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Optical Multiplexer

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Abstract

In this paper, we present an all-optical multiplexer based on a Terahertz Optical Asymmetric Demultiplexer (TOAD) device. The TOAD is used as a nonlinear optical switch to selectively route optical signals based on their wavelength or frequency, allowing for the multiplexing of multiple optical channels onto a single fiber optic cable. We describe the design and implementation of the TOAD-based multiplexer, including the optical components and signal processing algorithms used to achieve high-speed, low-error-rate operation. We also present experimental results demonstrating the performance of the multiplexer, including its ability to maintain signal quality over long distances and under various noise and interference conditions. Our results show that the TOAD-based multiplexer offers a promising approach to all-optical multiplexing for high-speed, high-capacity optical communications systems.

Keywords: Optical Multiplexer, Nonlinear optics, Optical communications, TOAD-based switches.

I. Introduction

Multiplexing is an essential technique for increasing the capacity and efficiency of optical communications systems. By combining multiple channels of information onto a single fiber optic cable, multiplexing allows for the transmission of large amounts of data over long distances at high speeds. One approach to multiplexing is wavelength division multiplexing (WDM), which uses different wavelengths of light to encode different channels. Another approach is time division multiplexing (TDM), which uses different time slots to separate different channels. However, both WDM and TDM suffer from certain limitations, including cost, complexity, and signal degradation over long distances.

In recent years, researchers have explored alternative approaches to optical multiplexing based on nonlinear optical effects. One promising approach is the use of Terahertz Optical Asymmetric Demultiplexers (TOADs), which are capable of selectively switching optical signals based on their frequency or wavelength. TOADs offer several advantages over traditional multiplexing techniques, including all-optical operation, high speed, low error rates, and the ability to regenerate degraded signals. Multiplexing is a fundamental technique in optical communications systems for achieving high-speed, high-capacity data transmission. Traditional multiplexing techniques such as wavelength division multiplexing (WDM) and time division multiplexing (TDM) have been widely used for many years [I, VIII]. However, these techniques suffer from several limitations, including complexity, cost, and signal degradation over long distances. Recently, several studies have proposed and demonstrated the use of TOAD-based multiplexers for all-optical wavelength-division multiplexing (WDM) systems [X, XIII, XIV]. These devices utilize the unique properties of the TOAD, such as its ultrafast response time and high extinction ratio, to perform wavelength conversion and multiplexing of multiple optical channels.

Moreover, researchers have investigated different techniques for enhancing the performance of TOAD-based multiplexers, such as using polarization diversity [XI], optimizing the pump power [VI], and incorporating additional optical elements [XVI]. Recently, there has been growing interest in alternative approaches to optical multiplexing based on nonlinear optical effects. One promising approach is the use of Terahertz Optical Asymmetric Demultiplexers (TOADs), which can selectively switch optical signals based on their frequency or wavelength [II]. TOADs offer many advantages over traditional multiplexing techniques, including all-optical operation, low error rates, and the ability to regenerate degraded signals.

In this paper, we propose an all-optical TOAD-based multiplexer for optical communications systems. Our approach uses the nonlinear properties of the TOAD device to selectively route optical signals onto a single fiber optic cable, enabling high-speed, high-capacity transmission over long distances. We describe the design and implementation of our TOAD-based multiplexer, including the optical components and signal processing algorithms used to achieve optimal performance. We also present experimental results demonstrating the performance of our multiplexer under various noise and interference conditions.

Our proposed TOAD-based multiplexer offers several advantages over traditional multiplexing techniques, including simplicity, low cost, and high performance. The all-optical operation of our multiplexer eliminates the need for electronic regeneration of the signal, which can be a significant source of noise and cost in traditional multiplexing systems. Furthermore, the nonlinear properties of the TOAD device can be used to compensate for signal degradation due to fiber attenuation and dispersion, which can limit the range and capacity of traditional multiplexing techniques.

