Rule-1- If Input probe traveling through MLL i.e., $I_{\text{probe}} = 0$, then after passing through SOA it is multiplied to corresponding pump signal i.e., I_{pump}.

Rule-2- If Input probe traveling through MLL i.e., $I_{\text{probe}} = 1$, then after passing through SOA it is added to corresponding pump signal i.e., I_{pump}.

Condition-2- Due to cross phase modulation (XPM) in MZI configuration.

There will be two Rules

Rule-1- After passing through SOAs, if data are same, then it will be canceled, and the output will be '0' at T-port.

Rule-2- After passing through SOAs, if data are different, then it will be added, and the output will be '1' at T-port.

At the upper arm of INVERTER gate Input one from CW laser, acts as a pump multiplexed with string of ones, generated from MLL laser acting as probe signal, therefore

Output of upper arm multiplexer is $(I_1 I_2)_{\text{CWL}} . (1_1\, 1_2)_{\text{MLL}}$
= (0 1). (1 1)

Output of SOA1 is = {(0 + 1). (1 + 1)} as condition-1 Rule-2,
= {1.0}

At the lower arm of INVERTER gate string of ones from CW laser, acts as a pump multiplexed with string of ones, generated from MLL laser acting as probe signal, therefore

Output of lower arm multiplexer is $(1_1\, 1_2)_{\text{CWL}} . (1_1\, 1_2)_{\text{MLL}}$
= (1 1). (1 1)

