



DESIGN AND SIMULATION PLASMONIC 2X1 MULTIPLEXER BASED ON ELLIPTICAL RING RESONATOR

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ABSTRACT

This research explores a new plasmonic multiplexer built with tiny ring-shaped waveguides made of insulator-metal-insulator IMI layers, and implemented using Finite Element Method FEM in a 2D format. Performance evaluation criteria included transmission, modulation depth, extension ratio, and insertion loss. Constructed with silver and oxide zinc materials, proposed design operates by precisely guiding light waves to either negate each other through destructive interference or enhance each other through constructive interference. At 1550 nm wavelength, the device can achieve a transmission threshold of 0.5 in a compact design, with features like transmission exceeding 240%, high Extension Ratio, small footprint, and significant modulation depth. This technology could be a key component in creating ultra-miniaturized circuits that use light instead of electricity, paving the way for even faster computers.

KEYWORDS

2×1 Multiplexer; plasmonic; Surface Plasmon Polaritons; IMI waveguide; Transmutation.



1. INTRODUCTION

Scientists observed a strange effect called "Wood's anomaly" where certain colors of light disappear when irradiate through a special kind of metal grid. This effect happens for specific colors in the middle range of the visible spectrum, in early 1902 Laid the groundwork for the development of the field of plasmonic (D. Maystre et al., 2012). Wood's anomaly was an early indication of the unique optical properties of metal nanostructures, which later became a focal point for research in the field. Then, the article explained the science behind why the sky appears blue, which is called Rayleigh scattering (L. Rayleigh et al., 1907), This unexpected pattern in the diffracted light creates unwanted scattered waves within a single wavelength on the surface. This phenomenon suggests the presence of long-lived, polarized waves resonating on the metal's surface. These waves, called surface plasmons SP, are created by excited electrons in the metal and lead to energy loss through interactions with these excited electrons (U. Fano et al., 1941). Surface Plasmon Polaritons SPPs are special light waves that travel along the border between a metal and another material like air or glass. These light waves are unique because they are created by the jiggling of electrons on the metal's surface (M. Dragoman and D. Dragoman et al., 2008 - E. Ozbay et al., 2006), This technology is seen as a promising step towards building even smaller and faster devices using light, known as nanophotonic devices (A. M. Ionescu et al., 2010 - D. E. Chang et al., 2007). Scientists are looking to light-based solutions, specifically devices using SPPs, to meet the ever-growing demand for ultra-fast data transmission. Compared to traditional electrical methods, SPPs offer several advantages: they're quicker, minimizing data transfer delays, and cooler, generating less heat. One of the most exciting features of SPPs is their ability to manipulate light at scales smaller than its wavelength. This shatters the limitations of conventional optics, opening doors for sub-wavelength light processing, this potential has researchers excited about tiny structures called plasmonic waveguides that can effectively control these ultra-small light patterns, these waveguides work because SPPs involve the interaction of light waves with electrons in metals, specifically at the boundaries between metals and insulators. By harnessing this interaction, scientists can steer light at sub-wavelength scales (C.A. Thraskias et al., 2018 , J.A. Schuller et al., 2010). Researchers have developed various building blocks for future photonic circuits utilizing plasmonic waveguides. These components include tiny resonators, light modulators, switches, and even logic gates (Y. Guo et al., 2013 - Mohammed N. Abbas, Saif H. Abdulnabi, et al., 2020). Many designs exist for multiplexers, employing various materials, structures, and channel numbers to achieve different resonance wavelengths and transmission values. This research introduces a novel plasmonic multiplexer design that achieves multiplexing

functionality, which the researchers achieved similar material properties (silver and glass), structural dimensions, resonant wavelength (1550 nm), and transmission threshold (0.5) as the previous design. They employ a Nano-ring resonator design coupled with Insulator-Metal-Insulator (IMI) plasmonic waveguides, creating a compact and efficient structure. Notably, the design and simulation are conducted using COMSOL Multiphysics software. Simulation results (likely computer modeling) support the potential of this multiplexer for building nanophotonic circuits. These circuits are key components in future all-optical computers, offering significant miniaturization.