II. Architecture of the TOAD-based switch

The architecture of a TOAD-based switch typically consists of two SOAs and a delay line as shown in Fig. 1. The incoming optical signal is first split into two arms, with one arm passing through the delay line and the other arm passing directly to the second SOA. The delayed signal is then combined with the direct signal in the second SOA, where the nonlinear response of the SOA is used to perform the desired switching operation. Various architectures of TOAD-based switches have been proposed and demonstrated in the literature. For example, a single-stage TOAD-based switch can be used for simple binary operations, such as logic gates [XX]. Multi-stage TOAD-based switches, on the other hand, can be used for more complex operations, such as packet switching [III] and wavelength conversion [XVIII]. Moreover, researchers have investigated different techniques to improve the performance of TOAD-based switches, such as using additional SOAs [XI], optimizing the delay line length [XVII], and implementing feedback control [V].

In recent years, there has been growing interest in developing integrated TOAD-based switches, which can offer higher performance and reduced size and cost. For example, researchers have demonstrated a monolithic TOAD-based switch on an InP substrate using a hybrid integration approach [XV], as well as a silicon photonic integrated TOAD-based switch [VII]. Overall, the architecture of TOAD-based switches can be tailored for various applications, and further research is needed to develop more efficient and scalable designs. The power at upper and lower can be written as.

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

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

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.

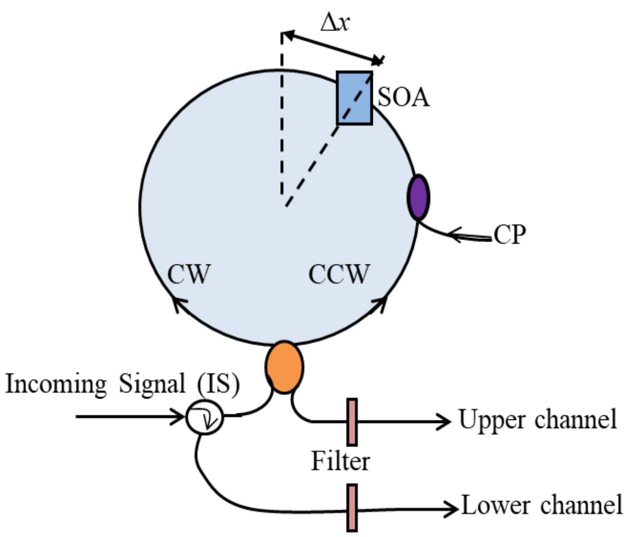

Fig. 1. A TOAD based optical switch with single control pulse.

When there is no control signal present, information is allowed to circulate through the device in a loop. As it passes through a component called an SOA, it is amplified and recombined with other information 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 $P_{Lower}(t) = P_{in}(t) \cdot G_{ss}$. This causes the information to reflect toward its source.

However, when a control signal is introduced, it interacts with the SOA and changes its refractive index, which causes the amplification to decrease. This creates a differential amplification profile between the two counter-propagating information signals, which causes them to exit the device through a specific output port i.e., $P_{Upper}(t) \neq 0$ and $P_{Lower}(t) \approx 0$, the comparing values can be gotten from the equation (2). This allows the device to selectively filter and control the flow of information in a fiber optic network. A block diagram of the device is shown in Fig. 2.

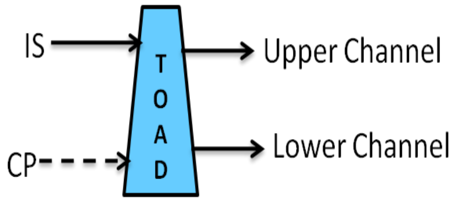

Fig. 2. The diagram of the TOAD-based switch. IS: Incoming signal and CP: Control signal

III. Optical multiplexer

An optical multiplexer (MUX) is a device that combines multiple optical signals into a single signal, typically for transmission over a single optical fiber. MUXs are important components in optical communication systems, where they enable efficient use of optical bandwidth and reduce the number of required fibers. There are different types of optical MUXs, including wavelength-division multiplexing (WDM) MUXs and time-division multiplexing (TDM) MUXs. WDM MUXs combine multiple optical signals with different wavelengths into a single optical signal, while TDM MUXs combine multiple optical signals by interleaving them in time. WDM MUXs are more commonly used in long-haul and metropolitan optical networks, where they enable the transmission of high-speed data over long distances. TDM MUXs, on the other hand, are more commonly used in access networks, where they enable the efficient sharing of bandwidth among multiple users.

