International Journal of
INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING

ISSN:2147-6799 www.ijisae.org Original Research Paper

Nano Elliptical Structure for Performing All-Plasmonic 1 × 2 Demultiplexer

Sajjad Mohanad Mustafa[1], Gholamreza Karimi[1*], Mazdak Rad Malek Shahi[1]

Submitted: 09/01/2024 **Revised**: 15/02/2024 **Accepted**: 23/02/2024

Abstract: This paper presents the design of an all-optical 1 × 2 demultiplexer utilizing elliptical Insulator-Metal- Insulator (IMI) plasmonic waveguides. The dimensions of the proposed structure are rather compact, measuring 400 nm × 400 nm, and it functions within the wavelength range of 1550 nm. The devised apparatus among the input signal along with the selector signal utilizes constructive and destructive interferences. Compared to the earlier works, this structure is considerably simpler. The plasmonic demux's performance can be assessed using the following five parameters: the first is Transmission (T), the second is Contrast Ratio (CR), and third parameter is the Modulation Depth (MD), fourth parameters is the Insertion Loss (IL), and the last parameter is the Contrast Loss (CL). The threshold for transitioning between logic 1 and logic 0 is determined to be 0.3. In addition, the suggested structural dimensions are deemed to be excellent and ideal, as indicated by the MD value of 97.56%. The plasmonic Demux structure being proposed plays a significant role in the advancement of all-optical Arithmetic Logic Units (ALUs) and all-optical signal processing Nano-circuits. The proposed plasmonic Demux is simulated via COMSOL Multiphysics 5.4 utilizing the Finite Element Method (FEM).

Keywords: *Elliptical Nano Resonator; IMI Plasmonic Waveguides; 1 × 2 Demultiplexer.*

1. Introduction:

The present researchers in the field of integrated circuit design are showing interest in optical devices that rely on Surface Plasmon Polaritons (SPPs) [1]. Surface plasmon polaritons (SPPs) refer to the surface electromagnetic waves that propagate over interfaces between metals and dielectrics. The interaction of the free electrons with electromagnetic waves and that are inherent in metals gives rise to these waves [1]. The fundamental concept behind the development of plasmonic devices involves the manipulation of destructive and constructive interferences among light signals within plasmonic waveguides [2-4].

In recent years, numerous plasmonic waveguide structures have been suggested, including resonators [5], switches [6], sensors [7-9], nanowires [10-11], logic gates [12-15], multiplexers[16-19], and demultiplexers [20-21]. This method employs two primary forms of plasmonic waveguides: IMI and MIM plasmonic waveguides. The IMI waveguides contain an extended propagation length, lowered propagation loss, and a streamlined fabrication process [19].

The present study introduces a novel configuration consisting of three linear waveguides interconnected with two elliptical IMI plasmonic waveguides, aiming to achieve a 1×2 demultiplexer. The structure that has been designed possesses a minimum dimension of 400 nm × 400 nm, with an operational wavelength of 1550 nm. The numerical outcomes are acquired by the utilization of the Finite Element Method (FEM) employing the COMSOL Multiphysics 5.4 software. The plasmonic demultiplexer under consideration exhibits potential for utilization in the development of all-optical signal processing Nano-circuits and all-optical Arithmetic Logic Unit (ALU). Section 2 outlines the proposed structural organization and theoretical concept of operation. The efficacy of the suggested design and the results of the simulations are elaborated upon in Section 3. In Section 4, the proposed structure is compared to the prior work .The final section of the article presents an overview of the primary conclusions derived from the investigation.

2. Structure layout

According to the reference cited as [19], a study proposes the optimal dimensions for a 1x2 Demultiplexer (Demux) based on an IMI plasmonic waveguide. The proposed design includes three linear stripes and two elliptical waveguides, as illustrated in Fig. 1. The metallic region is composed of silver, while the insulator medium is implemented using pure flint glass. In the event of a three-dimensional (3D) structure, the substrate is constructed using a semiconductor material, specifically silicon. Johnson and Christy [22] have calculated the permittivity of silver, whereas the refractive index of flint glass has been reported as 1.61 [23].

