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RESEARCH ARTICLE

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Simulation and numerical analysis of SOA- based all optical NAND gate for high data rate communication

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Abstract: As a result of the development of advanced semiconductor-based optical switching devices and their commercialization, concepts and technologies in all-optical signal processing have evolved significantly in the past few years. Universal gates are required for the realization of logical processes in photonic computing. In this study, a straightforward and small-footprint all-optical NAND gate was created utilizing semiconductor optical amplifier and simulated at high data rates between 10 to 40 Gbps. Numerical analysis of the performance of the suggested NAND gate for various input combinations and semiconductor optical amplifier (SOA) is shown. A numerical study is carried out by varying the wavelength, injection current, confinement factor, and optical elements such as sources, amplifiers, and filters. Unique results were obtained at a 10 Gbps to 40 Gbps data rate for NRZ-L user-defined bit sequences. This type of all-optical NAND gate will be the perfect alternative in the field of all-optical computing to realize a high-speed optical communication network. An extinction ratio of 15.323 dB is achieved at a high data rate of 40 Gbps. The output spectrum of the designed NAND logic is also obtained for a wide input spectrum and the system responds selectively to the input wavelength at 1548.3 nm, which is the probe signal wavelength.

Keywords: Cross-gain modulation, erbium doped fibre amplifier, extinction ratio, gain saturation, optical logic gate, semiconductor optical amplifier.

INTRODUCTION

Considerable research has gone into making all-optical integrated circuits, which are widely useful for doing ultrafast computing to handle ultrahigh bandwidth in the field of communication engineering technology. This technology is very helpful in developing miniaturized and noise-free integrated circuits, which are very difficult to realize using conventional electronic components. Among all the digital logic gates, these are the primary elements for performing any kind of function in electronic circuits. Therefore, similar kinds of gates will be replaced by optical logic gates so that all functions can be done with light.

All-optical logic gates are unique due to their small physical size, negligible electronic interference, excellent immunity against short circuits, and high bandwidth transmission with negligible loss. Implementing a nonlinear medium is essential to complete the design of an all-optical system which plays a major role in modulating the input light signals into the desired output. At a data rate of 80 Gbps, the configuration of the NAND logic gates employing a semiconductor optical amplifier (SOA) and PC-SOA with Mach-Zehnder interferometer (MZI) structure has been designed to achieve an extinction ratio of 7.1 dB and 16.2 dB, respectively (Heydarian *et al*., 2022). In addition, a three-input all-optical NAND gate that makes use of polarisation rotation in an SOA was demonstrated. The goal of this demonstration was to achieve a high extinction ratio with an unsaturated gain of 30 dB, despite the fact that the output signals had non-uniform amplitudes (Mukherjee & Raja, 2020).

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The design of all-optical logic gates comprises an encoding system, a frequency generator, and a frequency converter. For the representation of binary states, hybrid encoding techniques are preferred. A four-wave mixing semiconductor amplifier was adopted to develop a frequency generator, and a cross-polarization rotation effect was adopted to develop a frequency convertor. With these designed components, a universal all-optical NAND logic system has been studied (Mukherjee *et al*., 2019). The use of filters along with SOA can help improve the efficiency of the NAND gate.

Continuous improvement is made by the research community from the existing SOA-based NAND gate designs into the SOA-MZI configuration, which enables high switching efficiency, ER ratio, and high bit rate operation (Mehra *et al*., 2012). To achieve miniaturization, an integrated SOA-based MZI was used at a data rate of 10 Gbps, which opens a new horizon to realize all-optical routing (Ye *et al*., 2006). The enhancement of the existing design has been attained by introducing a distributed Bragg reflector laser integrated SOA. By increasing the signal rate between 1.25 Gbps and 10 Gbps, the extinction ratio was reduced from 28 dB to 6 dB (Yu *et al*., 2014).

