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Optimized Optical XNOR Gate at 80 Gb/s utilizing Single SOAs-MZI

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ABSTRACT

This research introduces a pioneering method utilizing a single semiconductor optical amplifiers (SOAs)-based Mach-Zehnder interferometer (MZI) to emulate the XNOR logic gate at 80 Gb/s. Compared to conventional methods, the proposed topology offers improved flexibility and efficiency while utilizing fewer hardware resources. By employing a single SOAs-MZI, the implementation of XNOR operation within optical circuits is simplified and optimized. Evaluation of the setup's performance, based on the quality factor (QF), yields an impressive QF value of 11.86, indicating robust signal integrity and noise tolerance. This underscores the approach's feasibility and potential for high-speed optical computing applications. In addition, an investigation is undertaken to assess the effects of essential operational variables, such as injection current and data rate, on the performance of the gate. The streamlined implementation and exceptional performance metrics suggest the potential of this approach to transform optical computing technologies. Ongoing research and development in this area hold promise for even more efficient and reliable optical computing systems, with wide-ranging applications across disciplines.

1. Introduction

Semiconductor optical amplifiers (SOAs) have become pivotal in optical systems due to their unique characteristics and versatile applications. Unlike traditional fiber amplifiers, SOAs utilize semiconductor materials for optical amplification, offering various functionalities beyond simple signal boosting. In recent years, SOAs have garnered significant attention for their potential in optical signal processing, logic operations, and all-optical (AO) switching. SOAs offer several advantages over other amplifiers. Their fast response time allows for high-speed signal processing, and they can be integrated with other semiconductor devices on a single chip, facilitating compact and efficient optical circuitry. Additionally, SOAs exhibit nonlinear optical properties, making them suitable for implementing nonlinear signal processing functions like wavelength conversion and optical regeneration [1].

An essential criterion in achieving information manipulation at a foundational and system-oriented level solely within the optical domain, known as AO signal processing, is the capability to perform Boolean functions exclusively using light between data-modulated signals at ultrafast line rates [2]. In the context of optical logic circuits, SOAs play a crucial role in enabling complex logic operations at high speeds. Researchers have demonstrated the implementation of various logic gates employing SOAs, opening new possibilities for realizing AO computing architectures [3–19]. The research presented in the cited papers signifies a notable advancement in the domain of AO logic gates utilizing SOAs and associated photonic technologies. Numerous studies have demonstrated the feasibility of multifunctional logic gates, encompassing operations such as AND, XOR, NOR, OR, XNOR, and NAND, all within a single compact scheme [3–9].

Emphasis has been placed on enhancing the performance and efficiency of these gates, with endeavors aimed at achieving higher speeds, lower power consumption, and improved signal integrity. Integration of SOAs with Mach-Zehnder interferometer (MZI) and other photonic structures has facilitated the realization of high-speed, reconfigurable optical logic gates, fostering compactness and scalability in optical computing architectures [10–18]. Additionally, investigations into the impact of amplified spontaneous emission (ASE) on gate performance have underscored the importance of mitigating ASE-induced noise and distortion for reliable operation [12, 19].

The experimental validation of theoretical proposals further corroborates the practicality and promise of AO logic gates for applications in ultrafast signal processing and photonic computing systems, heralding a new era of advancement in optical computing technologies [14, 16, 17]. Moreover, the

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MZI topology offers additional advantages in signal processing applications. MZIs are highly versatile devices that can be configured to perform various functions, including modulation, demodulation, filtering, and switching. Additionally, MZIs can be easily integrated with other optical components, allowing for compact and scalable optical circuitry designs [20, 21].

In our investigation, we introduce a pioneering method aimed at revolutionizing optical computing. Through the utilization of a single SOAs-MZI, we simulate the XNOR gate at an unprecedented speed of 80 Gb/s. This innovative approach capitalizes on the unique properties of SOA and MZI to achieve highly efficient and compact optical logic operations. Our primary aim is to propel the field of optical signal processing and logic circuitry forward by leveraging SOAs-based MZI technology. We strive to drive the development of future optical computing systems, ultimately contributing to transformative advancements in high-speed optical computing applications. Through rigorous evaluation and analysis, we aim to demonstrate the feasibility of our approach for high-speed optical computing applications, emphasizing its potential impact on advancing optical computing technologies. By laying the foundation for future optical computing systems, our research aims to make significant contributions to the field.