Output of SOA1 is = {(1 + 1). (1 + 1)} as condition-1, Rule-2
= {0.0}

At output of second coupler T-port, according to condition-2 Rule 2&1,

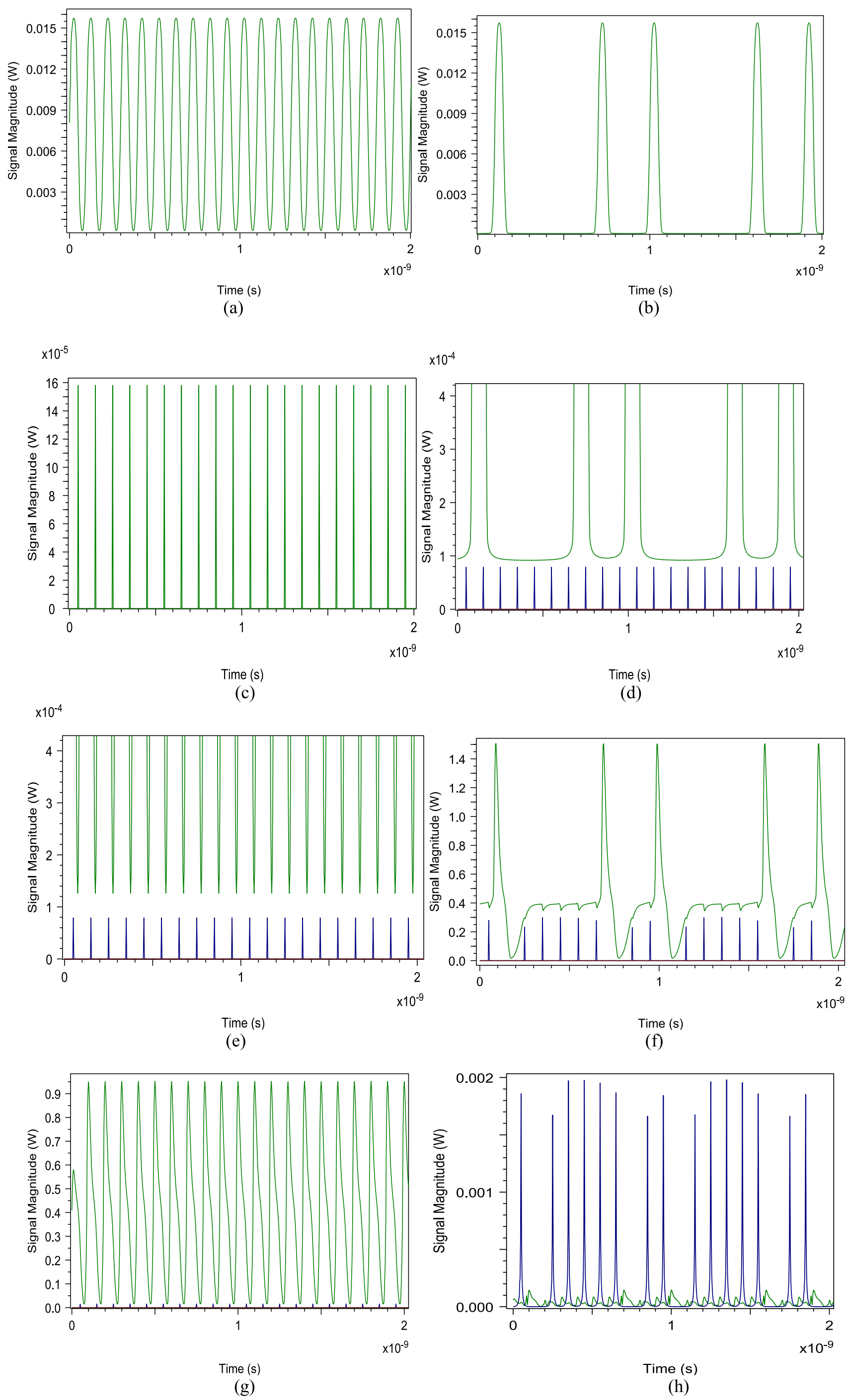

Figure 2: Result of INVERTER Gate (a) Strings of ones from CWL at upper input arm (b) Input data from CWL at lower input arm (c) String of ones from MLL at upper input arm of MZI (d) Output of multiplexer-1 (e) Output of multiplexer-2 (f) Saturated output pulse of SOA-1 (g) Saturated output pulse of SOA-2 (h) INVERTER output at Transmission port.

$\{1.0\} \oplus \{0.0\} = \{1.0\}$ = INVERTER

Boolean analysis for the proposed BUFFER gate is given with the same conditions and rules discussed above.

At the upper arm of BUFFER gate Input data, I from CW laser, acts as a pump multiplexed with same Input I, generated from MLL laser acting as probe signal, therefore

Output of upper arm multiplexer is $(I_1I_2)_{CWL} \cdot (I_1I_2)_{MLL}$

$= (0\ 1).\ (0\ 1)$

Output of SOA1 is $= \{(0.0).\ (1 + 1)\}$ as condition-1 Rule-1&2,

$= \{0.0\}$

At the lower arm of BUFFER gate string of ones from CW laser, acts as a pump multiplexed with Input I, generated from MLL laser acting as probe signal, therefore