1- Razi University, Electrical Engineering Department, Faculty of Electrical and Computer Engineering, Tagh-E-Bostan Kermanshah, Iran-6714414971.
**Correspondence: Gholamreza Karimi; E-mail: ghkarimi@razi.ac.ir.*

The dimensions of the design region of the proposed structure measure 400 nm x 400 nm. Additionally, it should be noted that the dimensions of the two side stripes measure 400 nm. This information can be found in Table 1, which provides a comprehensive overview of the length of the central stripe and all other parameters pertaining to the proposed construction. The operating wavelength of 1550 nm is considered the optimal selection for optical communication applications [19].

Table 1. The proposed structure's parameters.

Parameter	Explanation	Value
A	Width and Altitude of the structure	400 nm
L_{cs}	Length of the central stripes	240 nm
x	The two major axes, "a," greatest and smallest	80 nm,60 nm
y	The two minor axes, "b," greatest and smallest	40nm ,20 nm
W	strips' width and the nano ellipse resonator s' width	20 nm
d	Distance from the nano ellipse resonator to the stripes	10 nm

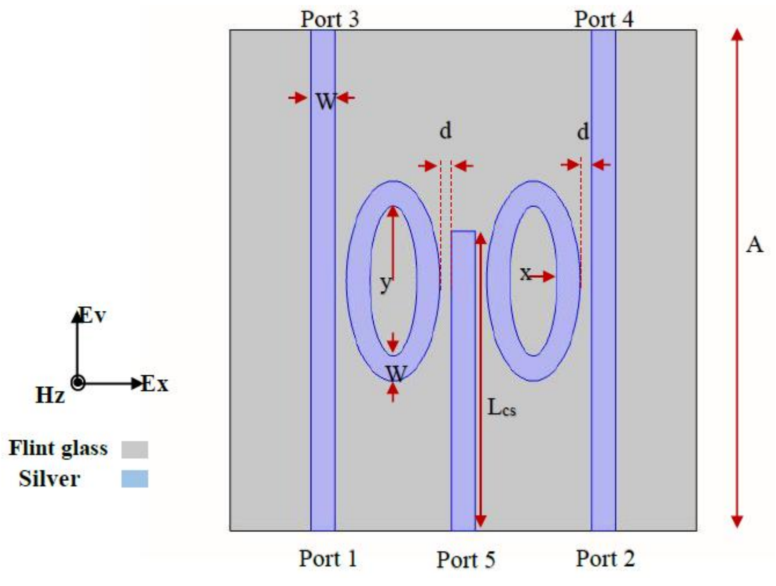


Fig 1. The suggested plasmonic 1×2 Demux has an area of 400 nm × 400 nm.

The Demux under consideration is founded upon the constructive and destructive interference principles that regulate the selector signal's relationship with the input signal. The phenomenon of constructive and destructive interferences occurring between the selector light signal and the input light signal is contingent upon both the phase of the light that arrives signal and the spatial arrangement of the input port and selector port. The constructive interference arises when the incidental signals at the selector and input ports exhibit in the identical phase and direction of propagation. In addition, the destructive interference arises when there is a difference in the direction or in the phase degree of the incidental signal's passage between the input port and selector port.

As per the equation (1), the phase disparity gives rise to a phenomenon of destructive interference between the signals. The references [12, 19] are provided.

$$m = (4n_{eff}\, d\cos\theta)/\lambda \qquad (1)$$

The variables m, n_{eff}, d, θ, and λ represent the sequence of interference (m), the silver substance's effective refractive index (neff), thickness of the metallic element (d), the phase of the signal incident (θ), and wavelength of incident (λ), respectively.

