ALL-OPTICAL LOGIC GATES USING SEMICONDUCTOR OPTICAL AMPLIFIERS(SOA)

Report submitted to GITAM (Deemed to be University) as a partial fulfillment of the requirements for the award of the Degree of Bachelor of Technology in Electronics and Communication Engineering

Dayanand Bisanal (BU22EECE0100435)
Tejas D (BU22EECE0100426)
Chetan Kumar Swadi (BU22EECE0100436)

GITAM
DEEMED TO BE UNIVERSITY

DEPARTMENT OF ELECTRICAL, ELECTRONICS AND COMMUNICATION ENGINEERING
GITAM SCHOOL OF TECHNOLOGY
GITAM (DEEMED TO BE UNIVERSITY)
BENGALURU -561203
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DECLARATION

We declare that the project work contained in this report is original and it has been done by us under the guidance of my project guide.

Name: Dayanand Bisanal (BU22EECE0100435)
Tejas D (BU22EECE0100426)
Chetan Kumar Swadi (BU22EECE0100436)

Date: 26-09-2025

Signature of the Student

Department of Electrical, Electronics and Communication Engineering
GITAM School of Technology, Bengaluru-561203

CERTIFICATE

This is to certify that *Dayanand Bisanal* bearing *BU22EECE0100435* has satisfactorily completed Mini Project Entitled in partial fulfillment of the requirements as prescribed by University for VIIth semester, Bachelor of Technology in “Electrical, Electronics and Communication Engineering” and submitted this report during the academic year 2025-2026.

[Signature of the Guide] [Signature of HOD]

Department of Electrical, Electronics and Communication Engineering
GITAM School of Technology, Bengaluru-561203

CERTIFICATE

This is to certify that *Tejas D* bearing *BU22EECE0100426* has satisfactorily completed Mini Project Entitled in partial fulfillment of the requirements as prescribed by University for VIIth semester, Bachelor of Technology in "Electrical, Electronics and Communication Engineering" and submitted this report during the academic year 2025-2026.

[Signature of the Guide] [Signature of HOD]

Department of Electrical, Electronics and Communication Engineering
GITAM School of Technology, Bengaluru-561203

GITAM
DEEMED TO BE UNIVERSITY

CERTIFICATE

This is to certify that *Chetan Kumar Swadi* bearing *BU22EECE0100436* has satisfactorily completed Mini Project Entitled in partial fulfillment of the requirements as prescribed by University for VIIth semester, Bachelor of Technology in "Electrical, Electronics and Communication Engineering" and submitted this report during the academic year 2025-2026.

[Signature of the Guide] [Signature of HOD]

Table of contents

Chapter 1: Introduction

1.1 Overview of the problem statement

The increasing global demand for **high-speed data transmission** and processing is rapidly pushing current electronic processing systems to their theoretical limits. While optical fibers offer immense bandwidth, the necessary conversion of signals from optical-to-electrical-to-optical (OEO) at every processing node creates an

"electronic bottleneck," severely limiting the system's overall speed and efficiency. Electronic components also face challenges with high power consumption and susceptibility to electromagnetic interference when handling voluminous data.

The problem is to develop a reliable and high-speed alternative to electronic processing. **All-Optical Signal Processing (AOSP)** eliminates OEO conversion by performing logic operations directly on photons, offering advantages in speed, power efficiency, and resistance to electromagnetic noise. This project addresses this problem by designing and simulating the fundamental **all-optical logic gates** necessary to build the next generation of ultra-fast optical digital circuits.

1.2 Objectives and goals

The main objective is to validate the practical implementation of fundamental and complex all optical digital circuits using SOA-based devices in a virtual environment.

Phase	Goal Description	Status	
I: Foundation	Complete a critical literature review and design/simulate the foundational All-Optical XOR Gate using the SOA-MZI configuration.	Completed	
II: Expansion	Design and simulate the complete set of fundamental logic gates:	AND, OR, and NOT using SOA-based principles (XGM, XPM).	In Progress
III: Complex Circuits	Construct and simulate more complex arithmetic circuits, specifically a	Full Adder and Full Subtractor, by interconnecting the designed basic logic gates.	Future
IV: Validation	Conduct a rigorous performance analysis, evaluating all designs using standardized metrics:	Quality Factor (QF), Extinction Ratio (ER), and Bit Error Rate (BER).	Future

Chapter 2: Literature Review

The review is structured around the components, architectures, operating principles, and demonstrated capabilities found in modern all-optical circuits.

2.1 Role and Principles of the Semiconductor Optical Amplifier

The SOA is the foundational component of this project. It is preferred over other components like EDFA or fiber-based gates due to its **compact size, integration capability, and strong nonlinear properties**. The two primary effects exploited for logic operation are:

- **Cross-Phase Modulation (XPM):** The presence of a high-power input signal (pump) changes the SOA's refractive index, which, in turn, causes a **phase shift** in a Continuous Wave (CW) probe signal. This is the principle used in **interferometric** structures like the MZI.
- **Cross-Gain Modulation (XGM):** A high-power input signal (pump) saturates the SOA's gain, reducing the amplification of a CW probe signal. This effect is typically used to realize the **NOT gate**.
- **Four-Wave Mixing (FWM):** A third, high-speed effect where two or more signals generate new optical frequency components.

2.2 SOA-Based Architectures: The Mach-Zehnder Interferometer

The **SOA-MZI** configuration is widely adopted for all-optical switching and logic gates due to its robustness and capability to integrate multiple logic functions.