Kim *et al*. (2006a) found that the NAND, NOR, and their combinations have the best chance of being able to do all kinds of logical operations in the future high-capacity optical communication networks. Excellent recovery time and high-speed operations have been achieved at 5 ps and 10 Gb/s, respectively, using nonlinear vertical-cavity semiconductor gates (Porzi *et al*., 2008). All-optical AND and NAND gates were designed using silicon-based micro ring resonators, which showed the free carrier dispersion effect (Ibrahim *et al*., 2003). To achieve 15 dB at 10 Gbps, one research team developed a structure with parallel SOA and MZI logic gates. These gates include XOR, OR, NOR, and NAND (Kim *et al*., 2006b).

To obtain an ER of 11 dB and a low penalty of 2.3 dB with a gate operating data rate of 42.6 Gbps, differently switched SOAs are used in a MZI configuration (Dailey *et al*., 2009). The design and modelling of an all-optical NAND gate employing an SOA with a high ER of 15.323 and a data rate of 40 Gbps are reported in this research. The necessary mathematical support from the current literature is used to effectively address the theoretical background of the EDFA and SOA. User defined random input sequences were used in the NAND gate simulations, and the accompanying numerical analyses are documented. The performance of the designed NAND operation was compared with those reported previously.

MATERIALS AND METHODS

Design arrangement

Figure 1 shows the block diagram of the proposed SOA-based all-optical NAND gate. It consists of an EDFA along with a TWSOA, which is the important optical component for the design of the NAND gate. As input sequences, A and B are combined by the optical multiplier and amplified by the EDFA, whereas the reference or probe signal from a continuous wave laser is combined with the amplified input data by an X-coupler. Continuous laser light from port 3 can be used as a reference signal to achieve an all-optical NAND gate function.

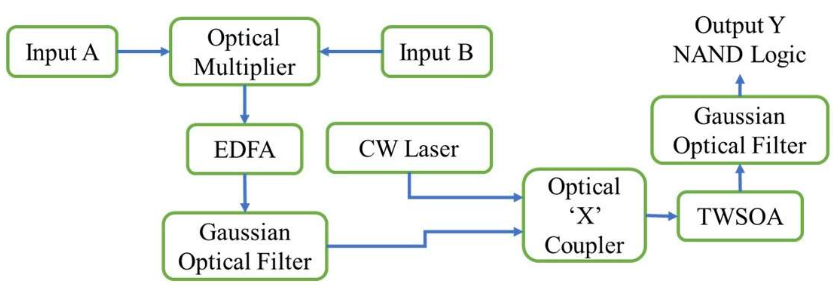

Figure 1: Block diagram representation of proposed NAND gate

Working principles of NAND logic

In the principles of operation, the two binary inputs A and B are converted into an analog waveform using an optical pulse generator, and will be given to the multiplier, which generates the multiplication of binary data. It looks like an AND logic operation. The Erbium-Doped Fibre Amplifier is used to boost the output of the multiplier. It has the lowest loss in all of the optical fibre telecommunication wavelength bands, so it can also be used to make up for signal loss as it travels.

The amplified data is further processed through a tuned Gaussian optical filter to get a specific centre wavelength. A continuous wave laser is employed to generate a probe or reference signal. An optical X coupler receives a combined input and probe signal simultaneously and its outputs are fed to a TWSOA where cross gain modulation (XGM) of carrier induced changes takes place in accordance with the changes in the input A and B (intensity modulation). During cross gain modulation, the gain is changed in SOA by the effect of gain saturation.

The modulated output wavelength of continuous wave (CW) laser is caused by gain variations of the intensity modulated input signals. The output of SOA module carries data that precisely matches the intensity-modulated input signals. The output signal is influenced by the directional characteristics of two signals, such as the reference signal and combined input signals, which can both enter the SOA in a co-directional or counter-directional manner. The optical bandpass filter receives the output of the amplifier.