The plasmonic Mux's performance is characterized by five characteristics, the first is Transmission (T), the second is Contrast Ratio (CR), and third parameter is the Modulation Depth (MD), fourth parameters is the Insertion Loss (IL), and the last one parameter is the Contrast Loss (CL). The transmission is associated with the optical power that is transmitted from the selector port (port 1) and the input port (port 2) to the output ports (port 3 and port 4). The transmission is formally denoted by equation (2) as referenced in source [24, 25].

$$T = \frac{P_{out}}{P_{in}} \qquad (2)$$

In this context, T represents the transmission, whereas P_{in} refers to the power input for ports 1, 2, and 5. The optical output power at ports 3 and 4 is referred to as "P_{out}". Transmission can be accomplished by the act of choosing a transmission threshold that distinguishes between the ON state, representing logic 1, and the off state, representing logic 0. The value of the transmission threshold between the logic 0 and the logic 1 at the output of the proposed 1×2 Demultiplexer is determined to be 0.3.

The Contrast Ratio is determined by the values of the smallest output optical power while in the ON state (P_{out} |ON) and the greatest optical output power while in the OFF state (P_{out} |OFF), as expressed in equation (3) [24, 25].

$$\text{CR (dB)} = 10\log\left(\frac{P_{out} \mid ON}{P_{out} \mid OFF}\right) \qquad (3)$$

A greater CR value signifies that the designed structure is performing in accordance with expectations. The source mentioned in [24] must be consulted in order to calculate the value of CR.

The third parameter, known as modulation depth (MD), this parameter measures the proportion between the highest transmission rate (T_{ON}|Max) and the lowest transmission rate (T_{OFF}|Min) while the system is in the OFF state. The equation denoted as (4) is formally defined as stated in reference [18, 25].

$$\text{MD} = \left(\frac{T_{ON} \mid Max - T_{OFF} \mid Min}{T_{ON} \mid Max}\right) \qquad (4)$$

MD measures the optimality of the dimensions chosen for the proposed design. As per reference [18], the values of MD are ascertained. The fourth criterion is insertion loss (IL), which is determined by the input optical power and the minimal optical output power in the active (ON) condition. It is calculated utilizing the subsequent equation [19]:

$$\text{IL (dB)} = -10\log\left(\frac{Pout_{ON} \mid Min}{Pin}\right) \qquad (5)$$

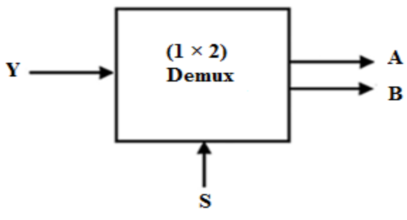
This parameter quantifies the losses that occur during the insertion of one device into another. The final extracted parameter is Contrast Loss (CL) that quantifies the losses caused by the contrast ratio. Inversely, induced losses are minimal when insertion loss is high and contrast ratio is low; thus, whenever CL is high, the total loss is minimal, as per equation (6) [19]:

$$CL(dB) = CR(dB) - IL(dB) \qquad (6)$$

3. Results of Simulations

In order to investigate the Demux operation, a plane wave spanning a wavelength of 1200 to 2000 nm has illuminated the proposed structure, as illustrated in Fig. 1. Fig. 2(a-b) displays the block diagram and truth table of a 1×2 Demultiplexer. In the constructed Demultiplexer (Demux), it is observed that port 5 remains consistently in the ON state, whereas the input port is denoted as Y and its status is associated with port 2. S is used for the selector port at port 1, while B and A states are used for the output ports at ports 3 and 4, respectively.

As depicted in Figure 3, when the input port (Y) as well as selector port (S) are in the deactivated state, the Demultiplexer's output ports (A and B) are likewise deactivated. On the other hand, when the input port (Y) is activated, the output ports (A and B) will be activated and deactivated, respectively.



(a)

S (port 1)	Y (port 2)	A (port 4)	B (port 3)
0	0	0	0
0	1	1	0
1	0	0	0
1	1	0	1

(b)

Fig 2. Demultiplexer (a) conventional symbol and (b) truth table.