This article is structured as follows: Section 2 details the designed structure; Section 3 discusses the analysis and simulation results; Section 4 highlights the main strengths of this work through comparisons with previous related studies; and Section 5 presents the conclusions of this research.

2. METHODOLOGY

The 2x1 multiplexer utilizes IMI waveguides and features a unique design. It combines a single elliptical ring waveguide with three straight sections, as shown in [Fig.1](#), the main advantage of using an elliptical shape in IMI plasmonic technology is its ability to enhance field confinement, tailor dispersion properties, achieve compact designs, and enable controlled polarization handling, thereby enhancing the performance and functionality of plasmonic devices. In the design of the plasmonic multiplexer, careful consideration was given to the choice of insulating material. Zinc Oxide (ZnO), with a refractive index of 2.015, was selected as the insulator due to its exceptional properties such as high transparency in the visible spectrum, low optical loss, and compatibility with the fabrication process ([Rah, Yoonhyuk et al., 2019](#)). Compared to other insulating materials such as silicon dioxide or silicon nitride, Zinc Oxide offers superior performance in terms of optical transparency and low absorption, making it an ideal candidate for integration into the plasmonic waveguides. Additionally, its wide bandgap ensures minimal leakage of surface plasmon polaritons (SPPs), thus enhancing the efficiency of light transmission through the waveguides ([Johnson et al., 2018](#)). Therefore, the choice of zinc oxide as the insulator contributes to the overall compactness and efficiency of the Nano-ring resonator design coupled with Insulator-Metal-Insulator IMI plasmonic waveguides.

The device uses tiny rings made of alternating layers of insulator and silver metal. The specific properties of silver (obtained from data by Johnson and Christy) are crucial for its light-manipulating abilities ([Johnson et al., 1972](#)). The researchers designed the multiplexer to be extremely small, with a target footprint of just 300 nanometers by 250 nanometers.

(Bashiri, S., & Fasihi, K., 2019) This paper reports a design with dimensions of 3000 nm x 2400 nm, (Abdulwahid, S. H., Wadday, 2022) This paper reports a design with dimensions of 400 nm x 400 nm, (Abdulnabi, S. H., & Abbas, M. N., 2022) This paper reports a design with dimensions of 350 nm x 250 nm. (Charles, I., Swarnakar., 2023, January) This paper reports a design with dimensions of $9.2 \mu\text{m} \times 7.8 \mu\text{m}$, these references indicate that previous designs of plasmonic multiplexers typically used larger dimensions compared to the $300 \text{ nm} \times 250 \text{ nm}$ dimensions presented in this work.

For more specific details about the size and other features, you can refer to f 1, including the length of the middle stripe (L_m), the width of all stripes (w), the separation between the right, left, and center Ellipse Ring waveguides (d_r , d_L , and d_m), the large and small diameters of the Ellipse Ring (b , c) and (a , d), and other relevant parameters. In optical communication applications, the preferred operational wavelength is 1550 nm.

Table 1. Parameters of proposed structure.

Parameter	Description	Value (nm)
H	High of structure	300
W	Width of structure	250
L_m	Length of middle stripes	94
b	Outer Ellipse Large diameter b	51
a	Outer Ellipse Small diameter a	48
c	Inner Ellipse Large diameter c	20
d	Inner Ellipse Small diameter d	10
w	Width of stripes	15
d_L	Distance between left stripe and Ellipse Ring	10
d_m	Distance between middle stripe and Ellipse Ring	5
d_r	Distance between right stripe and Ellipse Ring	5

the input optical power, with as the selector port and port 4 as the output optical power measured at specific, and port 5 will always be in the ON state in order to maintain the balance of the design.

2.1. Key Influences on Performance

2.1.1. Wavelength (λ):

Effect on Resonance: The resonant wavelength is determined by the dimensions and materials of the plasmonic structure. A change in wavelength can shift the resonance condition, affecting transmission efficiency.

Impact on Modulation Depth and Contrast Ratio: If the wavelength is tuned to the plasmonic resonance, it will maximize modulation depth and contrast ratio due to enhanced light-matter interaction.