The Gaussian optical filter centred at wavelength 1548.3 nm and bandwidth 40 GHZ selects the desired NAND operation. To get the optimum performance, the SOA parameters were adjusted. When inputs A and B are high, XGM can be generated at SOA, producing a low output (logic 0). If any one of the inputs is low, then the multiplier output is also low and then the output of SOA corresponds to CW laser only, which is the logic high output (logic 1). By filtering and amplifying the power of the CW laser, the NAND output can be seen.

The 'X' coupler is used to couple the output of the multiplier and the output of the CW laser; the coupling coefficient selected was 0.5 dB. The semiconductor optical amplifier receives the coupler output as its input. When either input A or B, or both, is low, a high-power output is produced. Because the multiplier output is low, cross gain modulation cannot take place. On the other hand, the CW laser reference signal makes the logic output high.

The XGM modulated signal can be generated with the combined use of the multiplier output and the signal from the continuous wave laser, whereas the output of the multiplier is high when all the two inputs are logic high. The Gaussian optical filter is used to select a preferred centre frequency from the SOA output and to remove unwanted noise. Then the output will be considered as logic "0". At least one of the inputs goes to zero (low), the output logic becomes logic "1", which indicates that the constructed logic gate reflects the NAND operations.

Theoretical background of EDFA and SOA

Erbium-doped fibre amplifiers (EDFA) are used to boost signals with a loss of less than 0.2 dB/km in the 1550 nm wavelength range. The amplification is purely optical and independent of the data rate (Durhuus *et al*., 1996). The proposed NAND gate has EDFA parameters of 2.2 μm for the core radius and doping radius. The EDFA's numerical aperture is 0.24, and the losses at 1500 nm are 0.1 dB/m. The wavelength and power for forward transmission are 1553 nm and 100 mW, respectively. Similar to this, the EDFA's backward pump wavelength and power are 980 nm and 0 mW, respectively. This demonstrates that there will be no back reflection while the gate is operating.

Simulated emission is the guiding principle behind the operation of the amplifier in erbium-doped fibre (Nakazawa *et al*., 1989). When the data is introduced into the fibre at a wavelength ranging from 1520 nm to 1560 nm, the desired result of stimulated emission can be attained. During the stimulated emission process, the signal is amplified by the photon that is just made (Agrawal, 1997).

The rate equation stated the working principles of EDFA. The population of the upper, middle, and ground state is represented byP_u, P_m andP_g, respectively. When T_p is the pumping rate, T_{ab} is the absorption of photons from the signal and τ_{12} is the lifetime of spontaneous emission, the following equations can be written as

$$\frac{dP_g}{dt} = \frac{P_m}{\tau_{mg}} + T_{ab}\left(P_m - P_g\right) - T_p\left(P_g - P_u\right), \quad \ldots(1)$$

$$\frac{dP_m}{dt} = \frac{P_u}{\tau_{um}} - T_{ab}\left(P_m - P_g\right), \quad \ldots(2)$$

$$\frac{dP_u}{dt} = -\frac{P_u}{\tau_{um}} + T_p\left(P_g - P_u\right). \quad \ldots(3)$$

In a SOA, population inversion refers to the condition, in which the population of electrons in the conduction band exceeds the population of holes in the valence band, $P_m > P_g$. Under steady state conditions, the time derivatives are not present. Since the photon lifetime at state u is much smaller than the lifetime of a photon at state m, the population of the excited state is defined by the Boltzmann distribution, β.

The population of upper level is $P_u = P_m\, e^{-\frac{E_u - E_m}{K_T}} = \beta P_m$, $\quad \ldots(4)$

where $\beta = e^{-\frac{E_u - E_m}{K_T}}$,

From (1), $\frac{P_m}{\tau_{mg}} + T_{ab}\left(P_m - P_g\right) - T_p\left(P_g - P_u\right) = 0$.