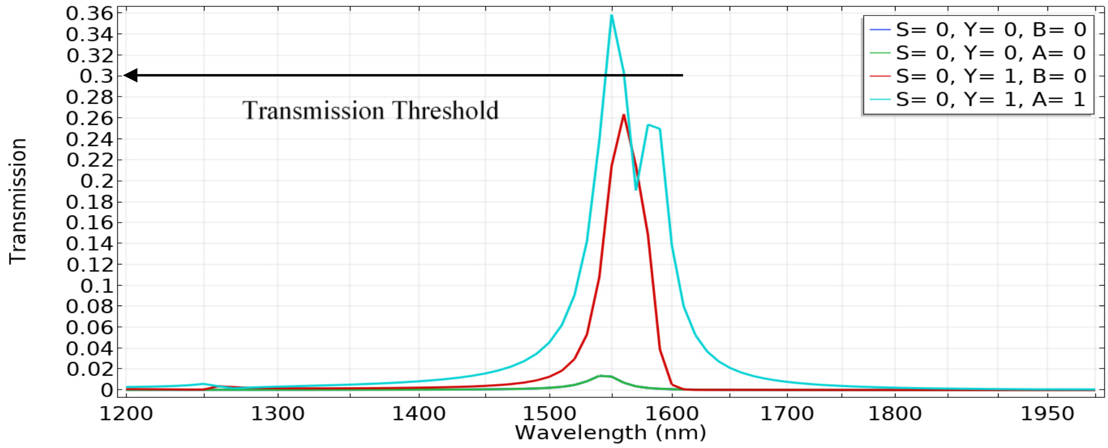


Fig 3. The transmission spectrum of the recommended plasmonic Demultiplexer in various states when the selector port is deactivated.

Furthermore, as illustrated in Fig. 4, when the input port (Y) is in the deactivated state and the selector port (S) is in the activated state with a 180-degree phase shift, the output ports (A and B) of the Demux are also deactivated. Conversely, in the event that the input port (Y) is activated with a signal of 180 degrees and the selector port is also activated, the output ports (A and B) will be deactivated and activated, respectively.

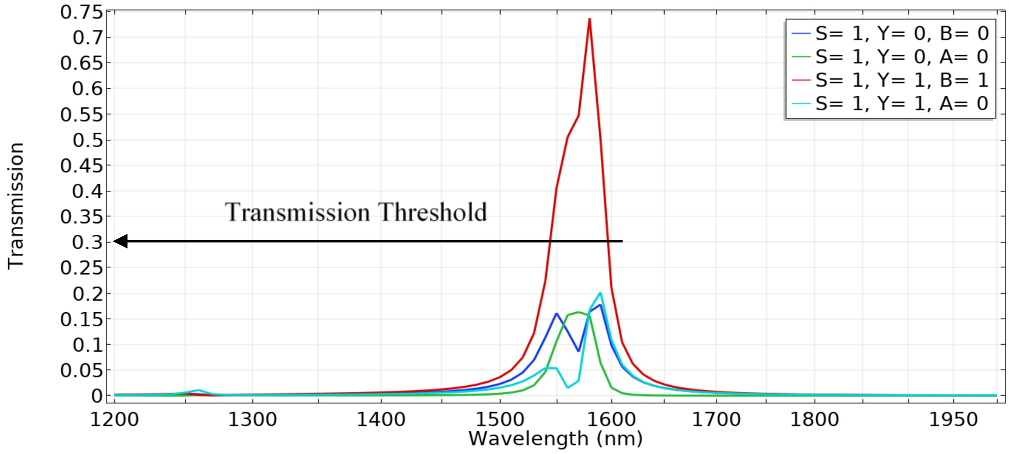


Fig 4. The transmission spectrum of the recommended plasmonic Demultiplexer in various states when the selector port is activated.

The structure exhibits a contrast ratio of 2.55 dB , and its performance is deemed acceptable, as stated in reference [24]. Moreover, a modulation depth of 97.56% demonstrates excellent and optimal performance, as stated in reference [18]. The measured value for insertion loss is 4.43 , and its acceptability is confirmed by reference [19]. Additionally, the contrast losses were determined to be -1.88 dB. The findings of the Demux simulation are displayed in Table 2.