2.1.2. Refractive Index (n):

Effect on Transmission and Insertion Loss: The refractive index of materials, such as Silver and Zinc Oxide, affects how light propagates through the structure. A higher refractive index contrast between the plasmonic material and the surrounding medium can enhance confinement of the plasmonic modes, thereby affecting transmission and insertion loss.

Impact on Modulation Depth: Changes in the refractive index can modify the effective index of the waveguide modes, which in turn affects the modulation efficiency.

2.2. Structural Parameters' Influence

2.2.1. H (Height) and W (Width):

These dimensions determine the overall size of the device and its ability to support plasmonic. Larger dimensions can support lower-frequency modes (longer wavelengths), while smaller dimensions are suited for higher-frequency modes (shorter wavelengths).

2.2.2. L_m (Length of Middle Stripes):

The length of the middle stripes influences the interaction length for plasmonic coupling, thereby affecting modulation depth and contrast ratio.

2.2.3. b, a (Outer Ellipse Diameters):

The shape and size of the outer ellipse affect the resonance conditions and field distribution within the structure, impacting the transmission and insertion loss.

2.2.4. c, d (Inner Ellipse Diameters):

Similar to the outer ellipse, the inner ellipse dimensions further refine the field distribution and resonance characteristics, crucial for achieving desired modulation properties.

2.2.5. w (Width of Stripes):

The width of the stripes determines the coupling strength between different parts of the structure, influencing the modulation depth and contrast ratio.

2.2.6. dL, d_m, d_r (Distances between Stripes and Ellipse Ring):

These distances control the coupling efficiency between the stripes and the ellipse ring, affecting the overall transmission and insertion loss. Optimal spacing is essential for minimizing losses and maximizing modulation depth (Maier, S. A. 2007).

The researchers evaluate the performance of the plasmonic multiplexer using four key metrics: transmission (the amount of light that passes through), contrast ratio (the difference between on and off light signals), modulation depth (the extent or effectiveness of the change in the optical signal's intensity when it is modulated), and insertion loss (the amount of light lost within the device).

Transmission (T) measure of how much light power travels from the device's input to its output. It's basically the ratio of the light power coming out (output) compared to the light power going in (input) (Kumar, Upkar et al., 2017):

$$T = \left(\frac{P_{out}}{P_{in}} \right)$$

Within the study, T signifies the optical power transmitted at the various input ports (1, 2) in Multiplexer, this notation defines Pin as output depends on comparing a calculated value to a set reference point, usually set at 0.5.

Contrast ratio (CR) is calculated as (Kumar, Upkar et al., 2017):

$$CR \text{ (dB)} = 10 \log \left(\frac{P_{out|ON_{min}}}{P_{out|OFF_{max}}} \right)$$

They measured the difference in light power coming out (output) when the device is turned "ON" ($P_{out|ON}$) compared to when it's turned "OFF" ($P_{out|OFF}$). A bigger difference between these values means the device works better at switching light on and off.

Modulation depth (MD) is a measure of contrast in a signal. It's expressed as the ratio between the maximum light transmission when the device is "on" ($T_{ON|Max}$) and the minimum light transmission when it's "off" ($T_{OFF|Min}$) (Ma, Song et al., 2021):

$$\text{Modulation depth (MD)} = \left(\frac{MaxT_{ON} - MinT_{OFF}}{MaxT_{ON}} \right)$$

This parameter evaluates the optimal dimensions for the proposed design.

Insertion loss (IL) is calculated as (Unser, Sarah et al., 2015):

$$IL \text{ (dB)} = -10 \log \left(\frac{P_{out|ON_{min}}}{P_{in}} \right)$$

This metric assesses the insertion loss, which refers to the decrease in power level experienced by a signal when it passes through a connection point between two devices. The description of these values is provided in Table 2.