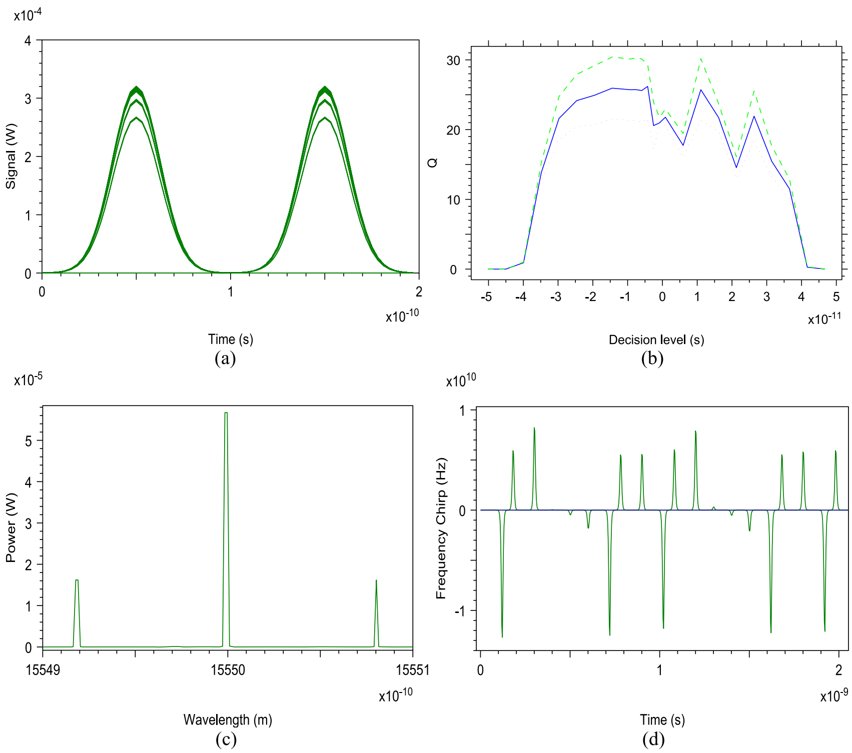

Figure 3: Simulated result of INVERTER gate (a) Eye diagram (b) Plot of Q-factor versus decision level (c) Plot of wavelength spectrum (d) Frequency chirp.

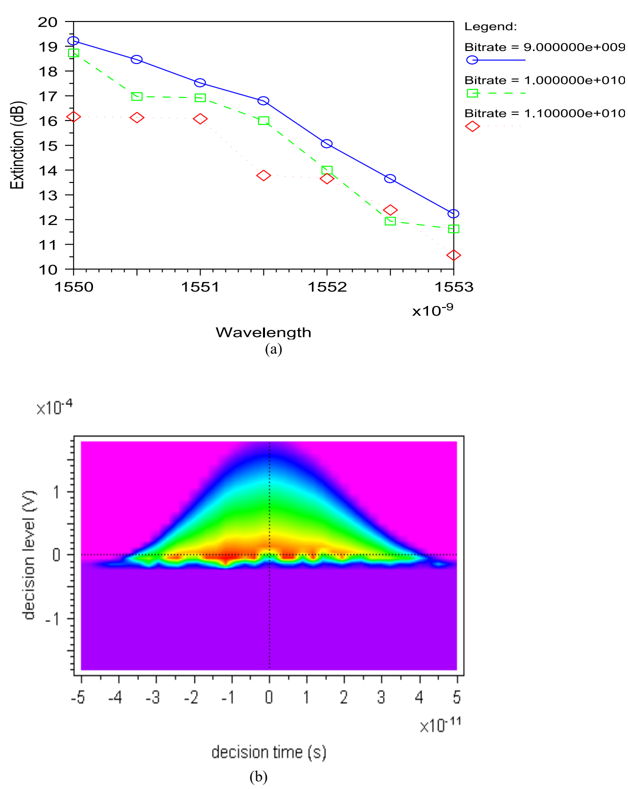

Figure 4: Simulated result of INVERTER gate (a) Plot of extinction ratio at different wavelengths (b) Plot of eye pattern.

Output of lower arm multiplexer is $(0_1\ 0_2)_{CWL}.\ (I_1 I_2)_{MLL}$
$= (0\ 0).\ (0\ 1)$

Output of SOA1 is $= \{(0.0).\ (0+1)\}$ as condition-1 Rule-1&2,
$= \{0.1\}$

At output of second coupler T-port, according to condition-2 Rule-1&2,

$\{0.0\} \oplus \{0.1\} = \{0.1\} =$ BUFFER

5 Specification and method

The proposed design of optical gates presented in Figure 1, of pump signal 10 Gb/s, with peak power of 0.05 W of continuous wave. Binary sequence of 1550 nm with chirp factor 0.5 A driven by raised cosine RZ pulse is generated through PRBS. Mach–Zehnder modulator is used to modulate the signal with point per bit 2^5–1. Pump signal peak power, generated through CW laser is 0.015×10^{-4} W and probe signal peak power, generated through ML laser is 1×10^{-3} W with same PRBS at 1555 nm. Modulated Gaussian pulse, chirped with 0.5 factors driven by raised cosine RZ pulse launched into multiplexer through 3 dB coupler. After passing through both the arms of interferometer, both the arms data are merged through second 3 dB coupler at T-port to achieve the required gate output.

