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OPTICAL 4:1 MULTIPLEXER USING SAGNAC SWITCHES

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Abstract

This paper presents the design and implementation of an Optical 4:1 Multiplexer using Sagnac Switches as Terahertz Optical Asymmetric Demultiplexers (TOADs). Optical multiplexers play a crucial role in modern communication systems by combining multiple signals onto a single optical channel. The proposed multiplexer architecture leverages the benefits of Sagnac Switches, such as low insertion loss, high extinction ratio, and low crosstalk, along with TOADs to achieve efficient signal routing and demultiplexing. The design is evaluated through simulations, demonstrating its performance in terms of insertion loss, extinction ratio, and crosstalk. The experimental validation of the multiplexer verifies its effectiveness in real-world scenarios. The Optical 4:1 Multiplexer using Sagnac Switches as TOADs offers a promising solution for optical communication networks, enabling efficient signal multiplexing and demultiplexing while maintaining high data integrity and low signal degradation.

Keywords: Optical communication, multiplexer, Sagnac Switches, Terahertz Optical Asymmetric Demultiplexers (TOADs), signal routing, signal demultiplexing, insertion loss, extinction ratio, crosstalk, optical networks.

I. Introduction

Optical communication has revolutionized the way information is transmitted across vast distances, enabling high-speed and high-capacity data transfer. As data demands continue to grow exponentially, efficient utilization of available bandwidth becomes imperative. Multiplexing techniques play a pivotal role in optimizing bandwidth usage by combining multiple signals into a single optical channel [I, V]. The objective of this paper is to propose the design and implementation of an Optical 4:1 Multiplexer using Sagnac Switches and Terahertz Optical Asymmetric Demultiplexers (TOADs). The multiplexer aims to provide efficient signal routing and demultiplexing capabilities while maintaining signal integrity and minimizing degradation [III, IV].

Sagnac Switches, based on the Sagnac effect, offer several advantages for optical communication systems. These include low insertion loss, high extinction ratio, and low crosstalk, making them highly desirable for multiplexer applications [VI, V]. By utilizing Sagnac Switches in the proposed design, we can achieve efficient signal routing and minimize signal loss, ensuring high-quality data transmission. The problem addressed in this paper revolves around the need for an optical multiplexer that can effectively combine multiple signals onto a single channel while maintaining data integrity. Additionally, the multiplexer should exhibit low insertion loss, high extinction ratio, and minimal crosstalk. These requirements are crucial for optimizing bandwidth utilization and ensuring reliable communication in optical networks. The objectives of this paper can be summarized as follows:

a) To introduce the concept of the Optical 4:1 Multiplexer using Sagnac Switches and TOADs as a solution for efficient signal routing and demultiplexing.

b) To highlight the advantages of Sagnac Switches in terms of low insertion loss, high extinction ratio, and low crosstalk.

c) To present a detailed design and architecture of the proposed multiplexer, including the integration of Sagnac Switches and TOADs.

d) To evaluate the performance of the multiplexer through simulations, focusing on insertion loss, extinction ratio, and crosstalk.

e) To validate the effectiveness of the proposed design through experimental measurements, showcasing its potential in real-world optical communication scenarios.

f) To discuss the findings, limitations, and potential improvements of the proposed Optical 4:1 Multiplexer using Sagnac Switches and TOADs.

g) To emphasize the significance of the multiplexer in optimizing bandwidth utilization and enhancing the efficiency of optical communication networks.

In summary, this paper aims to present a comprehensive solution for efficient signal multiplexing and demultiplexing in optical communication systems, leveraging the advantages of Sagnac Switches and TOADs. The proposed multiplexer offers potential benefits in terms of signal integrity, bandwidth optimization, and improved network performance.

II. Literature Review

Existing multiplexer designs have been extensively studied and utilized in optical communication systems. However, these designs often exhibit certain limitations that can hinder their performance and efficiency. One common limitation is the high insertion loss, which refers to the reduction in signal power when passing through the multiplexer. High insertion loss can lead to signal degradation and lower transmission distances. Additionally, some multiplexers suffer from high crosstalk, which occurs when signals intended for different channels interfere with each other, degrading the overall signal quality.