- The MZI acts as an **amplitude modulator**, converting the non-linear **phase shift (XPM)** into a measurable **intensity difference** (amplitude modulation) at the output.
- The presence of the data signal in one arm creates a differential phase shift of π radians, leading to **constructive interference** (Logic '1') or **destructive interference** (Logic '0') when the signals recombine.
- **Advanced SOAs:** Newer designs use **Carrier Reservoir SOAs (CR-SOAs)** to overcome the carrier recovery time limitation of traditional SOAs, achieving ultra-high data rates of up to **120 Gbps**.

2.3 State-of-the-Art in All-Optical Circuit Implementation

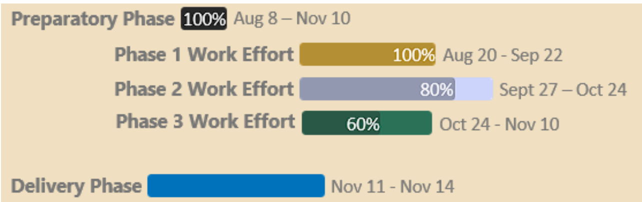
Circuit Type	Key Implementation Technique(s)	Data Rate / Speed	Source Examples
XOR & Basic Gates	SOA-MZI leveraging XPM and XGM for all fundamental gates.	Up to 20 Gbps (SOA)	
Full Adders/Subtractors	MZI-SOA used to directly realize SUM/CARRY/BORROW outputs. Cascade of XOR, AND, and OR gates based on SOAs.	Demonstrated at 10 Gbps.	

Universal Gates (NAND/NOR)	FWM in SOA or XGM/XPM in SOA-MZI. NAND is a key building block for memory circuits.	Up to 100 Gbps	
Sequential Circuits	Cascading logic gates (NAND, NOT) to form memory elements like	D flip-flops.	Demonstrated at 10 Gbps and 25 Gbps.
High-Speed/MUX	Utilization of	CR-SOAs to achieve highly functional circuits like the 2x1 MUX.	Demonstrated at 120 Gbps.

Chapter 3 : Strategic Analysis and Problem Definition

3.1 SWOT Analysis

3.2 Project Plan - GANTT Chart



3.3 Problem statement

Chapter 4 : Methodology

4.1 Description of the approach

The project follows a simulation-based, modular approach using the principles of all-optical signal processing.

1. **SOA-MZI Foundation (XOR Gate):** The Mach-Zehnder Interferometer (MZI) with SOAs in its arms is the fundamental unit. Our design utilizes the **XPM effect**, where the input data pulses induce a phase shift ($\Delta\phi$) on the continuous wave (CW) probe signal passing through the SOA. The MZI is calibrated so that when **only one** arm experiences a phase shift, the output results from constructive interference (Logic '1'); otherwise, it's destructive interference (Logic'0').

2. **Gate Expansion:**
   - **NOT Gate:** Achieved using the **XGM effect** in a single SOA, where a high input saturates the SOA's gain, suppressing a CW signal (inversion).
   - **AND/OR Gates:** Implemented primarily using the **XPM effect** in an MZI structure, similar to the XOR gate, but with optimized input signal configurations and power levels to achieve the desired Boolean function.

3. **Complex Circuit Integration:** The designed basic gates will be logically interconnected (cascaded) to construct the **Full Adder** (which requires XOR, AND, and OR gates) and the **Full Subtractor** (which shares the XOR structure for the Difference output)

4.2 Tools and techniques utilized

- **OptiSystem Software:** The core tool for all design, simulation, and analysis. It allows for the precise configuration of component parameters and the visualization of signals in both time and frequency domains.

- **Pseudorandom Binary Sequence (PRBS) Generator:** Used to generate realistic, randomized input bitstreams for data signals, essential for assessing actual system performance and pattern effects.

- **Eye Diagram and BER Analyzer:** Key modules within OptiSystem used to quantitatively assess the output signal quality by measuring **Q-factor** and predicting the **Bit Error Rate (BER)**.

4.3 Design considerations

- **Wavelength Planning:** Distinct wavelengths will be assigned to pump (data) and probe (CW) signals to enable wavelength multiplexing and proper selection via Band-Pass Filters (BPF) at the output.

• **SOA Parameter Tuning:** Careful optimization of SOA parameters, including **Injection Current** and **Length**, is crucial as these directly affect the non-linear gain and phase shift characteristics, influencing the logic output.

• **High-Speed Feasibility:** The design will prioritize minimizing complexity and loss to ensure the feasibility of operation at high bit rates (e.g., 10 Gbps and beyond), addressing the fundamental project goal.

• **Logic Functionality:** For the MZI designs, the core consideration is ensuring the differential phase shift is precisely aligned with π radians to maximize the distinction between logic '1' and logic '0' output powers

Chapter 5 : Implementation

5.1 Description of how the project was executed

5.2 Challenges faced and solutions implemented

Chapter 6: Results

6.1 outcomes

6.2 Interpretation of results

6.3 Comparison with existing literature or technologies

Chapter 7: Conclusion

Here write Suggestions for further research or development and Potential improvements or extensions

Chapter 8 : Future Work

Here write Suggestions for further research or development
Potential improvements or extensions

References

Bengaluru City Office No 5/1, First Floor, Prestige Terraces, Union Street, Infantry Road, Bengaluru - 560003 Karnataka, India

GIMSR
GITAM Medical College Rd., Gandhi Nagar, Rushikonda, Visakhapatnam - 530045 Andhra Pradesh, India

GITAM
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Bengaluru