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Design and Numerical Analysis of a High-Quality Factor Plasmonic 1 × 3 Demultiplexer Based on MIM Waveguides

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RESEARCH ARTICLE

Design and Numerical Analysis of a High-Quality Factor Plasmonic 1 × 3 Demultiplexer Based on MIM Waveguides

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ABSTRACT

This study aims to design plasmonic filters as essential components in photonic integrated circuits,based on surface plasmon polaritons (SPPs).Surface plasmon polaritons (SPPs) are electromagnetic waves that are transmitted at metal-insulator boundaries.Optical apparatuses founded on SPPs have been widely planned too deliberate because of their outstanding possessions, like beat the diffraction limit and treatment light at subwavelength range and at high speed in minor constructions. Design and analyzing a compact 1 × 3 optical demultiplexer in a plasmonic nano structure be also designed utilize the finite element method (FEM), and the suggested structure was arithmetically simulated utilize COMSOL Multiphysics 5.6 software. This construction contains of three square-ring-shaped resonators, designed utilize silver as the conductor and air as the dielectric, respectively. Its dimensions are (3000 × 1200) nm^2, and it activates in the wavelength channels (1100, 1650, and 960) nm. The results acquired from the designed plasmonic demultiplexer show a full- width at half-maximum (FWHM) of (13.8, 22, and 16) nm, respectively, through a high quality factor of (79.7, 75, and 60). Due to the adequate size of the proposed demultiplexer, it is possible to use it in optical communication integrated circuits. This paper investigates plasmonic filters as key components in photonic integrated circuits.

Keywords: Surface plasmon polaritons, Finite element method, Quality factor, Full, Width half-maximum

Highlights

1. A plasmonic 1 × 3 demultiplexer founded on metal insulator metal (MIM) waveguides is designed.
2. This suggested construction distinguishes a high quality-factor with well-separated resonance wavelengths.
3. Numerical simulations demonstrate maximum transmission efficiency and low crosstalk between output channels.
4. This structure presents strong potential for integration in nano-photonic and plasmon circuits.

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1. Introduction

(SPPs) are electromagnetic waves known as surface plasmon polaritons. Move through metal-insulator interfaces [1]. They are highly valued for enabling light control When the wavelength is measured and the diffraction limits are met, they are promising for optical integrated circuits. Plasm structures are classified into insulator – metal - insulator (IMI) and metal-insulator-metal (MIM): IMI wave guide classically experience low propagation lack than MIM wave guide [2]. This lower loss allows for Lengths-distance signals, suitable for applications needing minimal attenuation. MIM waveguides, offering better optical confinement, are preferred for high-density integration within dielectric layers [3, 4]. Applications of plasmonics include splitters, couplers, logic gates, filters, multiplexers, switches, and demultiplexers. This study emphases on plasmonic demultiplexers (DEMUX), vital for high-capacity plasmonic networks since they allow narrow channel spacing [5, 6]. Attention in DEMUX has grown due to its possible in nanophononics. They function by dividing input light into N channels founded on connections between electromagnetic waves and surface MIM structures [7, 8]. Various design plans, such as resonant cavities and waveguides, take been developed. Amongst these, plasmonic structures are preferred for their high light imprisonment, small power needs, and ease of conservation [9].

In 2024, Semih Korkmaz presented a study on the proposal and investigation of high-performance 1 × N demultiplexers founded on (MIM) waveguides armed with polygonal shape resonators. The investigator employed the FDTD arithmetical simulation method to investigate the spectral possessions of the projected mechanisms and assess the arrangement of the 1 × 2 and 1 × 3 demultiplexers. The consequences showed a important advance in performance, with a maximum quality factor of 47.7, a transmission ratio of 76%, minimal acoustic meddling (–30.37 dB), and a minimum full-spectrum width (FWHM) of 20.02 nm. As a consequence, the investigator declares that increasing the number of channels principals to a narrower bandwidth and an augmented quality factor, creation the future designs appropriate for high-efficiency, low-cost optical integrated circuit requests in optical communications [10].