This gives the inversion level as

$$n = \frac{P_m}{P_m - P_g} = \frac{(T_p + T_{ab})\tau}{T_p\tau(1-\beta) - 1}. \quad \ldots(5)$$

Equations (1) to (4) related with population inversion, while (5) shows the degree of inversion needed for a signal to successfully flow through the EDFA (Desurvire, 1994). The inversion level n is thus related to both the probe and input signal powers, probe signal wavelength through β (Sabella & Lugli, 1999).

The nonlinear optical effect and the carrier density of SOA can be theoretically analysed by rate equations (Ishikawa, 2008). The device considered for this work is the Travelling Wave Semiconductor Optical Amplifier (TWSOA), which is used to amplify modulated light signals in which the input signal power and the internal noise have an impact on the gain of SOA. Gain saturation will occur if the input power is high, which will decrease the lasing operation in SOA (Liou *et al.*, 1997), which will result in low output.

The carrier recombination lifetime decides the gain dynamics of the SOA and the condition underneath specified appears the carrier density which is created spatially along the whole length of the active region of the device. The carrier recombination lifetime decides the gain dynamics of the SOA and the condition underneath specifies the carrier density, which is created spatially along the whole length of the active region of the device. It combines the forward and turn-around traveling signal as well as the ASE mentioned in (6) (Manimaran & Madhan, 2020). The dynamic equation for the change in carrier density inside the device's active zone is provided by

$$\frac{dn(z)}{dt} = \frac{1}{edLW} - R(n(z)) - \frac{\Gamma}{dw}\left\{\sum_{k=1}^{N_s} [\![g_m(v_k, n(z))\left(N_{sk}^{+}(z) + N_{sk}^{-}(z)\right)\right\} -]\!]\, \frac{2\Gamma}{dw}\left\{\sum_{k=1}^{N_m - 1} [\![g_m(v_k, n(z)) K_j \left(N_j^{+}(z) + N_j^{-}(z)\right)\right\}]\!], \quad \ldots(6)$$

where Γ is the confinement factor, g_m is the material gain, while *L, W* are the length and the width of the active region of the SOA, respectively. The recombination rate is $R(n(z))$, an emitted photon in the positive and negative Z-direction are $N_{sk}^{+}(z)$ and $N_{sk}^{-}(z)$. For the transverse electric (*TE*) mode, the spontaneous emission photon rate is $N_j^+(z)$, and for the transverse magnetic (*TM*) mode, it will be $N_j^-(z)$. The carrier density can be altered within the active region by varying a few parameters or processes which are shown in (6). The infused current, unconstrained radiative and nonradiative recombination, forecast recombination process of carriers, invigorated recombination by the signal, and ASE photons. In the case of a traveling wave amplifier, the mirror losses will not affect the photon lifetime (Eisenstein, 1989; Obermann *et al*., 1997). In the proposed system, the parameters chosen for the SOA are confinement factor Γ = 0.35, length L = 0.5 mm, width W = 3 μm, height H = 80 nm, Line width enhancement factor = 5, differential gain $A_d = 27.8 \times 10^{-021}\text{m}^2$.

RESULTS AND DISCUSSION

The study of this numerical simulation explored the dynamics transfer characteristics of the NAND gate for user-defined or random sequence input of A and input B with a data rate of 40 Gbps. The wavelength of 1553.05 nm and 1557.75 nm was selected for A and B with a power of -1.21 dBm and -0.223 dBm, respectively. The centre wavelength of the Gaussian optical filter is 1555.40 nm, which is the average wavelength of both inputs A and B, whereas the wavelength, injection current, and power of the probe or reference signal are 1548.3 nm, 0.95A, and -2.6 dBm, respectively.