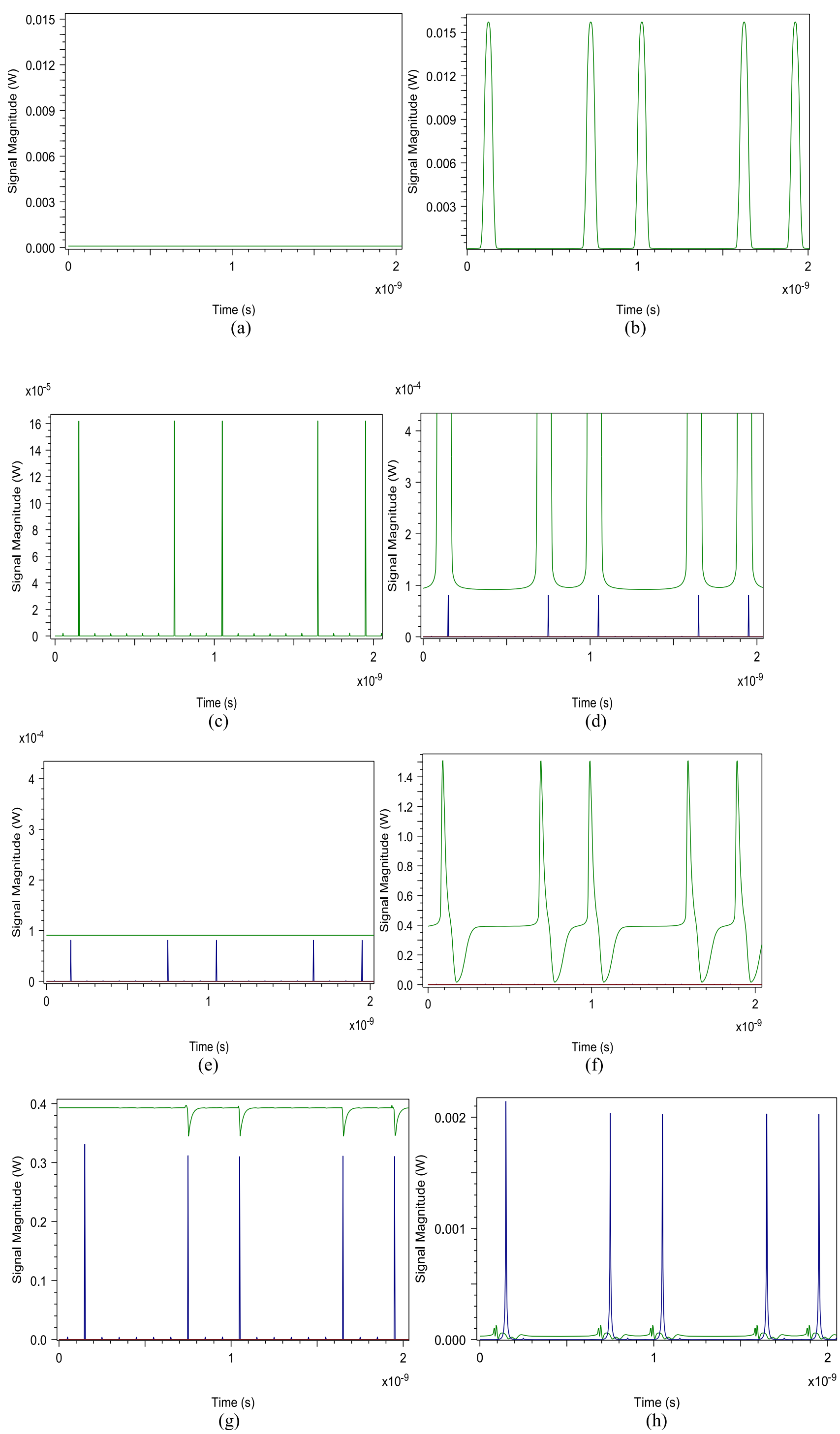

Figure 5: Results of BUFFER gate (a) String of zeros from CWL at upper input arm (b) Input data from CWL at lower input arm (c) Input data from MLL at upper input arm of MZI (d) Output of multiplexer-1 (e) Output of multiplexer-2 (f) Saturated output pulse of SOA-1 (g) Saturated output pulse of SOA-2 (h) BUFFER output at transmission port.

5.1 Simulated results and discussions for INVERTER gate

Figure 2(b) show simulated data generated through clock wave laser i.e., A = (01000001001000001001). Figure 2(a) and (c) show the string of ones generated through clock wave laser known as pump and Mode lock laser known as probe signal, respectively. The output of both multiplexers and SOAs are shown in Figure 2(d)–(g). Figure 2 (h) shows the output of INVERTER gate filtered by Lorentzian filter results at transmission port of 3 dB coupler.

In Figure 3(a) and (b) show the eye diagram and Q-factor which has very simple structure with indistinguishable levels of marks and space. At T-port Gaussian filter is used to filter the probe pulse giving the extinction ratio 18.71 dB where the maximum Q-factor lies between -4×10^{-11} and 4×10^{-11} s. This shows the significant effect of noise with decision point at zero decision offset which is 20 dB. The Q-factor is very useful parameter as it is evaluated from the eye diagram. It is also common in communication