Table 2. A summary of the simulation outcomes illustrated in Fig. 3 and 4.

S (port1)	Y (port2)	A (port4)	B (port3)	T threshold	T at A	T at B	CR (dB)	MD	IL (dB)	CL (dB)
0	0	0	0		0.01	0.01				
0	1	1	0	0.3	0.36	0.2	2.55	97.56%	4.43	-1.88
1	0	0	0		0.1	0.16				
1	1	0	1		0.05	0.41				

Fig. 5 (a-d) illustrates the magnetic field's z-component distribution (Hz) for all scenarios based on its truth table. The color bar depicted in Fig. 5 (a-d) visually represents the range of light power intensity. The transition from blue to red indicates a progressive increase in light power intensity, signifying a shift from low to high levels.

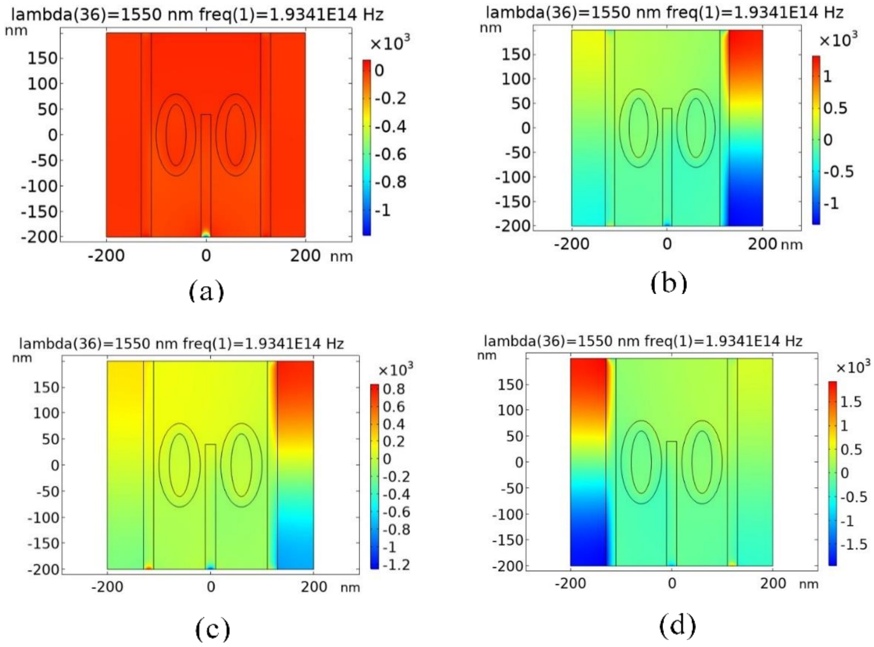


Fig 5. The distribution of magnetic fields (Hz-component) in the following scenarios: (a) S and Y are in an OFF state; (b) S is in an OFF-state and Y is in an ON -state; (c) S is in an ON-state and Y is in an OFF -state; and (d) S and Y are in an ON-state.

4. Comparing the Designed Work to Previous Works

The proposed structure is compared to the prior work, which is presented in Table 3. The table provided illustrates that the proposed structure exhibits favorable attributes

Table 6. Comparing the Designed Work to Previous Works.

References	Topology	Model of Metal	Operating Wavelength	Size	Performance Measured By	Complexity
[26]	Plasmonic MIM waveguide leading to a ring cavity in hollow	Johnson and Christy data	788 nm and 820 nm	About 1.8 μm × 1.5 μm	One parameter	More
[27]	Plasmonic slot resonator	Drude	1490 nm and 1522 nm	About 1.4 μm × 1.2 μm	One parameter	More
[28]	Crossing of a plasmonic (MIM) waveguide	Lorentz-	1553 nm and		One parameter	More

	with numerous side-coupled hexagonal resonators	Drude	1500 nm	3 μm × 3 μm		
[29]	Plasmonic rectangular (MIM) waveguide	Drude	650 nm and 980 nm	More than 1.6 μm × 600 nm	One parameter	More
[30]	Plasmonic rectangular resonators nanorods	Drude	1074 nm and 1307 nm	More than 560 nm × 500 nm	One parameter	More
This work	Nano Ellipse IMI Nano plasmonic waveguides	Johnson and Christy data	1550 nm	400 nm × 400 nm	Five parameters	Lesser