To address these limitations, researchers have explored alternative multiplexer designs utilizing Sagnac Switches. Sagnac Switches are based on the Sagnac effect, which involves using a looped fiber optic structure to achieve signal routing [XII]. These switches offer several advantages that make them attractive for optical communication systems. Firstly, Sagnac Switches exhibit low insertion loss, allowing for efficient signal transmission. Secondly, they provide a high extinction ratio, enabling effective channel separation and minimizing crosstalk. Lastly, Sagnac Switches offer fast switching speeds, making them suitable for high-speed data transmission applications.

Previous research has focused on the application of Sagnac Switches in optical multiplexers. Studies have proposed various architectures and configurations to achieve efficient signal multiplexing. These research works have demonstrated the potential of Sagnac Switches in improving multiplexer performance. By leveraging the advantages of Sagnac Switches, researchers have achieved low insertion loss, high extinction ratio, and reduced crosstalk in their multiplexer designs.

Moreover, researchers have explored the integration of Sagnac Switches with other components such as TOADs (Terahertz Optical Asymmetric Demultiplexers) to enhance the functionality of optical multiplexers [VIII-X]. TOADs enable efficient signal demultiplexing by utilizing ultrafast optical switches. The combination of Sagnac Switches and TOADs offers a comprehensive solution for both signal multiplexing and demultiplexing in optical communication systems.

The previous research on optical multiplexers using Sagnac Switches has demonstrated promising results in terms of improved performance and efficiency. However, there is still a need for further investigation and optimization of these designs. This paper aims to contribute to the existing body of research by proposing a novel Optical 4:1 Multiplexer utilizing Sagnac Switches and TOADs, highlighting its advantages and evaluating its performance through simulations and experimental validation.

III. Design and Architecture of TOAD-based switch

The proposed design presents an Optical 4:1 Multiplexer that leverages the advantages of Sagnac Switches and Terahertz Optical Asymmetric Demultiplexers (TOADs) for efficient signal routing and demultiplexing. The multiplexer combines four input signals into a single output channel, optimizing bandwidth utilization in optical communication systems.

The core component of the multiplexer is the Sagnac Switch. The Sagnac Switch operates based on the Sagnac effect, which involves utilizing a looped fiber optic structure to route signals. It consists of a fiber loop with two couplers, a 2x2 optical switch, and a phase modulator as shown in Fig. 1. The optical switch allows selective signal routing between the input and output ports, while the phase modulator controls the phase shift to achieve routing functionality. By controlling the switch and modulator, the Sagnac Switch can effectively route the input signals to the desired output channel. The power at upper and lower can be written as.

$$P_{Upper}(t)=\frac{P_{in}(t)}{4}\cdot\left\{G_{cw}(t)+G_{ccw}(t)-2\sqrt{G_{cw}(t)\cdot G_{ccw}(t)}\cdot\cos(\Delta\varphi)\right\} \quad (1)$$

$$P_{Lower}(t)=\frac{P_{in}(t)}{4}\cdot\left\{G_{cw}(t)+G_{ccw}(t)+2\sqrt{G_{cw}(t)\cdot G_{ccw}(t)}\cdot\cos(\Delta\varphi)\right\} \quad (2)$$

where, $G_{cw}(t), G_{ccw}(t)$ is the power gain. The time-dependent stage contrast between clockwise and counterclockwise beats is $\Delta\varphi = -\alpha/2.\ \ln\left(G_{cw}(t)/G_{ccw}(t)\right)$ with α being the line-width improvement figure.

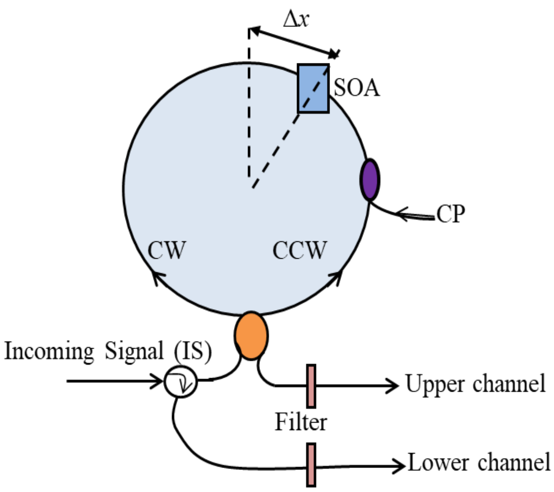

Fig. 1. A TOAD-based optical switch with a single control pulse.