2. Materials and Methods

2.1. Operation principle

In the illustrated design shown in Fig. 1, a continuous wave (CW), functioning as the 'probe,' undergoes division using a 3 dB optical coupler (OC), then directed into both branches of the SOAs-MZI. Simultaneously, the complement of data signals NOT A ($\bar{A}$) and B, designated for XNOR operation, are injected into the upper and lower arms of the SOAs-MZI via wavelength-selective couplers (WSCs), respectively. OC and wavelength-selective couplers play critical roles in optical communication infrastructures. OC segregates and combines optical signals, while wavelength-selective couplers enable various functionalities such as WDM, add-drop multiplexing, optical filtering, and signal monitoring within WDM networks.

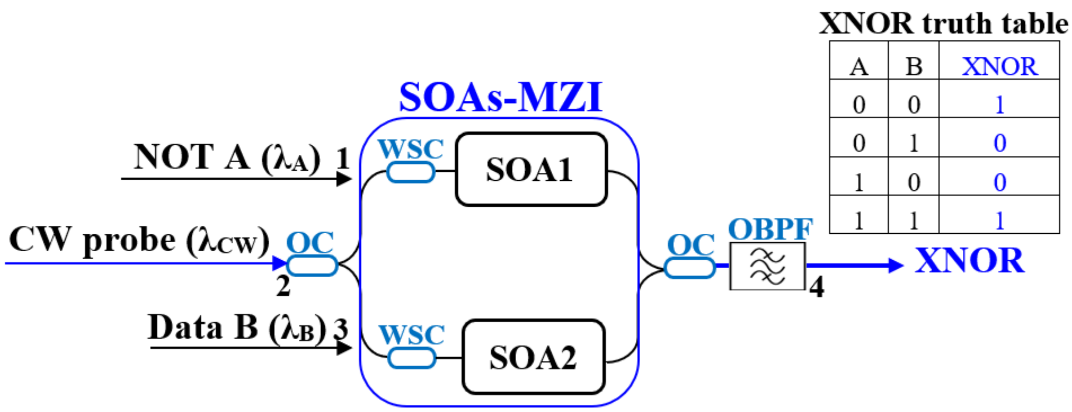

Fig. 1. Schematic of XNOR employing single SOAs-MZI. CW: continuous wave. OC: 3 dB optical coupler. WSC: wavelength-selective couplers. OBPF: optical bandpass filer.

The pump signals A and B induce perturbations in the dynamics of the SOAs-MZI arms, resulting in a phase shift of the CW signal used for the switching process at output port 4 of the SOAs-MZI. Essentially, when both $\bar{A}$ and B are identical ('0' or '1'), SOAs-MZI remains balanced, causing no phase alteration in the CW components. Consequently, when these components merge at output port 4, they interfere destructively, producing a low-amplitude output signal ('0'). Conversely, when $\bar{A}$ and B differ (e.g., $\bar{A}$ = '0' and B = '1' or $\bar{A}$ = '1' and B = '0'), the dynamic symmetry of the MZI is disrupted, resulting in a phase shift in the CW components. This shift leads to high-level amplitude modulation ('1') due to constructive interference at the output. Hence, the XNOR operation is conducted between signals A and B, and this result is imposed on the transmitted CW probe, which is specifically filtered using an optical bandpass filter (OBPF). The mathematical representation for this logical operation can be succinctly stated as A XNOR B = $\bar{A} \oplus$ B.

2.2. Simulation

The coupled equations governing SOAs provide a detailed description of the complex interaction between carriers and the optical field in these devices, incorporating carrier heating (CH) and spectral hole burning (SHB). CH arises from the non-equilibrium distribution of carriers, resulting in increased carrier temperatures and altered carrier dynamics as excess energy is absorbed during injection. Conversely, SHB causes the SOA's gain spectrum to narrow, as specific optical frequencies are preferentially amplified, leading to the formation of spectral holes within the spectrum. These phenomena, addressed within the SOAs' coupled equations, are essential for understanding and optimizing SOA performance across various applications in optical communication and signal processing, i.e. [1]:

$$\frac{dh_{CD}(t)}{dt} = \frac{h_0 - h_{CD}(t)}{\tau_C} - (exp[h_{CD}(t) + h_{CH}(t) + h_{SHB}(t)] - 1)\,\frac{P_{in}(t)}{E_{sat}} \tag{1}$$

$$\frac{dh_{CH}(t)}{dt} = -\frac{h_{CH}(t)}{\tau_{CH}} - \frac{\varepsilon_{CH}}{\tau_{CH}}(exp[h_{CD}(t) + h_{CH}(t) + h_{SHB}(t)] - 1)\,P_{in}(t) \tag{2}$$

$$\frac{dh_{SHB}(t)}{dt} = -\frac{h_{SHB}(t)}{\tau_{SHB}} - \frac{\varepsilon_{SHB}}{\tau_{SHB}}(exp[h_{CD}(t) + h_{CH}(t) + h_{SHB}(t)] - 1)\,P_{in}(t) - \frac{dh_{CD}(t)}{dt} - \frac{dh_{CH}(t)}{dt} \tag{3}$$