Aparna Udupi et al. (2021) deliberate and designed a multiplier/demultiplexer (MIM) founded on arrays of nanogrooves integrated through waveguides. This learning aims to decrease the size of optical circuits and improve the coupling competence of (SPPs) inside the waveguides. Arithmetical simulations using the FEM were used to analyse the performance of the optional structure. The consequences showed an death ratio (ER) above 11 dB and high separation efficiency at wavelengths of 650 nm and 850 nm, by low interference of –19 dB and a FWHM reaching from 71 to 102 nm. The consequences of this study settle that the future design has the potential to integrate multiple functions on a single waveguide, making it suitable for nanophotonics dispensation and integrated communication requests [11].

In 2022,U.Aparna, et al. considered the proposal of a unidirectional plasmonic dissector structure containing of slot-shaped cavities etched on together sides of the MIM waveguide. Simulation (FEM) was used to learning the waveform features between the cavities and the chief waveguide. The results showed that the future design achieves remaining presentation with a maximum half-bandwidth (FWHM) of lower than 50 nm, an extinction-ratio (ER) exceeding 10dB, and a crosstalk (CT) of under –10dB. The design claims a small footprint and high integration possible in optical integrated circuits, creation it a talented choice for advanced signal dispensation and optical communications applications [12].

In 2022, E. Medina et al.future a study on the presentation of plasmonic filters using the Drude model to simulate the transmission of optical waves done a(MIM) waveguide. The learning meant to use the filter as a structure block for the proposal of a demultiplexer in

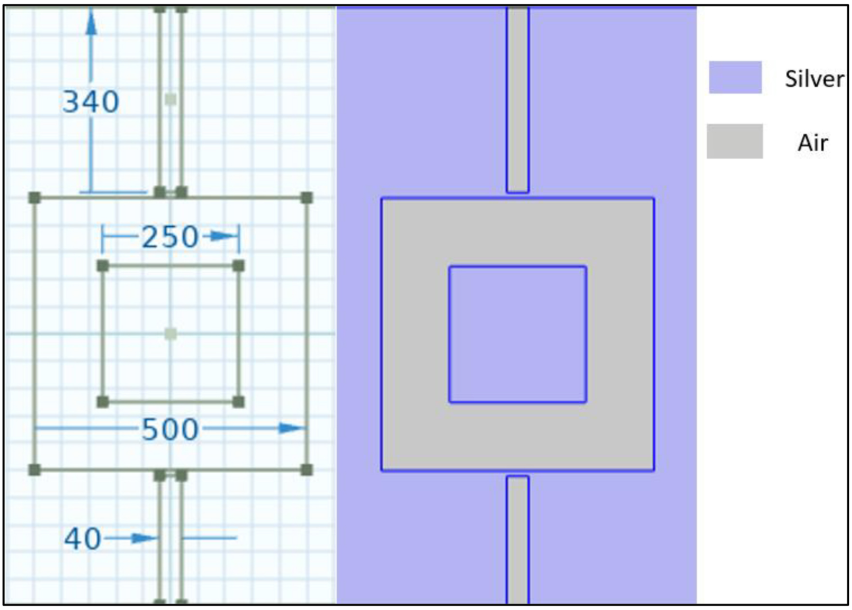

Fig. 1. The suggested filter for the response at 1100 NM.

satellite communications. The investigator obtainable a filter design built from a silver-air cavity array that filters many wavelengths in the 500–2100 nm range, which covers the optical communications spectrum. The consequences displayed that the future design can filter 12 self-governing channels with a transmission effectiveness exceptional 50%, with a high option of regulatory the number of channels by altering the cavity dimensions [13].

In 2021, Cao Dong Truong et al.industrialized a three-wavelength optical filter design constructed on plasmonic micro-inductors (MIMs) for nano-optical communications applications. The investigators used conjugate time theory (CMT) and eigenmode expansion (EME) arithmetical simulations to evaluate the optical performance of the device. The design uses Fabry-Perot cavities and nano-arms to upsurge effectiveness and decrease loss. The results demonstration that the obtainable filter achieves highly well-organized three-channel communication through wavelengths of 1310, 1430, and 1550 nm, through fine entrainment and extensive bandwidth, creation it appropriate for plasmonic demultiplexing applications in optical networks and photonic integrated circuits [14].