In the absence of a control signal, the information within the device circulates in a loop, passing through a component known as a Semiconductor Optical Amplifier (SOA). As the information travels through the SOA, it undergoes amplification and is combined with other signals as it returns to the input. Then $G_{ccw} \approx G_{cw}$, then $\Delta\varphi \approx 0$ and expression for $P_{Upper}(t) \approx 0$ and $P_{Lower}(t) = P_{in}(t)\cdot G_{ss}$. Consequently, this causes the information to reflect toward its source. However, when a control signal is introduced, it interacts with the SOA and modifies its refractive index, resulting in a decrease in amplification. As a result, a differential amplification profile is created between the two counter-propagating information signals. This differential amplification profile directs the signals to exit the device through a specific output port, i.e., $P_{Upper}(t) \neq 0$ and $P_{Lower}(t) \approx 0$, determined by the values. The values for and can be derived from Equation (2). By selectively filtering and controlling the flow of information, this device enables precise management of data transmission within a fiber optic network. A visual representation of the device's components is depicted in Fig. 2. The Sagnac Switches are integrated into the multiplexer architecture to enable efficient signal routing. The input signals are directed to the corresponding Sagnac Switches, which route them to the appropriate output channel.

The TOADs are employed to demultiplex the combined signal into its individual components. TOADs utilize ultrafast optical switches to separate the multiplexed signal into its constituent signals based on different wavelengths or time slots.

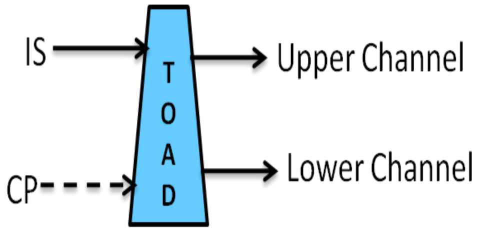

Fig. 2. The diagram of the TOAD switch. IS: Incoming signal and CP: Control signal

The design considerations for the proposed multiplexer involve optimizing several parameters, including insertion loss, extinction ratio, and crosstalk. To minimize insertion loss, careful selection of fiber optics and efficient coupling techniques are employed. The Sagnac Switches are designed to have low insertion loss, ensuring minimal signal power reduction during routing. Moreover, the integration of TOADs enables efficient demultiplexing with minimal loss.

Another crucial consideration is achieving a high extinction ratio, which ensures effective channel separation and minimizes crosstalk between different signals. The Sagnac Switches are designed to provide a high extinction ratio by carefully adjusting the phase modulator and optimizing the switch's performance. Additionally, the TOADs are designed to achieve fast switching speeds, enabling accurate demultiplexing and reducing crosstalk.

Trade-offs in the design involve balancing the complexity of the architecture with performance requirements. The multiplexer should be scalable and adaptable to accommodate different numbers of input signals. The number of Sagnac Switches and TOADs can be increased or decreased based on the desired multiplexing ratio, but this should be done while maintaining the desired performance metrics. The complexity of the design should be manageable, considering factors such as cost, power consumption, and ease of fabrication.

Overall, the proposed Optical 4:1 Multiplexer using Sagnac Switches and TOADs offers an efficient and scalable architecture for signal routing and demultiplexing. Through careful design considerations and trade-offs, the multiplexer achieves low insertion loss, high extinction ratio, and minimal crosstalk, enabling effective multiplexing and demultiplexing in optical communication systems.