Table 2. Describe the Insertion Loss values

IL (dB) ranges	Description	Assessment of IL
More than 5	Very High	Bad and Inefficient
More than 3 - 5	High	Accepted
More than 1 - 3	Medium	Moderate
More than 0 - 1	Low	Good

This research proposes a plasmonic multiplexer based on the structure shown in Fig.1. The device operates by exposing it to a broad light wave (1300nm to 1800nm) directed at designated input ports and a control port. To achieve optimal performance, refer to Fig.1, we are employing a trial-and-error approach to identify the ideal configuration for these ports (input, control,

output) within the structure. This optimization aims to maximize light transmission, achieve high contrast between on and off states, create deep signal modulation, and minimize signal loss during operation. To get the best performance, the researchers experimented with different configurations for the input and output ports. This fine-tuning aimed to boost the amount of light getting through (transmission), maximize the difference between high and low light levels (contrast ratio), create very strong switching (deep modulation), and minimize any signal weakening (insertion loss).

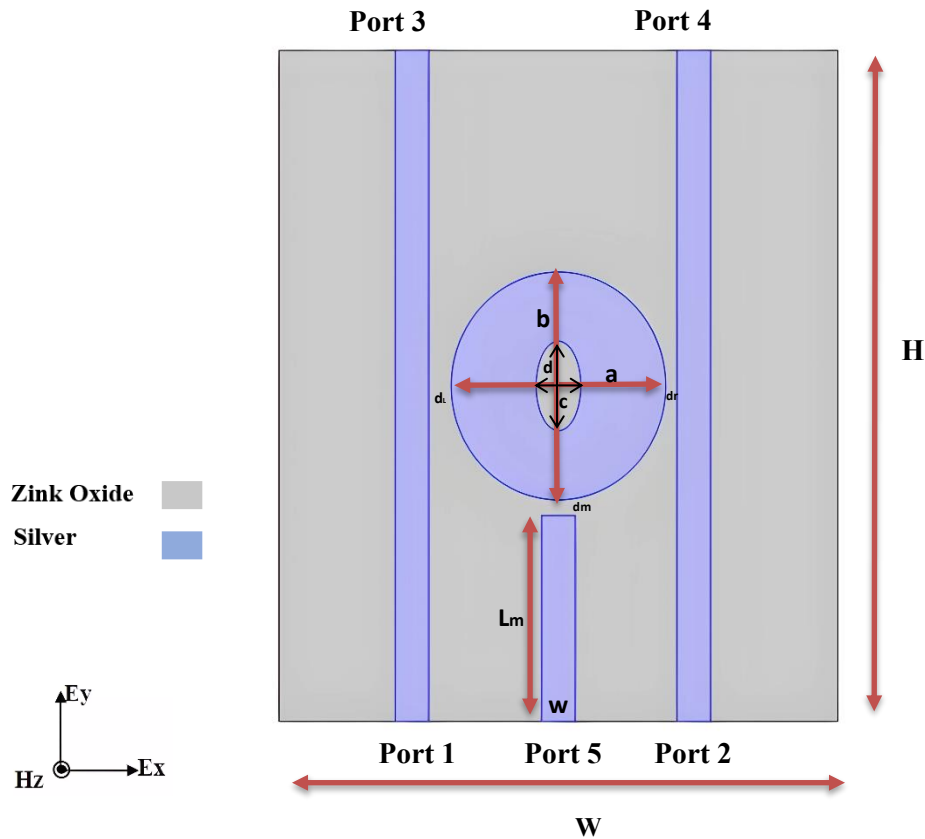


Fig.1. The proposed plasmonic 2×1 Multiplexer with 300 nm × 250 nm area.

3. RESULTS AND DISCUSSION

In a plasmonic Multiplexer, the structure is illuminated by a plane wave with a wavelength ranging from 1300nm to 1800nm. This illumination is directed towards input port (1, 2) (ON state) and the control port 3. To utilize the proposed structure Fig.1 as a plasmonic Multiplexer, the input port, the control port, and the output port need to be determined to achieve the functionality of the proposed plasmonic logic devices. The process of selecting these ports for the proposed plasmonic Multiplexer is carried out using a trial-and-error method to enhance transmission performance, achieve a high contrast ratio, high modulation depth, and minimize insertion loss.