Here, $G0 = \exp[h0] = a\Gamma(I\tau c/eV - Ntr)$ [1] represents the unsaturated (small-signal) power gain, while $Esat = Psat\ \tau c$ [1] denotes the saturation energy. These operating parameters and their respective values are detailed in Table 1 [3–19]. To optimize the functionality of the XNOR gate, precise adjustments to the primary input signals and parameters of the SOAs are imperative, achieved through meticulous numerical simulations. These simulations are conducted employing direct band-gap semiconductor materials, with a focus on utilizing materials such as InGaAsP/InP [1].

Table 1: Default simulation parameters [3–19].

Symbol	Definition	Value	Unit
E_0	Pulse energy	0.5	pJ
τ_{FWHM}	Pulse width	1	ps
T	Bit period	8.33	ps
n	PRBS length	127	-
λ_A	Data A wavelength	1547	nm
λ_B	Data B wavelength	1540	nm
λ_{CW}	CW wavelength	1550	nm
P_{CW}	CW power	0.3	mW
I	Injection current	300	mA
P_{sat}	Saturation power	30	mW
τ_c	Carrier lifetime	200	ps
α	α-factor	5	-
α_{CH}	CH linewidth enhancement factor	1	-
α_{SHB}	SHB linewidth enhancement factor	0	-
ε_{CH}	CH nonlinear gain suppression factor	0.1	W^{-1}
ε_{SHB}	SHB nonlinear gain suppression factor	0.1	W^{-1}
τ_{CH}	Temperature relaxation rate	0.3	ps
τ_{SHB}	Carrier-carrier scattering rate	0.1	ps
Γ	Confinement factor	0.3	-
a	Differential gain	10^{-20}	m^2
N_{tr}	Transparency carrier density	10^{24}	m^{-3}
L	Active region length	500	µm
d	Active region thickness	0.3	µm
w	Active region width	3	µm
G_0	Unsaturated power gain	30	dB

The total gain G(t) for each SOA is expressed as follows [1]:

$$G(t) = exp[(h_{CD}(t) + h_{CH}(t) + h_{SHB}(t))] \tag{4}$$

The phase variation encountered by the signal propagating through each SOA is articulated as follows [1]:

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

Significantly, the αSHB value is null owing to the symmetrical spectral hole produced by SHB [3, 5]. To facilitate the intended logic operation, we assume that signals $\bar{A}$ and B exhibit Gaussian-shaped characteristics, with the length of the pseudorandom binary sequence (PRBS), denoted as n [1, 3, 5]:

$$P_{\bar{A},B}(t) \equiv P_{in}(t) = \sum_{n=-\infty}^{n=+\infty} a_{(n\bar{A},B)} \frac{2\sqrt{\ln(2)}\,E_0}{\sqrt{\pi}\,\tau_{FWHM}} \exp\left[-\frac{4\ln(2)(t-nT)^2}{\tau_{FWHM}^2}\right] \tag{6}$$

Here, $\alpha_{(n\bar{A},B)}$ represents the n-th pulse, which can assume '1' or '0' for signals $\bar{A}$ and B. The selected data pulse modulation format is return-to-zero, a commonly used scheme in various optical systems [22].

To implement the XNOR operation with the proposed scheme, we denote the input powers within the SOAs-MZI as follows:

$$P_{in,\,SOA_1}(t) = P_{\bar{A}}(t) + 0.5\,P_{CW} \tag{7}$$

$$P_{in,\,SOA_2}(t) = P_B(t) + 0.5\,P_{CW} \tag{8}$$

The XNOR output power is then given by [7, 8]:

$$P_{XNOR}(t) = 0.25\,P_{CW}\left(G_{SOA1}(t) + G_{SOA2}(t) - 2\sqrt{G_{SOA1}(t)G_{SOA2}(t)}\,cos[\Phi_{SOA1}(t) - \Phi_{SOA2}(t)]\right) \tag{9}$$

Here, GSOA1,2(t) and ΦSOA1,2(t) represent the time-varying total gains and phase shifts occurring within SOA1 and SOA2 of the SOAs-MZI, respectively.