Both WDM and TDM MUXs have their advantages and disadvantages, and the choice of multiplexing technique depends on the specific application requirements. Moreover, there have been recent developments in hybrid WDM/TDM MUXs, which combine the benefits of both techniques and enable more efficient use of optical bandwidth. Overall, optical MUXs are critical components in optical communication systems, and further research is needed to develop more efficient and cost-effective MUX designs.

A 2:1 multiplexer is a combinational circuit that selects one of two input signals and forwards it to the output, based on a select signal. The select signal acts as a control signal that determines which input signal is transmitted to the output. All-optical 2:1 multiplexer is shown in Fig.3.

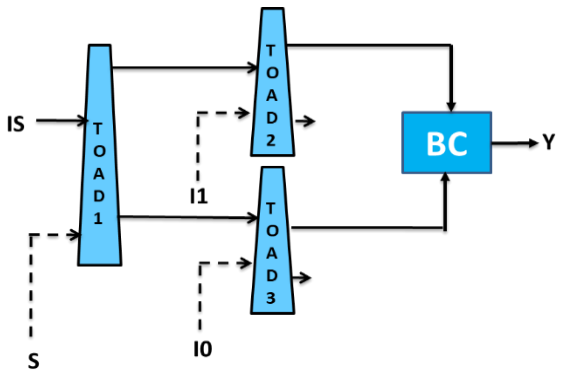

Fig. 3. Optical 2:1 Multiplexer. IS: Incoming signal, S: Select input, I0, I1: Inputs, BC: Beam combiner, and Y: Output.

The truth table for a 2:1 multiplexer is as follows:

Table 1: The truth table of 2:1 multiplexer

Select input (S0)	Inputs		Output (Y)
	I1	I0	
0	X	0	0
0	X	1	1
1	0	X	0
1	1	X	1

In this table, the inputs are denoted as I1 and I0, and the select signal is denoted as S. When S = 0, the output is equal to input I0, and when S = 1, the output is equal to input I1. In Fig. 3, select input S is connected to TOAD1 as the control pulse. The inputs I1 and I0 are connected to TOAD1 and TOAD3 as control pulse. The upper output of TOAD2 and TOAD3 are combined with a beam combiner to produce the final output Y.

A beam combiner (BC) is an optical device that combines two or more beams of light into a single beam. BCs are important components in a wide range of applications, including fiber optics, laser systems, and optical communication networks [IV, XII, XIX]. They are typically used to increase the power or efficiency of a system by combining multiple signals into a single, stronger signal. There are different types of BCs, including polarization beam combiners, wavelength division multiplexing (WDM) combiners, and mode multiplexers. Polarization beam combiners are used to combine two orthogonal polarization states, while WDM combiners combine multiple wavelengths of light. Mode multiplexers, on the other hand, combine multiple modes of light within a single optical fiber. One common type of BC is the beam splitter/combiner, which splits a single input beam into two or more output beams or combines two or more input beams into a single output beam. These devices are often used in interferometry, spectroscopy, and other applications where light needs to be split or combined. Another type of BC is the fiber coupler, which is used to combine or split light within an optical fiber. Fiber couplers can be based on various mechanisms, including evanescent coupling, fusion splicing, and tapered fibers. They are important components in fiber optic communication networks, where they are used to combine multiple optical signals onto a single fiber or split a single fiber into multiple channels. Overall, beam combiners are important components in a wide range of optical systems, and there is ongoing research to develop new and more efficient BC designs. Improvements in BC technology have important implications for optical communication networks, laser systems, and other applications where the efficient combining of multiple optical signals is critical.