3.1. Plasmonic 2×1 Multiplexer

Fig.2 depicts the conventional symbol and truth table for the proposed Multiplexer (A, B, S, Y). Port 5 in the proposed Multiplexer is consistently in the ON state. The input ports 2 and 1 are represented. The selection port 3, while the output port 4. In each of the four cases, as illustrated in Fig.3, is OFF. The input power through the input ports (2, 1) is 1W.

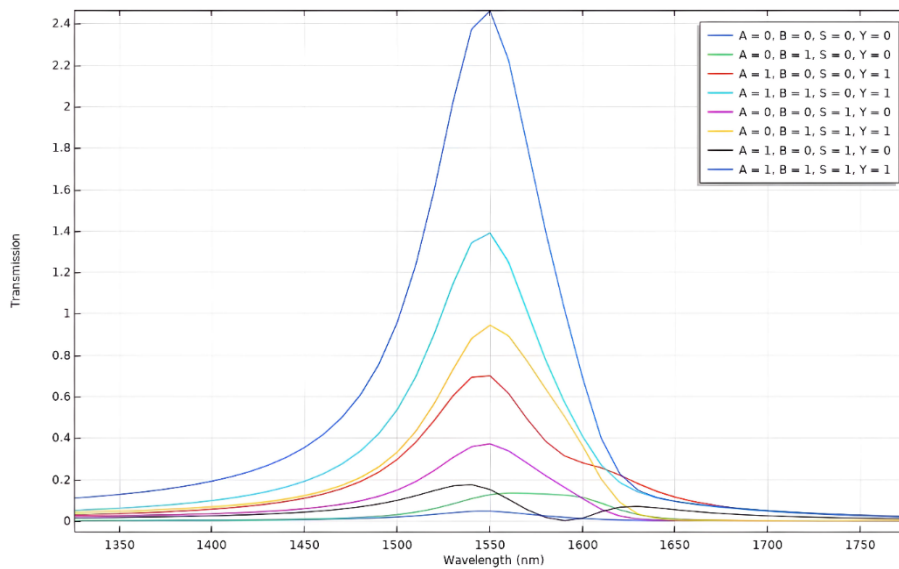
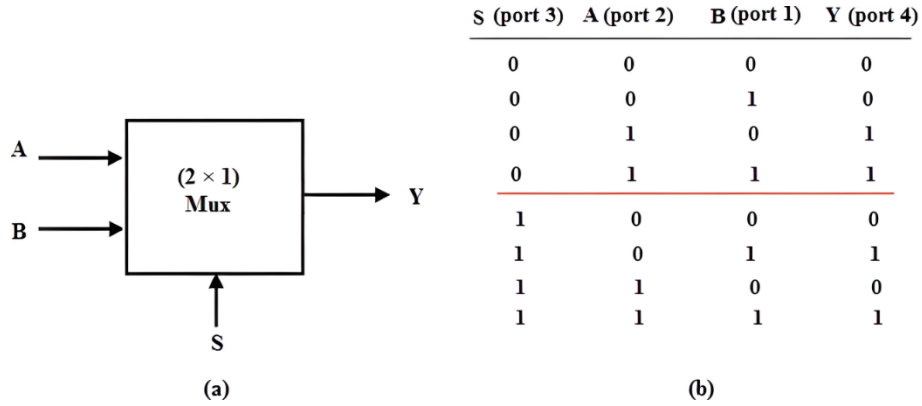


Fig.2. Multiplexer's: (a) conventional symbol; (b) truth table.

Fig.3. The transmission spectrum of the proposed plasmonic Multiplexer at different states when selector port is OFF.

The output port 4 of the Multiplexer is considered OFF when both input ports 2 and 1 are in the OFF state, resulting in a transmission value of 0.0479. Similarly, when only port 1 is ON with a 180-degree phase, the transmission value at 1550 nm is 0.1281. In both instances, the transmission falls below the transmission threshold.

Constructive interference occurs between port 2 and port 5 or between input ports and port 5 when 2 is in the ON state or when all inputs ports 2 and 1 are ON, thereby increasing the

transmission. In these scenarios, the transmission values are 0.7013 and 1.3901 respectively, surpassing the transmission threshold.