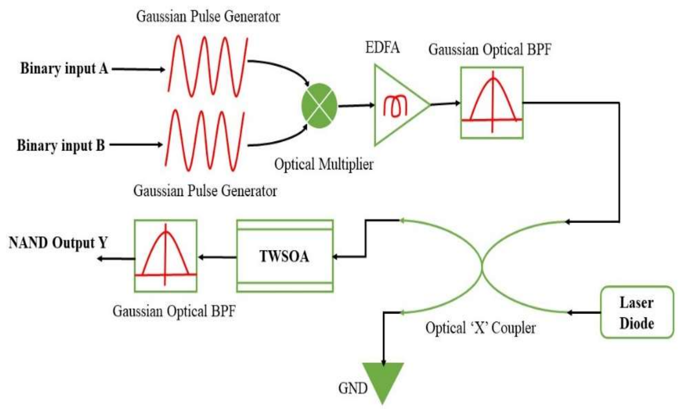

Figure 2: The schematic diagram of the proposed NAND gate design

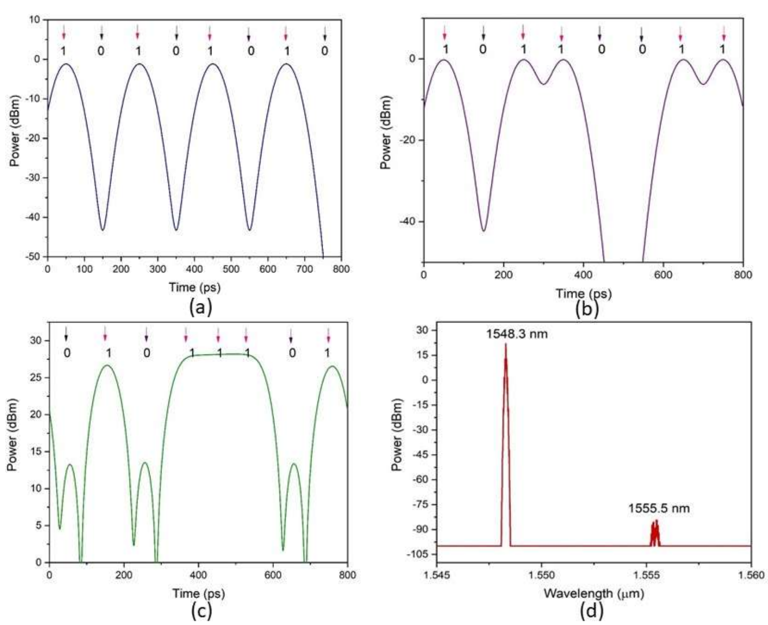

Figure 3: (a). Input sequence A; (b) Input sequence B; (c) Output of NAND logic; (d) Output Power spectrum of designed NAND logic.

The SOA parameters are set as 0.5 mm length, 3 μm width, 80 nm height, and the optical confinement factor is 0.35. The centre wavelength of the Gaussian optical filter placed before SOA is 1555.4 nm and after SOA is 1548.3 nm. Figure 2 shows the schematic of the proposed NAND gate. Figures (3a) and (3b) represent the user-defined input sequence of A: 10101010 and B: 10110011, and Figure (3c) shows the output of NAND logic Y: 01011101. From the NAND gate logic output, we observe that, the output power for logic 1 is 28.575 dBm and the output power for logic 0 is 13.252 dBm. The figure (3d) shows the output spectrum of the NAND logic and it was measured for different wavelengths ranging from 1545 to 1560 nm. The system gives a highly selective response at a 1548.3 nm input wavelength with about 28.5 dBm of output power. All other wavelengths are forbidden from transmission. Around 1555.5 nm, a small output signal (-82 dBm) arises, but it is negligible when compared to 28.5 dBm. Table 1 shows the proposed NAND gate logic output for user-defined input sequences with corresponding logical outputs with power in dBm.