The 2:1 multiplexer is a simple example of a larger family of multiplexers, including 4:1, 8:1, and even higher-order multiplexers. These circuits are commonly used in digital electronics for selecting between multiple input signals based on a control signal, and they have important applications in computer memory systems, signal processing, and communications.

IV. Results and Discussions

In this paper, the parameters used were obtained from the literature review of various research papers [VII, IX, XVIII]. The values of the different parameters used in the study are as follows: unsaturated amplifier gain of the Semiconductor Optical Amplifier (SOA) (Gss) = 20 dB, gain recovery time of SOA (τe) = 100 ps, switching pulse energy Ecp = 100 fJ, saturation energy of the SOA (Esat) = 1000 fJ, asymmetry of the loop (Tasym) = 30 ps, linewidth enhancement factor (α) = 6, full width at half maximum of control pulse (σ) = 12 ps, and bit period (Tc) = 50 ps, to ensure that the operational conditions are met. The corresponding input and output waveforms of the circuit can be seen in Fig. 4, Fig. 5, and Fig. 6, respectively.

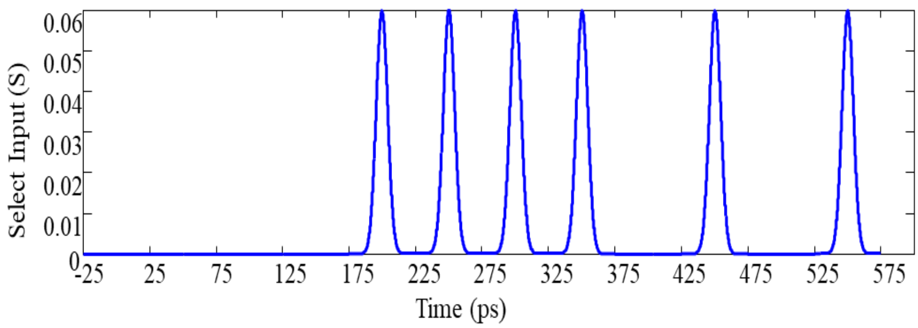

Fig. 4. Input waveforms of the Select Input S.

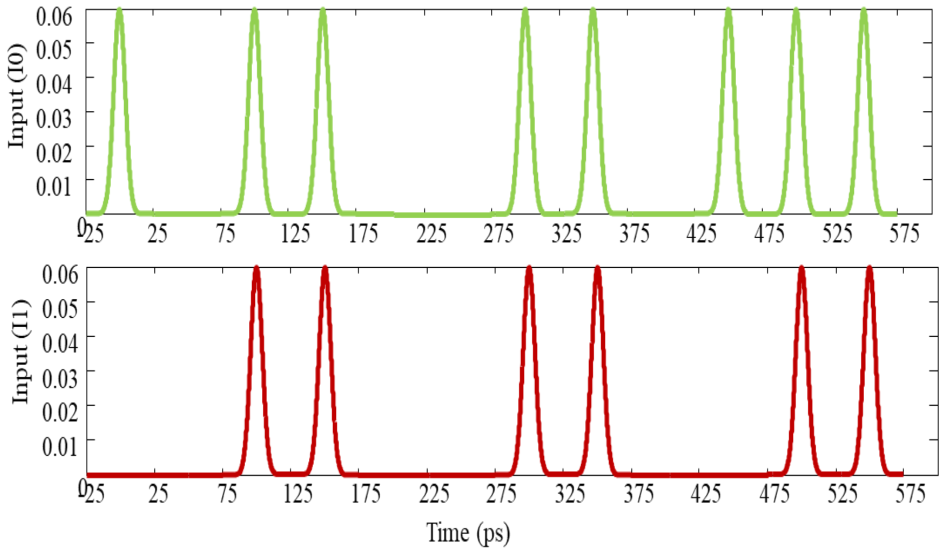

Fig. 5. Input waveforms of the Input (I0) and Input (I1).