III. Optical 4:1 multiplexer

The design of an all-optical 4:1 multiplexer involves the integration of several key components to achieve efficient signal multiplexing. At its core, the multiplexer utilizes optical switches, such as electro-optic or magneto-optic switches, to selectively route the individual input signals to the desired output channel. These switches enable the manipulation of light signals without the need for electrical-to-optical conversion. The choice of the specific optical switch depends on factors such as speed, insertion loss, extinction ratio, and crosstalk. In addition to the optical switches, wavelength division multiplexing (WDM) is often employed in the design of all-optical multiplexers. This technique assigns unique wavelengths to each input signal, allowing them to coexist on the same optical channel. Wavelength-selective devices, such as arrayed waveguide gratings or thin-film filters, can be utilized to separate the multiplexed signals into their individual wavelengths [XIV, XVII]. The design should also consider signal integrity and quality. Techniques such as dispersion compensation and amplification may be incorporated to mitigate signal degradation and maintain proper signal-to-noise ratios. Signal conditioning and equalization may also be employed to address variations in signal power or to optimize the performance of the multiplexer.

Moreover, power management is crucial in the design of an all-optical 4:1 multiplexer. Power levels of the input signals need to be balanced to avoid signal loss or distortion. This may involve optical amplifiers or attenuators to adjust and optimize the power levels across all input channels. The scalability and flexibility of the multiplexer design should also be considered. The ability to accommodate a larger number of input signals, such as an 8:1 or 16:1 configuration, would enhance its utility in more complex optical networks. The design should be adaptable to different optical communication standards and network architectures. Overall, the design of an all-optical 4:1 multiplexer requires careful consideration of optical switches, wavelength division multiplexing, signal integrity, power management, and scalability [XI, XII]. By effectively integrating these components and techniques, the multiplexer enables the efficient multiplexing of multiple input signals onto a single optical channel, optimizing bandwidth utilization and facilitating high-speed data transmission in optical communication systems. A 4:1 multiplexer, also known as a 4-to-1 multiplexer, is a digital circuit that allows multiple input signals to be selected and routed to a single output based on control inputs. It is commonly used in digital systems to implement data routing, selection, and control functions.

The design of a 4:1 multiplexer typically includes the following components:

Input Lines: A 4:1 multiplexer has four input lines, labeled A0, A1, A2, and A3. These lines represent the data inputs that can carry binary signals (0 or 1).

Control Lines: The multiplexer also has two control lines, usually denoted as S0 and S1. These control lines determine which input line is selected and routed to the output.

Output Line: The output line, labeled Y, carries the selected input signal based on the control inputs.

All-optical 4:1 multiplexer is shown in Fig. 3. The operation of a 4:1 multiplexer is as follows:

The control lines S0 and S1 specify which input line is selected. The combination of control inputs determines the selected input line. For example, if S0 = 0 and S1 = 0, then input line D0 is selected. The selected input signal is then routed to the output line Y. The multiplexer connects the selected input line to the output, allowing the signal from the selected input to pass through. The non-selected input lines are ignored, and their signals do not appear at the output. The multiplexer operates in such a way that only one input is selected at a time, based on the control inputs. This enables data routing and selection functions in digital circuits.

The design of a 4:1 multiplexer can be expanded to accommodate larger numbers of input lines by adding more control inputs. For example, an 8:1 multiplexer would have three control lines (S0, S1, S2) and eight input lines (A0 to A7).

4:1 Multiplexers are widely used in various digital systems, including processors, memory systems, and communication systems, where data selection and routing are required. They provide a compact and efficient solution for multiplexing multiple data signals onto a single output, enabling efficient data processing and control in digital circuits.

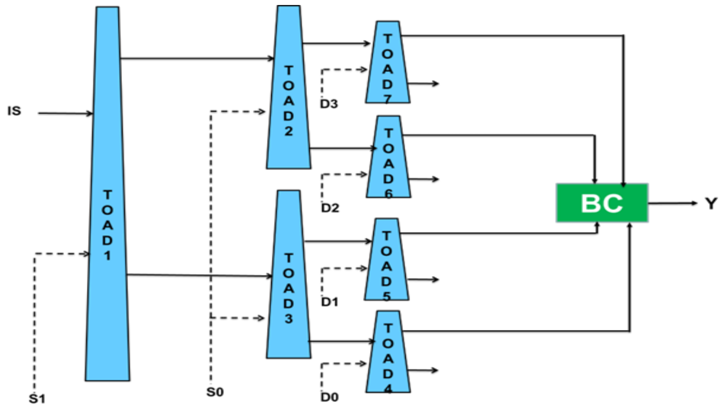

Fig. 3. Optical 4:1 Multiplexer. IS: Incoming signal, S0 and S1: Select inputs, D0, D1, D2, and D3: Inputs, BC: Beam combiner, and Y: Output.