The future plasmonic demultiplexer is designed with three different resonators. The original resonator is placed in the midpoint of the structure and is a square ring. The additional resonator is located to the right of the structure and covers eight square holes of different sizes. The third resonator is located to the left of the construction and is a square ring with inner curvatures. It has an inlet and three openings, by means of air as the insulator and silver such as the metal.

2. Structure configuration and mathematical description

The central square-ring-shaped filter structure is designed as shown in Fig. 1. It exhibits the dimensions of two strips: an input port per a width of 40 nanometer and a height of 238.75 nanometer, a square-ring resonator with an outer side length of 490 nanometer and an inner side length of 250 nm, and an output port with a width of 40 nanometer and a height of 340 nanometer, forming a plasmonic MIM configuration. The input and

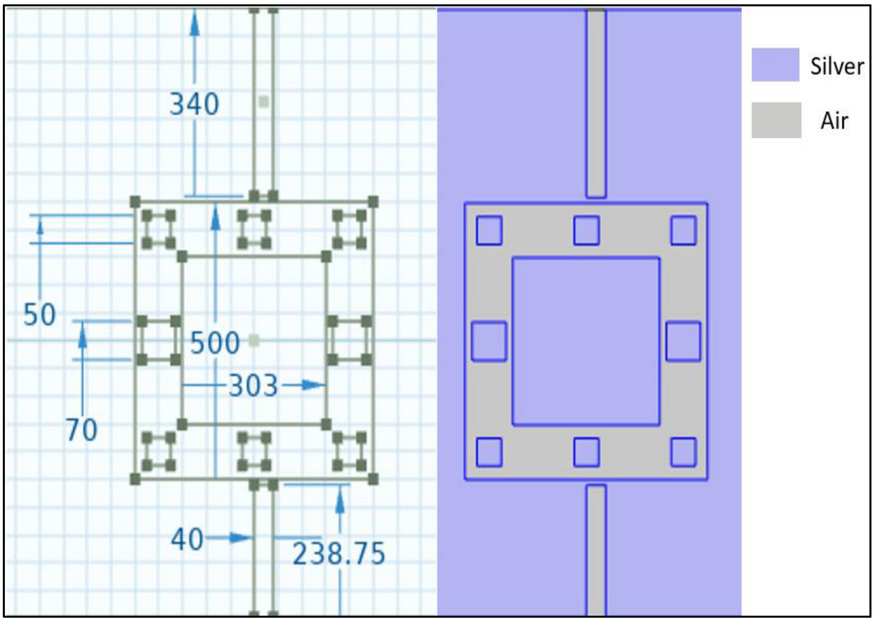

Fig. 2. The suggested filter for the response at 1650 NM.

output ports and the square ring resonator are air-filled, and the rest of the structure is made of silver [15, 16].The two main standard significant for determining and choosing the resonant wavelength of the scheme are the kind of material and the dimensions of the construction. FEM is utilized arithmetically to resolve Maxwell's equations, and the opening border condition of the convolutional perfect matching layer (CPML) is applied. The waves are start in a plane-polarized TM pattern to induce surface waves at the input band port. The next equation gives the effective SPP resonant wavelength of the nanoresonators [17, 18].

The second filter structure is a square ring structure with eight square slits of varying sizes, as shown in Fig. 2. The six slits closest to the input and output ports are square with a side length of 50 nm, while the remaining two slits, located along the horizontal axis, are square with a side length of 70 nm. The towed dimensions are shown in two bands: the input port (40 nm wide and 238.75 nm high), the square ring resonator (490 nm wide and 250 nm high), and the output port (40 nm wide and 340 nm high) to formation a plasmonic MIM configuration. The input and output ports and the square ring resonator are full of through air,and the of the structure,the eight slits are composed of silver.