In these four instances, the selector port 3 state is ON. The transmission is 0.373, and the port 4 state is OFF when ports 2 and 1 are both turned OFF. Destructive interference occurs between port 2 and the selector port when the state of 1 is ON, resulting in a transmission of 0.946. Port 4 is ON when port 2 is ON and the phase of 2 signal equals 3. In this case, the output port 4 state will be OFF with a transmission value of 0.1527.

When all input ports are in the ON state due to constructive interference between the input ports and selector port signals, the transmission reaches 246 percent (2.46%). This structure exhibits a 2.7419 dB contrast ratio and a 71.52 percent modulation depth. The insertion loss is 1.5409 dB.

Table 3. Summarized simulation results in Fig.1.

port 3	port 2	port 1	port 4	T	MD (%)	CR (dB)	IL (dB)	Threshold
0	0	0	0	0.0479				
0	0	1	0	0.1281				
0	1	0	1	0.7013				
0	1	1	1	1.3901	71.52%	2.7419	1.5409	0.5
1	0	0	0	0.3730				
1	0	1	1	0.9460				
1	1	0	0	0.1527				
1	1	1	1	2.4625				

Due to the substantial contrast between the highest transmission in the ON state and the lowest transmission in the OFF state, as depicted in [Table 3](#), the transmission threshold proves suitable, resulting in a remarkably high modulation depth. Consequently, the dimensions of the proposed structure are considered excellent and optimal, as per reference ([Abdulnabi, Saif H., and Mohammed N. Abbas et al., 2022](#)). Moreover, in accordance with findings from ([Abbas, Mohammed N., and Saif H. Abdulnabi et al., 2020](#)), the optical output's performance is deemed acceptable despite the poor contrast ratio and low optical output minimum power in the ON state. Additionally, [Table 2](#) illustrates that the insertion loss (IL) is m.

Lastly, [Fig.4\(a\)](#) presents the magnetic field distribution (Hz-component) when both the selector and input ports are in the off state, while [Fig.4\(b\)](#) illustrates it when the selector is on and the input ports are off. [Fig.4\(c\)](#) depicts the selector in an ON state with the input ports off. When both the input ports and the selector are in the ON state, it is depicted in [Fig.4\(d\)](#). The color bar in [Fig.4](#) illustrates the variation in light power intensity, as discussed in the Multiplexer section. Another interpretation is that light intensity increases from low to high as it changes from blue to red.