3. Results and Discussions

The performance evaluation of the analyzed logic operation is conducted using the QF. This metric is computed using the formula QF = $(P_1 - P_0) / (\sigma_1 + \sigma_0)$, where P_1 and P_0 represent the mean peak power, and σ_1 and σ_0 [AK1]represent the standard deviation of the logical '1's and '0's, respectively. Ensuring that the QF exceeds the threshold value of 6 is essential to maintain a bit-error rate [6] below 10^{-9}, rendering it suitable for digital logic applications [3, 5, 7, 9]. Figure 2 illustrates the simulation outcomes for the XNOR function with a single SOAs-MZI at 80 Gb/s. This eye diagram demonstrates clarity and openness, affirming the feasibility of executing the XNOR operation at 80 Gb/s with a high QF = 11.86.

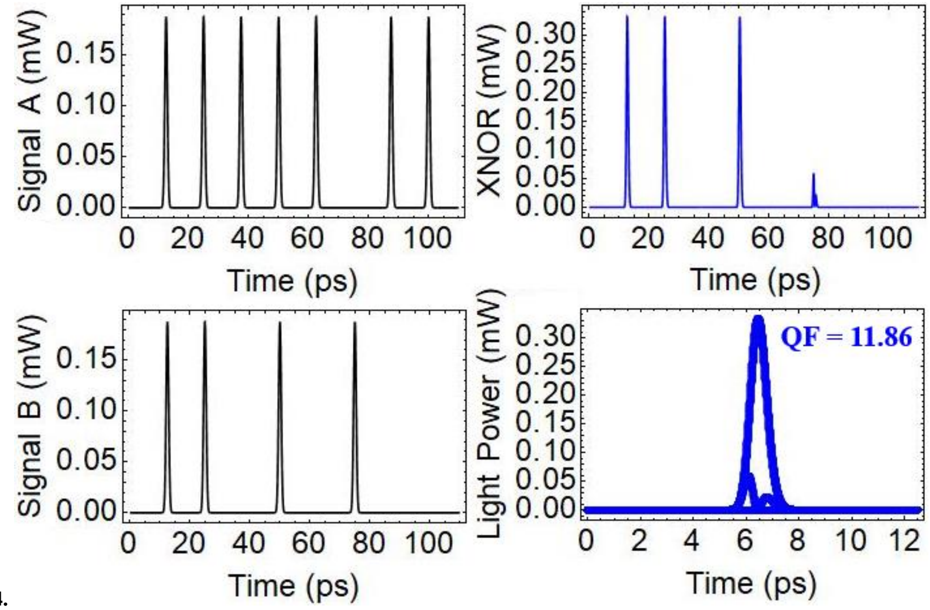

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Fig. 2. Simulated logical outcome pulse profile and eye diagram for XNOR operation employing single SOAs-MZI at 80 Gb/s with QF = 11.86.

Figure 3 provides insights into the relationship between the injection bias current (I) and the QF for the XNOR gate utilizing SOA-based MZI at 80 Gb/s. As I increases, more carriers penetrate the SOA active region. This expedites the recovery process and aids in replenishing the depleted active region layer caused by input pulses. Consequently, the observed increase in the QF indicates improved signal quality with a higher I. Optimizing I can thus enhance the efficiency and accuracy of logic operations performed using SOAs-MZI.

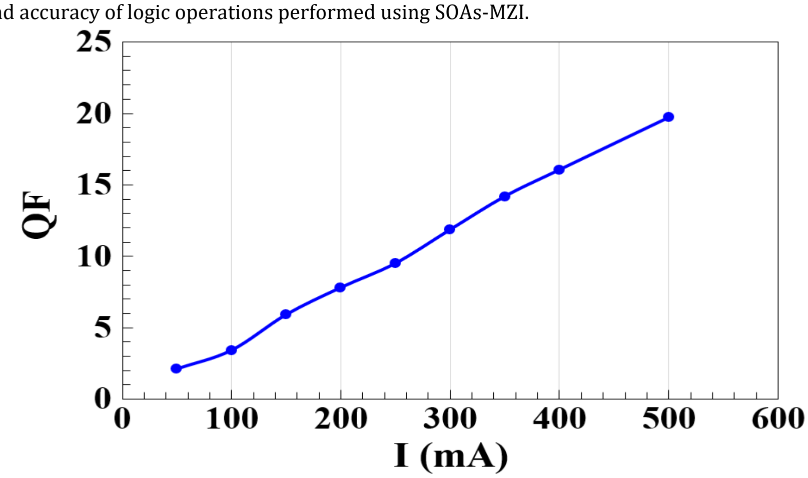

Fig. 3. QF against injection bias current (I) for XNOR gate employing single SOAs-MZI at 80 Gb/s.