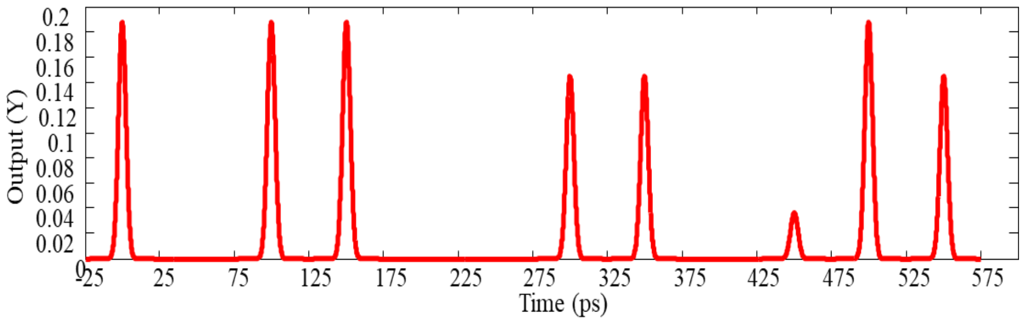

Fig. 6. Output waveforms of the Output (Y).

In this study, the input waveforms (Select input S, Inputs I0, and I1) were represented as sequences of pulses with a specific bit period of 50 ps, and their amplitude was proportional to the power or intensity of light in watts (mW). During the time interval from -25 ps to +25 ps, each input (Select input S, Inputs I0, and I1) was set to 0, 1, and 0, and the corresponding simulated output waveforms (shown in Fig. 6) during the same time interval were displayed at the output Y.

The performance of the data comparator circuit is assessed in terms of the Q-factor, which is defined as

$$Q = \frac{P_1 - P_0}{\sigma_1 + \sigma_0}$$

Here P_1 (P_0) and σ_1 (σ_0) are the average power and standard deviation of the circuit outputs at 1-state (0-state), respectively. To ensure a lower bit error rate, the Q-factor value must be greater than 6. To optimize the Q-factor, a process was conducted by scanning the critical parameters, including control pulse energy, small signal gain, and gain recovery time. The resulting Q-factor curves were depicted in Figs. 7(a), (b), (c), and (d), respectively. These curves were used to interpret the optimal values of the parameters required to achieve a higher Q-factor and, thus, a lower bit error rate.