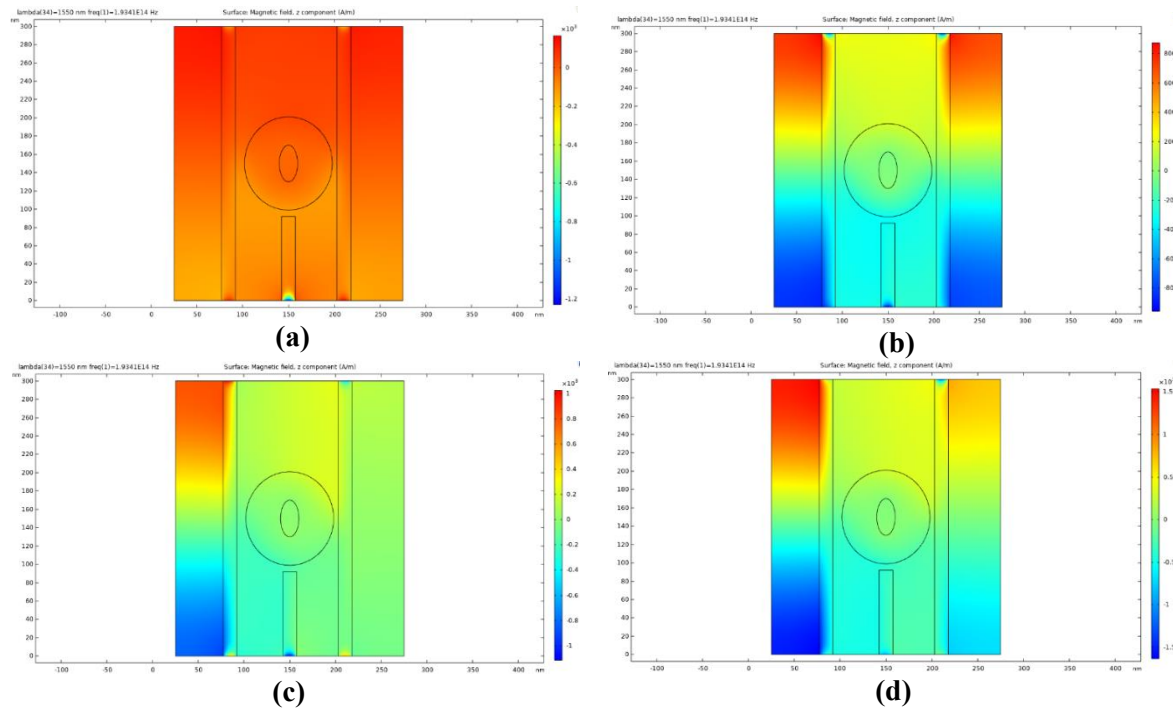


Fig.4. The magnetic field distribution (Hz-component) when: (a) S, A and B are OFF states, the output Y is OFF states; (b) S is OFF, A and B are ON states, the output Y is ON states; (c) S is ON, B and A are OFF states, the output Y is OFF states; (d) S, A and B are ON states, the output Y is ON states.

4. COMPARISON

Our work was compared with previous work, as shown in the following table:

Ref.No Year	Topology	Model of Metal	Operating Wavelength	Size	Performance Measured	Transmission	Threshold	Complexity
Bashiri, S., & Fasihi, K. (2019)	Nano- racetrack resonator side coupled to air (MIM) waveguide	Drude model	685nm, 793.2nm	3000 nm × 2400 nm	Two parameters (T, CR)	70%	0.5	More
Abdulwa hid, S. H., Wadday, (2022)	hybrid plasmonic waveguides	Johnson and Christy data	1310 nm	400 nm × 400 nm	Four parameters (T, CR, MD, IL)	202.3%	0.3	More
Abdulna bi, S. H., & Abbas, M. N. (2022)	Nano ring IMI Nano plasmonic waveguides	Johnson and Christy data	1550 nm	350 nm × 250 nm	Three parameters (T, CR, MD)	186.5%	0.4	Less
Charles, I., Swarnak ar, (2023, January)	(MIM) Plasmonic Waveguide	Not Availabl e	1550 nm	9.2 μm × 7.8 μm	Two parameters (T, CR)	Less than 10%	0.5	More
Mustafa, S. M., (2023)	Nanoellipse IMI nanoplasmo nic waveguides	Johnson and christy data	1550 nm	400nm × 400nm	Five Parameters (T, CR, MD, IL, CL)	163%	0.5	Less

Ref.No Year	Topology	Model of Metal	Operating Wavelength	Size	Performance Measured	Transmission	Threshold	Complexity
This work	Nano ring IMI Nano plasmonic waveguides	Johnson and Christy data	1550 nm	300 nm × 250 nm	Four parameters (T, CR, MD, IL)	246.2%	0.5	Lesser

5. CONCLUSION

In this research, a Multiplexer is proposed, constructed, and analyzed using a novel configuration based on Ellipse Ring. The threshold separates the ON and OFF states. The performance of the suggested plasmonic Multiplexer is described by four parameters: transmission (T), contrast ratio (CR), modulation depth (MD), and insertion loss (IL) at 1550 nm. Notably, the device achieves a maximum transmission efficiency of 246 percent, a feature not seen in earlier developments. The modulation depth for Multiplexer exceeds 71%, making the proportions of this design outstanding. Remarkably, all these achievements are realized while maintaining a compact size of only (300nm x 250nm). The proposed architecture holds significance for the advancement of all-optical Arithmetic Logical Units (ALUs), Optical Signal Processing (OSP) circuits, Photonic Integrated Circuits (PICs), and applications based on Terahertz (THz) technology.

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