system to refer Q-factor in linear unit. It was developed to address the need for a practical and accurate way of measuring the system margin and defined as linear unit of SNR for decision circuit Figure 3(c) shows the wavelength spectrum, which indicates that the highest power pulse occurs at 1555 nm with 5.9×10^{-5} W. Other two pulses of lower power are resultant of four waves mixing which are filtered by Lorentzian filter at the output. When probe and pump pass through SOA, then due to XGM, there is a phase modulation which gives raises an instantaneous change in refractive index. This creates a variation in optical frequency with time given in Figure 3(d).

Figure 4(a) shows the variation of ER at different data wavelengths for three different bitrates i.e., 9.0, 10.0 and 11.0 Gb/s. The extinction ratio for RZ modulation format at 9.0 Gb/s is higher than 11.0 Gb/s by 3.0 dB at 1550 nm pump wavelength as for higher bit rate resultant output is degraded. Maximum extinction ratio 19.25 dB is found at 1550 nm for 9.0 Gb/s. Figure 4(b) shows the eye pattern with color code with respect to decision time and decision level. The highest intensity of light is shown in red and lowest with pink.

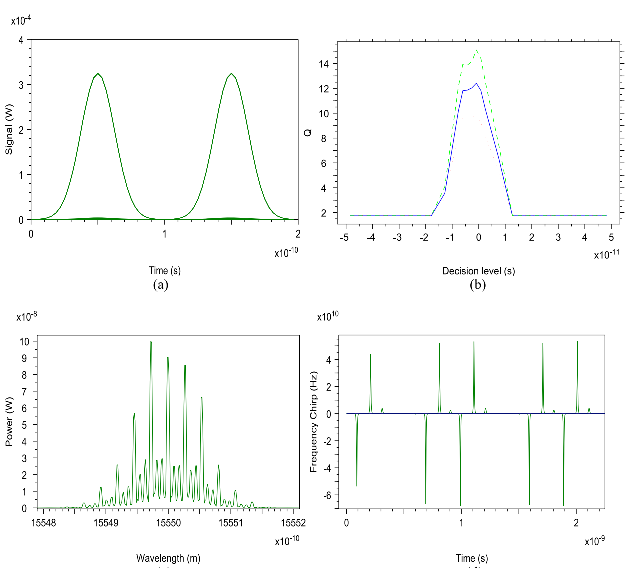

Figure 6: Sim0.ulated result of BUFFER gate (a) Eye diagram (b) Plot of Q-factor versus decision level (c) Plot of wavelength spectrum (d) Frequency chirp.