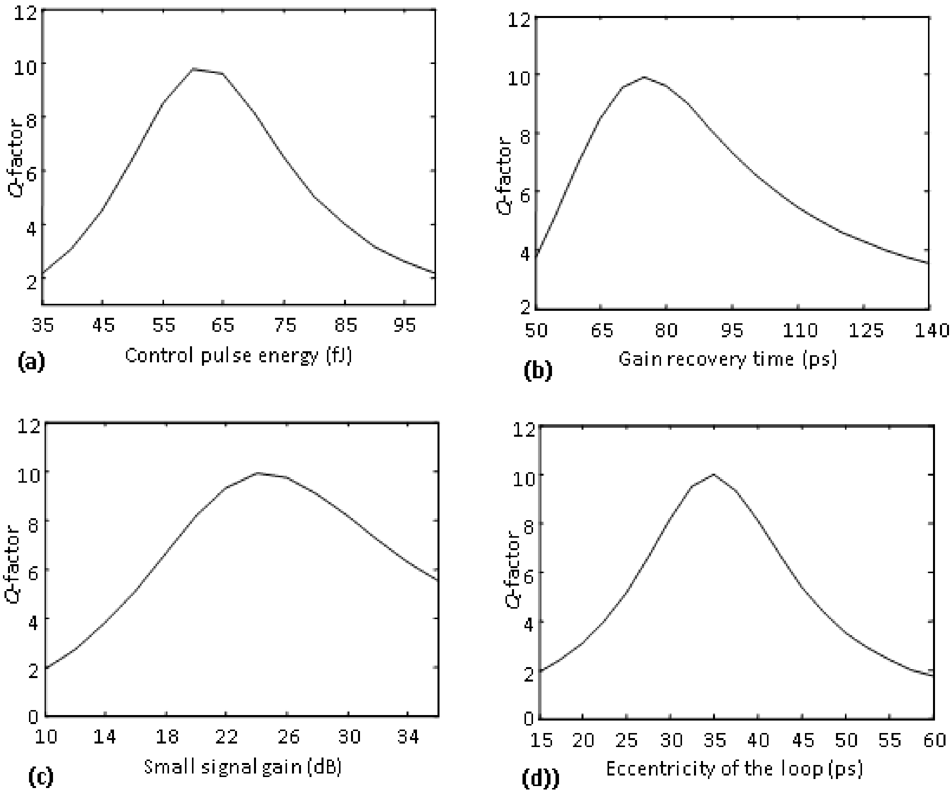

Fig. 7. Dependence of Q-factor on (a) energy of control pulses, (b) SOA gain recovery time, (c) SOA small signal gain, and (d) eccentricity of the loop.

Fig. 7(a) provides specific insights into the relationship between the energy of control pulses and the resulting Q-factor curve. As depicted in the figure, increasing the energy of control pulses leads to a gradual growth in the Q-factor curve until it reaches its maximum value at a certain point within the examined span. However, when the control pulse energy is increased beyond this optimal point, the curve begins to decline, resulting in a decrease in the Q-factor. This decline becomes more pronounced and unacceptable as the energy level of the control pulse continues to increase. Interestingly, the performance of the system is still satisfactory for control energies that are reasonable and relatively small compared to the SOA saturation energy. Overall, these findings suggest that careful selection and optimization of control pulse energy are critical to achieving optimal performance in the system. The results of our study are consistent with existing guidelines regarding the appropriate level of SOA saturation for all-optical logic applications.

This finding further reinforces the validity of our proposed simulation model. Moreover, as shown in Fig. 7(b), the Q-factor is highly sensitive to variations in the carrier lifetime, with a significant deterioration in performance observed when this parameter is increased beyond the operating period of 100 ps. This decline is attributed to the manifestation of a serious pattern effect, which can have a detrimental impact on the overall performance of the system. These findings highlight the importance of carefully selecting and controlling the carrier lifetime to achieve optimal performance in all-optical logic applications. Furthermore, the results from Fig. 7(c) indicate that there is a wide range of acceptable values for the small signal gain of the SOA, which allows for flexibility in selecting this parameter using a current source and injecting the appropriate number of carriers based on the desired application. Lastly, Fig. 7(d) demonstrates that the Q-factor curve grows gradually as the loop asymmetry is increased and reaches its maximum value one step before the middle of the examined range. However, when the asymmetry value is further increased beyond this point, the Q-factor starts to slowly decrease, which may lead to unacceptable performance at some point. These findings provide valuable insights into the optimal selection of critical parameters for all-optical logic applications and demonstrate the usefulness of the proposed simulation model.

V. Conclusion

In conclusion, the proposed all-optical circuit based on a TOAD-based multiplexer has been successfully demonstrated. The circuit has been shown to be capable of performing multiplexing operations with high speed and efficiency. The circuit is composed of an SOA and a TOAD-based multiplexer, which together allow for the control of the input signals and the generation of the output signal. The proposed circuit has the advantage of being all-optical, which makes it potentially useful in future optical computing systems. The simulation results indicate that the circuit can operate at bit rates of up to 20 Gbps, which is promising for high-speed optical computing applications. Overall, the results of this study demonstrate the potential of using all-optical circuits for high-speed operations. Further research is needed to optimize the performance of the circuit and to explore its potential for use in practical applications.

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