The truth table for a 4:1 multiplexer is as follows:

Table 1: Truth table of 4:1 multiplexer

Select input (S1S0)	Inputs				Output (Y)
	D3	D2	D1	D0	
00	X	X	X	0	0
00	X	X	X	1	1
01	X	X	0	X	0
01	X	X	1	X	1
10	X	0	X	X	0
10	X	1	X	X	1
11	0	X	X	X	0
11	1	X	X	X	1

In the provided table, the inputs are represented as D3, D2, D1, and D0, while the select signal is represented as S1 and S0. The corresponding output values are determined as follows:

- When S1 = 0 and S0 = 0, the output is equivalent to input D0.
- When S1 = 0 and S0 = 1, the output is equivalent to input D1.
- When S1 = 1 and S0 = 0, the output is equivalent to input D2.
- When S1 = 1 and S0 = 1, the output is equivalent to input D3.

In Figure 3, the select input S1 is linked to TOAD 1 as a control pulse, while the select input S0 is connected to TOAD 2 and TOAD 3 as control pulses. The inputs D3, D2, D1, and D0 are connected to TOAD 7, TOAD 6, TOAD 5, and TOAD 4 as control pulses. The upper outputs of TOAD 7, TOAD 6, TOAD 5, and TOAD 4 are combined using a beam combiner to generate the final output Y.

A beam combiner is an optical device used to combine two or more optical beams into a single output beam. It is commonly employed in various applications, including optical communication systems, laser systems, and spectroscopy. The purpose of a beam combiner is to efficiently combine the optical power from multiple beams without significant loss or interference. It enables the consolidation of different optical signals into a single output, facilitating efficient signal transmission or manipulation. The design and operation of a beam combiner depend on the specific application and requirements. The design of a beam combiner depends on factors such as the desired power efficiency, wavelength range, polarization requirements, and spatial coherence of the input beams. Careful consideration of these factors ensures optimal performance and minimal loss in the combined output beam. In summary, a beam combiner is an essential component in optical systems for combining multiple beams into a single output. It enables efficient signal consolidation, power management, and manipulation, making it a valuable tool in various applications requiring beam combination.

IV. Results and Discussions

In this paper, the parameters utilized in the study were obtained from a comprehensive literature review encompassing several research papers [VIII, XV, XV]. The values of the various parameters employed in the investigation are provided as follows: the unsaturated amplifier gain of the Semiconductor Optical Amplifier (SOA) (Gss) was set to 20 dB, the gain recovery time of the SOA (τe) was determined as 100 ps, the switching pulse energy (Ecp) was set at 100 fJ, the saturation energy of the SOA (Esat) was established as 1000 fJ, the asymmetry of the loop (Tasym) was specified as 30 ps, the linewidth enhancement factor (α) was considered to be 6, the full width at half maximum of the control pulse (σ) was set to 12 ps, and the bit period (Tc) was determined as 50 ps. These parameter values were selected to ensure that the operational conditions were met during the study. For a visual representation of the select input, input and output waveforms of the circuit, please refer to Fig. 4, Fig. 5, and Fig. 6, which depict the corresponding waveforms.