5. Conclusion

This work presents a novel configuration for an all-optical 1×2 Demultiplexer (Demux) utilizing elliptical IMI plasmonic waveguides. The suggested configuration, which functions at a wavelength of 1550 nm, possesses a diminutive form (400 nm x 400 nm) and exhibits a straightforward design. The operational mechanism of the structure relies on the relationship of destructive and constructive interferences of the input signal with the selector signal. The performance evaluation of the plasmonic Mux under consideration encompasses five important parameters, namely the Transmission (T), the Contrast Ratio (CR), the Modulation Depth (MD), the Insertion Loss (IL), and the Contrast Loss (CL), all measured at a wavelength of 1550 nm. The recommended structural dimensions are deemed to be excellent and ideal, as indicated by the MD value of 97.56%. The results of the simulation were acquired by the utilization of the Finite Element Method (FEM) employing the COMSOL Multiphysics 5.4 software.

References:

[1] M. Dragoman and D. Dragoman, "Plasmonics: Applications to nanoscale terahertz and optical devices," Progress in Quantum Electronics, vol. 32, no. 1, pp. 1–41, 2008.

[2] E. Ozbay, "Plasmonics: Merging Photonics and Electronics at Nanoscale Dimensions," science, vol. 311, pp. 189–193, 2006.

[3] Fu, Y.; Hu, X.; Lu, C.; Yue, S.; Yang, H.; Gong, Q. "All-optical logic gates based on nanoscale plasmonic slot waveguides," Nano Lett, 12, 5784–5790, 2012.

[4] Abdulnabi, S.H.; Abbas, M.N. "Design an All-Optical Combinational Logic Circuits Based on Nano-Ring Insulator-Metal-Insulator Plasmonic Waveguides," Photonics, 6: 30, 2019.

[5] Y. Guo, L. Yan, W. Pan, B. Luo, K.Wen, Z. Guo and X. Luo, "Transmission characteristics of the aperture-coupled rectangular resonators based on metal–insulator–metal waveguides," Optics Commun. 300, 277–281, 2013.

[6] J. Tao, Q.J. Wang, and X.G. Huang, "All-optical plasmonic switches based on coupled nano-disk cavity structures containing nonlinear material," Plasm. 6(4), 753–759, 2011.

[7] Rakhshani, M.R., et al. "Design of a plasmonic sensor based on a square array of nanorods and two slot cavities with a high figure of merit forglucose concentration monitoring, " Appl. Opt., 57(27), 7798–7804, 2018.

[8] Enoch, S., R. Quidant, and G. Badenes. "Optical sensing based on plasmon coupling in nanoparticle arrays," Opt. Express, 12(15), 3422-3427, 2004.

[9] Van Oosten, D., M. Spasenovic, and L. Kuipers. "Nanohole chains for directional and localized surface plasmon excitation," Nano Lett., 10(1), 286-290, 2010.

[10] Min, C., P. Wang, X. Jiao, Y. Deng, and H. Ming. "Beam focusing by metallic nano-slit array

containing nonlinear material," Appl. Phys. B, 90(1), 97-99, 2012.

[11] Dickson, R. M. and L. A. Lyon, "Unidirectional plasmon propagation in metallic nanowires," J. Phys. Chem. B, Vol. 104, 6095-6098, 2000.

[12] Saif H. Abdulnabi, Mohammed N. Abbas, "All-optical logic gates based on nanoring insulator–metal– insulator plasmonic waveguides at optical communications band," J. Nanophoton. 13(1), 016009, 2019.

[13] Sadeq, S. A., et al. "Design of Ultrasmall Plasmonic Logic Gates Based on Single Nanoring Dielectric-Metal-Dielectric Waveguide," International Journal of Optics, 2023, 4489791, 2023.