Table 1: Truth table for NAND gate logic (user defined input)

User defined sequence		NAND gate logic	Output power
Input 1 logic	Input 2 logic	$y = \overline{A * B}$	(dBm)
1	1	0	13.252
0	0	1	28.575
1	1	0	13.252
0	1	1	28.575
1	0	1	28.575
0	0	1	28.575
1	1	0	13.252
0	1	1	28.575

Numerical analysis

The analysis of the proposed design can be performed by varying the parameters as well as the optical components. Different wavelengths of output for NAND logic can be observed. At a wavelength of 1548.3 nm, the performance of the pump laser is compared with the CW laser output shown in Figure 4. Even though the optical output power of the pump laser is more stable than the CW laser output, we have chosen a continuous wave laser, which is mainly used in optical low-loss applications.

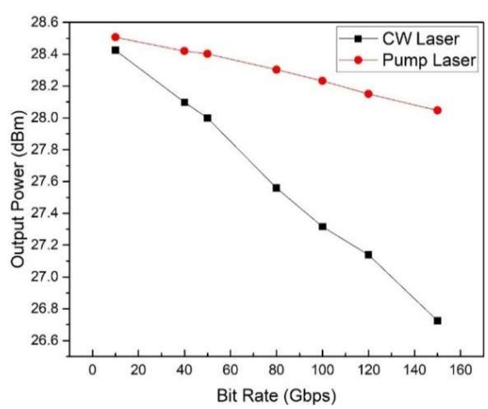

Figure 4: Output optical power at various data rates for CW and pump lasers

The impact of various types of amplifiers on the output power of NAND logic can be seen in Figure 5, in which we observe that the output is greater in optical fibre amplifiers and TWSOA. Likewise, filters were also tested to identify the better performance of the proposed logic gate. In the input stage of the proposed system, the impact of filters is high, but in the case of filters at the output stage, no impact is there, as mentioned in Table 2.

Table 2: Types of filters (vs) output power at λ= 1548.3 nm and bandwidth= 10 GHz

Sl. no	Types of filters	Output power (dBm)
1	Trapezoidal optical filter	27.416
2	Gaussian optical filter	28.575
3	Butterworth optical filter	28.202
4	Bessel optical filter	28.202
5	Fabry Perot optical filter	24.217
6	Optical digital filter	26.622
7	Periodic optical filter	28.231

The selected components from the analysis can be used for the design of a universal optical NAND gate. Figure 4 shows the relationship between the optical laser source and the operating data rate. Here the same structure can be further tested for various data rates of 10 Gbps to 200 Gbps.

Finally, the required performance can be attained at a bit rate from 10 Gbps to 40 Gbps. Afterward, its output power value can be reduced considerably, and finally, no proper transmission has occurred at a speed of 180 Gbps to 200 Gbps. The rate of change of output power for pump laser and CW laser was calculated from the plot based on the simulated output values of 0.00382 dBm/Gbps and 0.0126 dBm/Gbps, respectively. In order to improve the quality of the output signal, it is recommended to use the appropriate filter in front of the SOA.

In this study, various filters have been analysed and their outputs are observed and listed in Table 2. From the tabulated values, it is obvious that the Gaussian filter and Periodic Optical filter showed better output power compared to other filters, and their output power values are 28.575 dBm and 28.231 dBm, respectively. Since the Gaussian optical filter shows the best output power and also has an optimum shape to get high resolution in the output, it has been selected for the development of the NAND gate logic system.