When evaluating the XNOR gate's performance within the proposed scheme, the QF plotted against the data rate emerges as a crucial metric for reliability in high-speed optical computing applications. As depicted in Fig. 4, lower data rates may exhibit higher QFs for the XNOR gate, benefiting from relatively relaxed constraints on signal integrity and noise tolerance. However, as the data rate increases, various factors come into play that can impact the QF. Elevated data rates expose the XNOR gate to increased signal distortion and nonlinear effects within the SOAs, resulting in a deterioration of signal quality and a subsequent reduction in the QF. These distortions arise from phenomena such as gain saturation and carrier-induced nonlinearities within the SOAs. Nevertheless, the proposed configuration, employing single SOAs-MZI, achieves an acceptable QF of 6.87 even at 100 Gb/s. The conventional SOA is crucial for AO logic gates due to its stronger nonlinearity compared to optical fibers and its easier integration. However, the operational speed of conventional bulk SOAs is hindered by the slow temporal response of gain and phase recovery. Typically, phase-recovery times extend to several hundred picoseconds, limiting optical logic speeds to surpass 100 Gb/s [1]. On the other hand, it underscores the potential for enhancing operational data rates by integrating quantum dots into the SOA's active region [23–25].

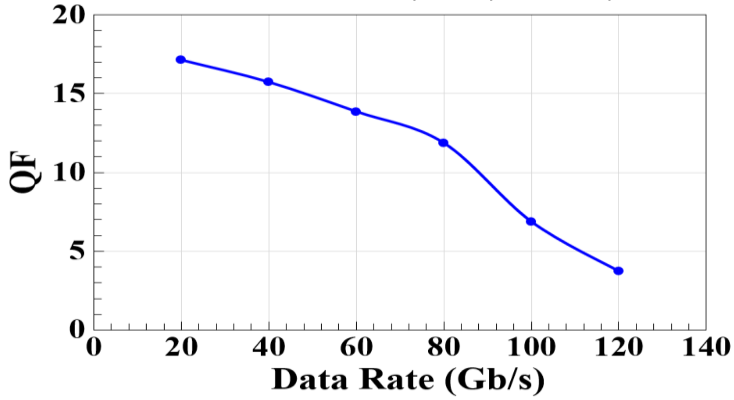

Fig. 4. QF against data rate for XNOR gate using single SOAs-MZI at 80 Gb/s.

4. Conclusion

This study introduces an innovative approach employing a single SOAs-based MZI to replicate an XNOR gate at 80 Gb/s. This new arrangement not only enhances flexibility and autonomy in managing and optimizing the setup but also lowers hardware demands compared to traditional methods with similar aims. The performance assessment of the proposed setup primarily relies on the QF, achieving a notable QF of 11.86 at 80 Gb/s. Utilizing a single SOAs-MZI facilitates the streamlined implementation of XNOR logic operations within optical circuits, highlighting its efficiency. The achieved performance metrics underscore the feasibility and potential of this approach for high-speed optical computing applications. Moreover, the proposed scheme-based XNOR gate attains a QF of 6.87 even at 100 Gb/s, demonstrating its versatility across various operational speeds. These findings open avenues for further research and development in optical computing, offering possibilities for even more efficient and robust systems catering to diverse applications.

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Author Contributions

Conceptualization: A. Kotb; Data curation: A. Kotb; Formal analysis: A. Kotb; Funding acquisition: A. Kotb; Investigation: A. Kotb, and K.E. Zoiros; Methodology: A. Kotb; Resources: A. Kotb; Validation: A. Kotb and K.E. Zoiros; Visualization: A. Kotb; Project administration: A. Kotb; Writing – original draft: A. Kotb; Writing – review & editing: A. Kotb, K.E. Zoiros, and W. Chen. Supervision: W. Chen. All authors read and approved the final manuscript, Funding None. Availability of data and materials Simulation software.

Declarations of Competing Interest

The author has no competing interests to declare that are relevant to the content

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