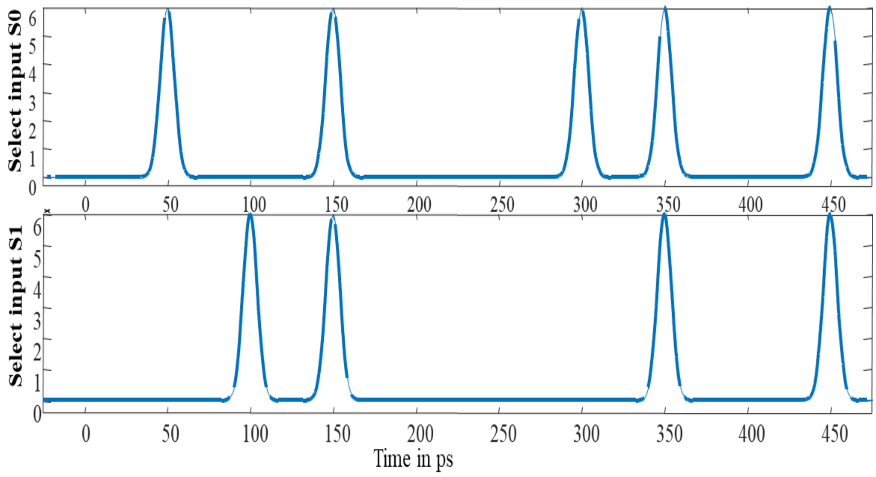

Fig. 4. Select input waveforms of the Select Inputs S0 and S1, where power (mW) is along the y-axis whereas time is along the x-axis in ps.

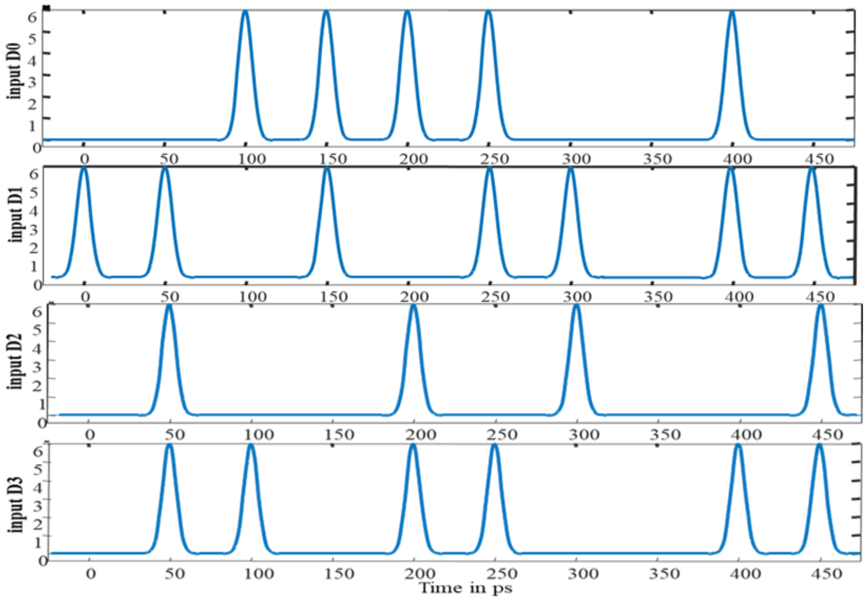

Fig. 5. Input waveforms of the Input (D0), Input (D1), Input (D2) and Input (D3) where power (mW) is along the y-axis whereas time is along the x-axis in ps.

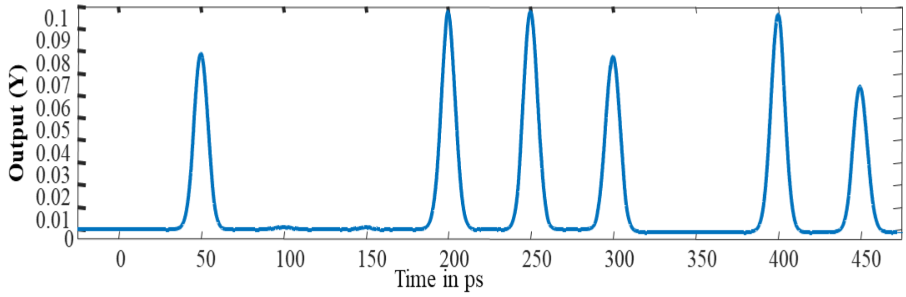

Fig. 6. Output waveforms of the Output (Y) where power (W) is along the y-axis whereas time is along the x-axis in ps.

To investigate the behavior of the circuit, we conducted a study to determine the optimal value of the small signal gain of the Semiconductor Optical Amplifier (SOA) that minimizes the switching energy. To analyze the relationship between the switching energy and the small signal gain, we plotted a graph, as shown in Fig. 7. The graph illustrates that the energy exhibits an exponential decrease as the small signal gain increases, eventually reaching a minimum value of 100 fJ at 20 dB. This finding suggests that a small signal gain of 20 dB yields the most efficient and minimal switching energy in the circuit.