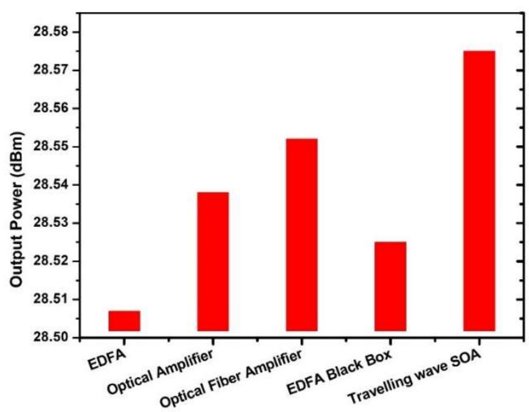

Figure 5: Output optical power for different amplifiers

Figure 6, shows the tuning of the wavelength of the carrier signal in order to get the maximum output power, which will favour efficient information transmission. After doing a large-scale variation from 1400 nm to 1600 nm, it has been identified that the system responds better around 1548 nm. Then, the signal wavelength varied from 1548.0 to 1548.9 nm with an increment of 0.1 nm. The output power is maximal when the wavelength is set as 1548.3 nm. The output power drastically decreases on the higher and lower side of the spot of 1548.3 nm, which can be interpreted as the window being optimum for the proposed system. The third optical window, which has a wavelength between 1400 and 1600 nm, was identified in the literature as an appropriate one for achieving low-loss transmission.

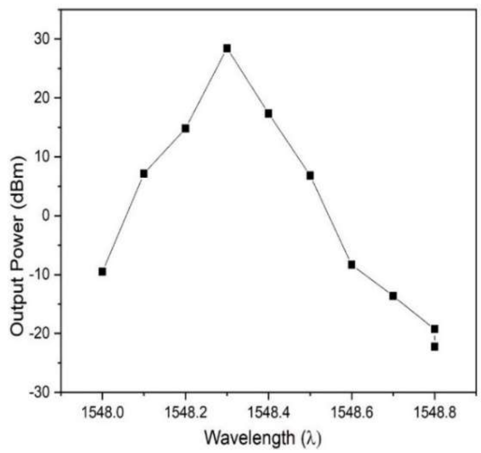

Figure 6: Wavelength (vs) output optical power using CW laser.

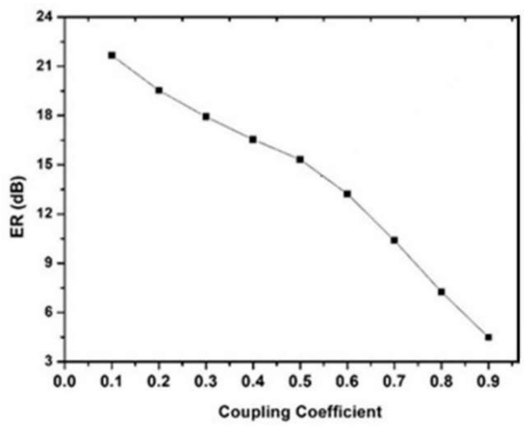

Figure 7: The response of ER to variation in coupling coefficient.

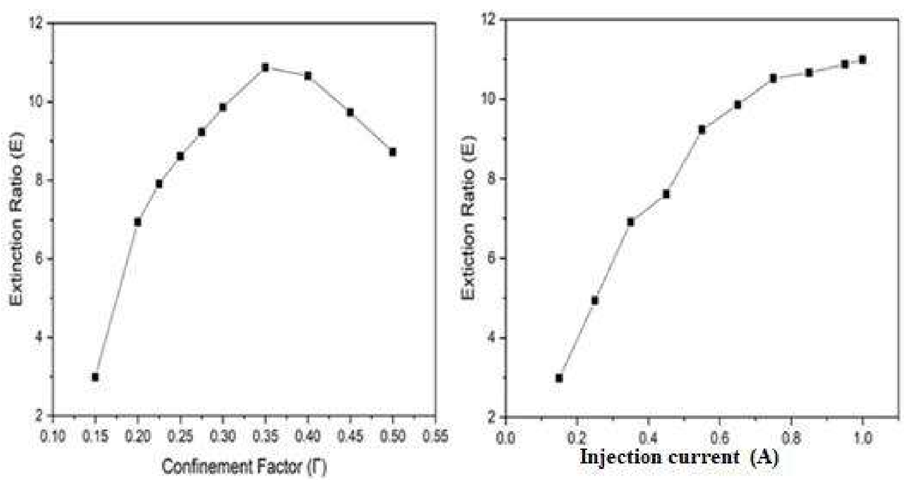

Figure 8: Relationship between confinement factor, injection current and extinction ratio at 10 Gbps data rate.