[14] Saif H. Abdulnabi, Mohammed N. Abbas, "All-Optical Universal Logic Gates at Nano-scale Dimensions," Iraqi Journal of Nanotechnology, synthesis and application, 2, 34-43, 2021.

[15] Al-Tameemi, S., Al-Sabea, Z. S., Hayati, M., & Sadeq, S. A. "Fundamentals Plasmonic Logic Gates at Nano Scale Structure and 1550 nm Wavelength," Iraqi Journal of Natural Sciences and Nanotechnology, 4, 40-53, 2023.

[16] Qiu, Ying, et al., "Broadband mode converter and multiplexer based on dielectric-loaded plasmonic waveguides," Current Applied Physics, 20.2, 244-248, 2020.

[17] Bashiri, Sajjad, and Kiazand Fasihi, "A 2× 1 all-optical multiplexer using Kerr nonlinear nano-plasmonic switch," Optical and Quantum Electronics, 51.11, 1-16, 2019.

[18] Abdulnabi, Saif H., and Mohammed N. Abbas, "Design and simulation of an all-optical 2× 1 plasmonic multiplexer," Journal of Nanophotonics, 16.1, 016009, 2022.

[19] Mustafa, S. M., et al., "Nanomaterials in Nanophotonics Structure for Performing All-Optical 2 × 1 Multiplexer Based on Elliptical IMI-Plasmonic Waveguides," Nanomaterials and Nanotechnology, 2023, 7790674, 2023.

[20] Abdulnabi, Saif Hasan, and Mohammed Nadhim Abbas, "Theoretical investigation of a nano scale all-optical 1× 2 demultiplexer," AIP Conference Proceedings, Vol. 2651. No. 1, 2023.

[21] Azar, Milad TH, et al., "Design of a high-performance metal–insulator–metal plasmonic demultiplexer," Journal of nanophotonics, 11.2, 026002, 2017.

[22] Johnson, P.B.; Christy, R.W., "Optical constants of the noble metals," Phys. Rev, 6, 4370–4379, 1972.

[23] Kurkjian, Charles R. and Prindle, William R., "Perspectives on the History of Glass Composition," Journal of the American Ceramic Society, 81 (4), 795-813, 1998.

[24] Mohammed N. Abbas, Saif H. Abdulnabi, "Plasmonic reversible logic gates," J. Nanophoton. 14(1), 016003, 2020.

[25] Sadeq, Salma Ali, Mohsen Hayati, and Saba Khosravi, "High Transmission All-Optical Combinational Logic Circuits Based on a Nanoring Multi-Structure at 1.31 μm," Micromachines, 14.10, 1892, 2023.

[26] Huaiqing Liu, Yixiao Gao, Bofeng Zhu, Guobin Ren, Shuisheng Jian, "A T-shaped high resolution plasmonic demultiplexer based on perturbations of two nanoresonators, " Optics Communications 334, 164–169, 2015.

[27] Azzazi and M. A. Swillam, "Nanoscale highly selective plasmonic quad wavelength demultiplexer based on a metal-insulator–metal," Opt. Commun. 344, 106–112, 2015.

[28] Xie, Y.-Y., Chao He ,Jia-Chao Li, Ting-Ting Song, Zhen-Dong Zhang, Qian-Ren Mao. "Theoretical investigation of a plasmonic demultiplexer in MIM waveguide crossing with multiple side-coupled hexagonal resonators," IEEE Photon. J. 8, 1–12, 2016.

[29] Aparna Udupi, and Sathish Kumar Madhava, "Plasmonic Coupler and Multiplexer/Demultiplexer Based on Nano-Groove-Arrays," Plasmonics 16, 1685–1692, 2021.

[30] Shiva Khani, Ali Farmani & Ali Mir, "Reconfigurable and scalable 2, 4-and 6-channel plasmonics demultiplexer utilizing symmetrical rectangular resonators containing silver nano-rod defects with FDTD method," Scientific Reports 1-11, 2021.