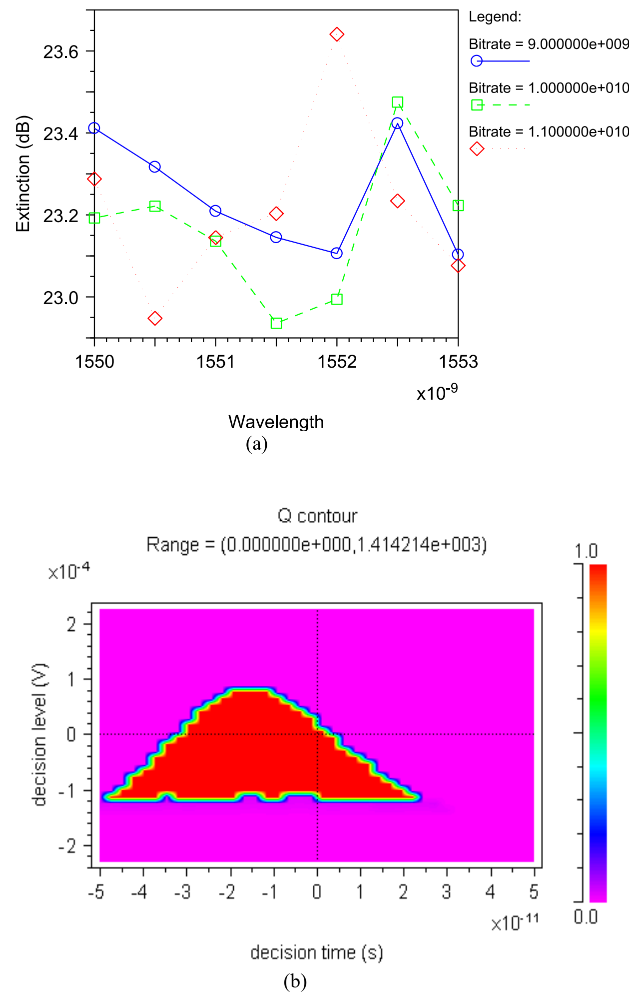

Figure 7: Simulated result of BUFFER gate (a) Plot of extinction ratio at different wavelengths (b) Plot of eye pattern.

5.2 Simulated results and discussions for BUFFER gate

Figure 5(b) and (c) show the data generated through Clock wave laser and Mode lock laser i.e., A = (01000001001000001001). Figure 5(a) shows the string of zeros generated through Clock wave laser. Depending upon the pulse generation, these data are defined as pump and probe signals. The output of both multiplexers and SOAs are shown in Figure 5(d)–(g). Figure 5(h) shows the output of BUFFER gate results at transmission port.

In Figure 6(a) and (b) show the eye diagram and Q-factor filtered by Gaussian filter at T-port with extinction ratio 30.0 dB where the maximum Q-factor lies between -1.5×10^{-11} and 1.5×10^{-11} s. In eye diagram, the effect of pattern dependence is due to the laser properties as dispersion, nonlinearity, or certain noise. This problem with eye exhibiting pattern dependence is impossible to fit as a simple Gaussian distribution to either the mark or space level. Eye diagram of the received signal is important because it represents a direct measure of a system performance deprivation caused by transmission deficiency and environmental change. Figure 6(c) shows the wavelength spectrum, which indicates that the probe pulse power occurs at 1555 nm with 10.0×10^{-8} W. Wavelength spectrum at the output T-port is due to the four-wave mixing (FWM) which is analogous to intermodal distortion occurring at output signal. Other pulse at 1550 nm is a resultant of pump power which is filtered at the output. During the modulation process in SOA a time dependent phase change lead to a variation in optical frequency of the pulse at each instant given in Figure 6(d).