In telecommunications and optical systems, the extinction ratio (ER) is a measure of the contrast or ratio of power between the "on" and "off" states of an optical signal which considered as an important factor in evaluating the performance of the system at a particular data rate.

The performance of the NAND gate is verified using the Extinction Ratio (ER) as shown in Figure 7, by adjusting the coupling coefficient of the X-coupler. According to this, ER ratio increases if the coupling coefficient is smaller than 0.5. The ER is decreased when the coupling coefficient lies between 0.5 and 0.9. The NAND logic operation will not function correctly, after the coupling coefficient approaches one. The coupling coefficient selected for the current work is 0.5 in order to achieve an appropriate NAND gate logical operation at a high data rate of 40 Gbps. Moreover, both the confinement factor and injection current varied independently and the extinction ratio based on the output results is shown in Figure. 8. The confinement factor and the injection current of 0.35 and 0.95 A, respectively, produced an excellent extinction ratio of 15.323 dB. The same high extinction ratio can be maintained for the high-speed data rate of 10 Gbps to 40 Gbps. Similarly, the important parameters such as the Extinction Ratio (ER) and Bit Error Rate (BER) were calculated and listed in Table 3.

Table 3: Calculated parameters of the designed NAND logic system

Sl. No	Parameters	Metrics
1	Extinction ratio	15.323 dB
2	Bit error rate (BER)	4.27×10^{-26}

Table 4: Comparison of NAND gate designs

Sl. no.	Author name and year	Title	Optical components used	Data rate (Gbps)	Extinction ratio (dB)
1	Heydarian *et al*., 2022	Design and analysis of an all-optical NAND logic gate using a photonic crystal semiconductor optical amplifier based on the Mach–Zehnder interferometer structure	SOA	80	7.1
			PC-SOA	80	16.2
2	Mukherjee *et al*., 2019	All-optical logic gate NAND using semiconductor optical amplifiers with simulation	Two SOA	10	13.0
3	Oliveira *et al*., 2019	New design of all-optical logic universal NAND gate formed by NOT (A AND B) gates using Michelson Interferometer based on semiconductor optical amplifier	SOA- MI	10	-
4	Yu *et al*., 2014	All-optical decision gate with extinction ratio improved scheme using a SOA-DBR laser	SOA-DBR Laser	10	24
5	Mehra *et al*., 2012	All optical universal logic Gates Design and Simulation using SOA	Two SOA	40	8.75
6	Mehra *et al*., 2012	SOA based all-optical NAND gates and their comparison	SOA- filter	80	9.73
			SOA- MZI	80	11.09
7	Nakarmi *et al*., 2012	Demonstration of all-optical NAND gate using single-mode Fabry–Pérot laser diode	Fabry Perot laser diode	10	14.6

We deduce from the comparison table that the majority of research on the design of all-optical NAND gates for optoelectronic integrated circuits has a data rate of 10 Gbps. If the data rate rises, the extinction ratio may decline. With a single SOA and filter combination, the NAND gate in the proposed work is created with a high data rate of 40 Gbps and an enhanced extinction ratio of 15.323 dB.

CONCLUSION

A unique all-optical NAND gate using a single TWSOA has been developed and implemented in this study, and by numerical simulation, a high ER of 15.323 dB at a data rate of 10 Gbps to 40 Gbps is achieved. Additionally, the functionality of all-optical NAND gate is examined in various scenarios. By adjusting the input data, SOA, CW laser, or optical filter parameters, the maximum extinction ratio for the NAND gate was achieved. Calculated values for the ER and BER were 15.323 dB and 4.27×10^{-26} respectively.

Conflict of interest

The authors declare that there is no conflict of interest.

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