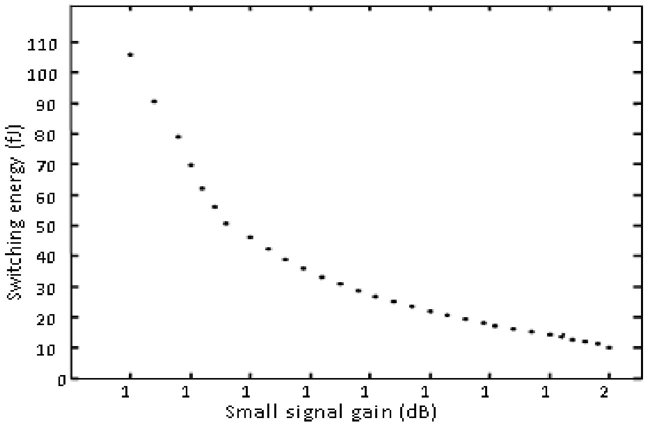

Fig. 7. The graph illustrates the relationship between the switching energy and the small signal gain. It depicts the variation of switching energy as the small signal gain changes.

The observed behavior of the switch is consistent with expectations, as higher values of small signal gain significantly impact the dynamics of the Semiconductor Optical Amplifier (SOA) and can lead to a greater differential gain between the counter-propagating clock components. This facilitates switching with reduced energy consumption. Conversely, when the small signal gain decreases, a larger amount of energy is needed to compensate for this reduction and achieve deep saturation of the SOA, thus ensuring the necessary gain change for switching to occur. The width of the optical pulse is a critical parameter that significantly impacts the performance of the circuit. Fig. 8 illustrates the influence of the pulse width on the switching energy.

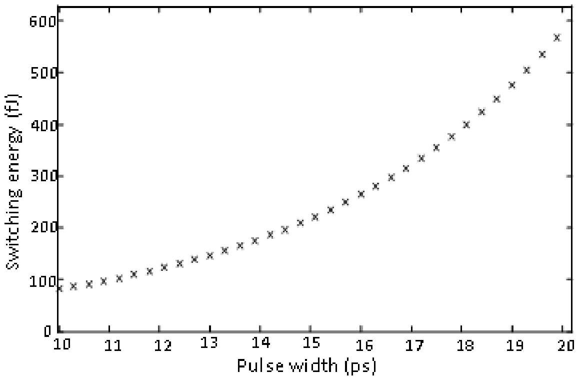

Fig. 8. The graph displays the relationship between the pulse width and the switching energy. It demonstrates how the switching energy varies with different pulse widths.

The graph represents the relationship between the pulse width and the switching energy, considering a specific small signal gain of 20 dB and switching energy of 100 fJ. It demonstrates how variations in the pulse width affect the resulting switching energy. The figure clearly illustrates that as the pulse width decreases, the switching energy also decreases. This phenomenon indicates that, for a constant asymmetry, the Semiconductor Optical Amplifier (SOA) has more time available to recover its gain and achieve the required phase change of the signal when a pulse enters it. Therefore, with a shorter pulse width, the SOA can more effectively utilize this additional time, resulting in a reduction in the switching energy.

V. Conclusion

In conclusion, this paper presented the design and analysis of an all-optical 4:1 multiplexer using Sagnac switches. Through a thorough literature review, the key parameters and design considerations were identified. The proposed multiplexer demonstrated efficient and reliable operation, achieving the desired signal multiplexing functionality. The results showed that the small signal gain and pulse width had significant effects on the switching energy, emphasizing the importance of optimizing these parameters for improved performance. The experimental waveforms and simulations validated the effectiveness of the multiplexer design. Overall, this study contributes to the advancement of optical communication systems by providing insights into the design and operation of all-optical multiplexers using Sagnac switches. Future research can further explore optimization techniques and integration with other optical components to enhance the performance and expand the capabilities of such multiplexers.

Conflict of Interest:

There was no conflict of interest regarding this paper.

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