Figure 7(a) shows the variation of ER at different data wavelengths for three different bitrates i.e., 9.0, 10.0 and 11.0 Gb/s Maximum ER is obtained at 11.0 Gb/b at 1552 nm i.e., 23.64 dB. The extinction ratio higher for 9.0 than 10.0 Gb/s by the amount 0.50 dB at 1550 nm pump wavelength. Figure 7(b) shows the eye pattern of maximum intensity of light with red color with respect to decision time -5×10^{-11}–2.3×10^{-11} s and decision level -1.1×10^{-4}–1.0×10^{-4} V.

6 Decisions

Extinction ratio for RZ modulation format at 10.0 Gb/s is compared in Figure 8, for Inverter and Buffer. It is seen that the extinction ratio of Buffer is higher than Inverter for the pump wavelength in the range of 1550–1553 nm because in Inverter when string of ones from clock wave laser passes through SOA, it is not totally suppressed but still some fraction of light is left out which gives the inferior extinction ratio than Buffer.

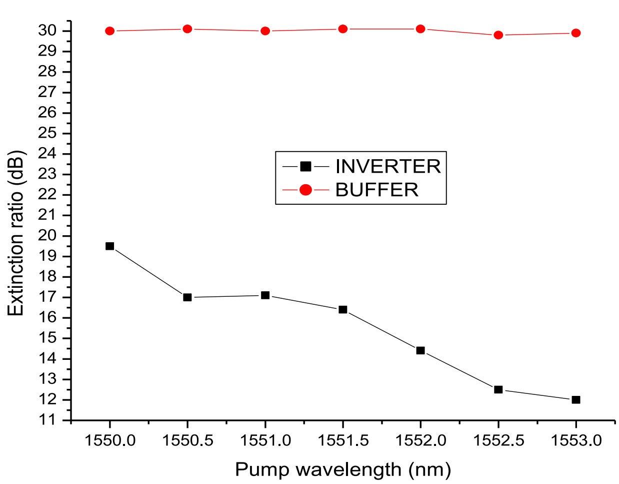

Figure 8: Comparative simulated results of BUFFER and INVERTER gate for extinction ratio at different pump wavelengths.

7 Scope of the work

Tremendous developments in all-optical semiconductor optical amplifier-based Mach–Zehnder Interferometer gates have been achieved in the last decade. Advance research and technological innovations have improved the design of all optical gates. Nowadays, it has become necessary to build all-optical logic gates that can be controlled optically on the same platform so that it may be easily integrated on a photonic chip. Gates that can be controlled optically are basic elements for high speed signal processing which can avoid optoelectronic conversion in communication systems. In future, all-optical logic gates are the key elements for optical signal processing such as, data encryption, address recognition and label swapping etc. The designs aim to achieve the goal through simulation and Boolean analysis in terms of gates to provide simple design rule. Still there is a vast scope to develop the memory element with the help of semiconductor optical amplifier-based Mach–Zehnder Interferometer structure. Therefore, there is broad scope for the future work in the field of all-optical digital circuit.

8 Conclusions

In the paper, we demonstrated the basic design perform all-optical INVERTER/BUFFER gates. The purpose is to get the output pulse at same wavelength for comparative study. And also develop a common Boolean rule for all-optical logic gates at same output pulse as in digital gates. Extinction ratio is a key parameter to optimize the gate operation to get a similar result as in Digital gates. In digital gates we define the gate operation if zero i.e., less than threshold voltage and one i.e., above threshold voltage. In optical gates zero, is significance of no light pulse and one is presence of light pulse. Therefore explaining optical gates with extinction ratio will make it easy to analyze and compare with digital gates. Furthermore, as we go for a higher linewidth enhancement factor, it limits the Extinction ratio to optimize the gate performance.

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References

1. Meymand RE, Soleymeni A, Granpayeh N. All-optical AND, OR, and XOR logic gates based on coherent perfect absorption in graphene-based metasurface at terahertz region. Optic Commun 2020;458: 124772.
2. Li P, Wang Y, Xu P. All-optical logic gates based on unidirectional surface plasmon polaritons. Appl Optic 2019; 58:4205–10.
3. Tavakoli G, Alipour-Banaei H, Kashtiban MH. A noval proposal for all-optical compact and fast XOR/XNOR gate based on photonic crystal. J Mod Optic 2019;66:599–605.
4. Webb RP, Manning RJ, Maxwell GD, Poustie AJ. 40 Gbit/s all-optical XOR gate based on hybrid-integrated Mach–Zehnder interferometer. Electron Lett 2003;39:79–80.
5. Reis C, Chattopadhyay T, Andre P, Teixeira A. Single Mach–Zehnder interferometer based Boolean logic gates. Appl Optic 2012;51:8693–701.
6. Senior JM. Optical fiber communication. India: Pearson; 2010.
7. Miller DBA. Device requirement for digital optical processing in digital optical computing. SPIE Digital Libr 1990;35:68–76.
8. Kim JY, Kang JM, Kim TY, Han SK. All-optical multiple logic gates with XOR, NOR,OR, and NAND functions using parallel SOA-MZI structures: theory and experiment. J Lightwave Technol 2006;24: 3392–9.
9. Ye X, Ye P, Zhang M. All-optical NAND gate using integrated SOA-based Mach–Zehnder interferometer. Opt Fiber Technol 2006;12:312–6.
10. Bhattacharyya A, Gayan DK, Chattopadhyay T. All-optical parallel parity generator circuit with the help of semiconductor optical amplifier (SOA)-assisted Sagnac switches. Optic Commun 2014; 313:99–105.
11. Tsiokos D, Kehayas E, Vyrsokinos K, Houbanlis T, Stampoulidis L, Kanellos GT, et al. 10 Gb/s all-optacal half-adder with interferometric SOA gates. IEEE Photon Technol Lett 2004;16:284–6.
12. Zhang S, Li Z, Liu Y, Khoe GD, Dorren HJS. Optical shift register based on an optical flip-flop memory with a single active element. OSA, Opt Express 2005;13:9708–13.
13. Lazzeri E, Berrettini G, Meloni G, Bogoni A, Poti L. N-bits all-optical circular shift register based on semiconductor optical amplifier buffer. Proc SPIE Photon USA 2011;7948:1–6.
14. Lai DMF, Kwok CH, Yuk HI, Wong KKY. Picosecond all-optical logic gates (XOR, OR, NOT, and AND) in a fiber optical parametric amplifier. In: Conf OFC/NFOEC. IEEE, San Diego CA; 2008:1–3 pp.
15. Dong J, Zhang X, Wang Y, Xu J, Huang D. 40 Gbits reconfigurable photonic logic gates based on various nonlinearities in single SOA. Electron Lett 2007;43:884–6.
16. Berrettini G, Simi A, Malacarne A, Bogoni A, Potí L. Ultrafast integrable and reconfigurable XNOR, AND, NOR, and NOT photonic logic gate. IEEE Photon Technol Lett 2006;18:917–19.
17. Singh P, Dixit HK, Tripathi DK, Mehra R. Design and analysis of all-optical inverter using SOA based Mach–Zehnder interferometer. Optik 2013;124:1926–9.
18. Singh P, Tripathi DK, Jaiswal S, Dixit HK. Design of all-optical buffer and OR gate using SOA-MZI. Opt Quant Electron 2013;46:1435–44.
19. Marz R. Integrated optics. Design and modeling. Boston: Artech House; 1995.
20. Madsen CK, Oswald P, Cappuzzo M, Chen E, Gomez L, Griffin A, et al. Reset-free integrated polarization controller using phase shifters. IEEE J Sel Top Quant Electron 2005;11:431–8.
21. Singh P, Tripathi DK, Jaiswal S, Dixit HK. Design and analysis of all-optical AND, XOR and OR gates basedon SOA-MZI configration. Optic Laser Technol 2015;66:35–44.