A third filter structure, a square-ring-shaped structure, is designed, displaying the drag dimensions of two bands: an input port through a width of 40 nanometer and a height of 238.75 nanometer; a square-ring-shaped resonator with an outer side length of 490 nanometer and an inner side length of 443 nanometer, with a zigzag shape; and an output port through a width of 40 nanometer and a height of 340 nanometer, forming a plasmonic MIM configuration. The input and output ports and the square-ring-shaped resonator are full of with air, and the rest of the structure, as shown in Fig. 3, is made of silver.

$$L = m \left(\lambda \text{resonance}/\text{Re}\left(\text{neff}\right)\right) \tag{1}$$

To calculate the dimensions of square ring resonators, this equation is used, in which the resonator is condition becomes where L is the side length, Neff: refractive index, λSPP

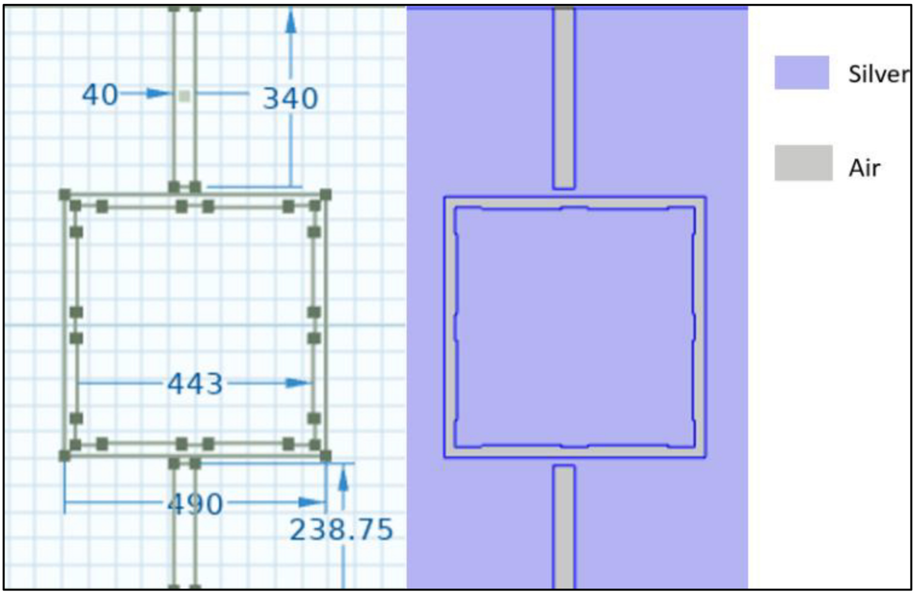

Fig. 3. The suggested filter for the response at 960 NM.

is the resonant wavelength, and m is an integer representing the resonant mode number (wave number parity - e.g., m = 1, 2, 3…). The resulting wavelength, the type of material the nanoresonator is made of, and the dimensions of the structure play a key role in limit the design performance. [19, 20] Based on this, the incidental magnetic wave is suggested as a master equation to represent the system construction mathematically [21].

$$\varepsilon_e \mathrm{X_i} + \varepsilon_i \mathrm{X_e} \times \tanh\left(\frac{\mathrm{Xe}}{2}\, tk\right) = 0 \tag{2}$$

εe and εi represent the permeability of the metal and the insulator, respectively. tk is the thickness of the metal. Xe is the wavelength for the metal. Xi is the wavelength for the insulator [14].

$$\mathrm{Xe} = \left(H^2 + \varepsilon_e\, k^2\right)^{\frac{1}{2}} \tag{3}$$

$$\mathrm{Xi} = \left(H^2 + \varepsilon_i\, k^2\right)^{\frac{1}{2}} \tag{4}$$

H is the propagation constant, and the wave number in free space represents K [22, 23].

The quality factor Q-F is one of the proposed parameters to discuss and simulate the plasmonic nanowave structure by dividing the resonance response by 2, identifying the intersection points and projecting them onto the horizontal axis to calculate the FWHM, as in the equation below [24].

$$\mathrm{Q-Factor} = \lambda\mathrm{resonance} \,/\, \mathrm{FWHM} \tag{5}$$

Optical decoders are primarily and directly based on constructive and destructive interference between input and output ports [25]. When optical decoders operate, they are touched by the port locations and the phase difference amongst shape, and material of the structure) remain unchanged. [26–28]. When Constructive interference occurs when light waves travel in the selfsame direction and are in phase. When there are phase differences,

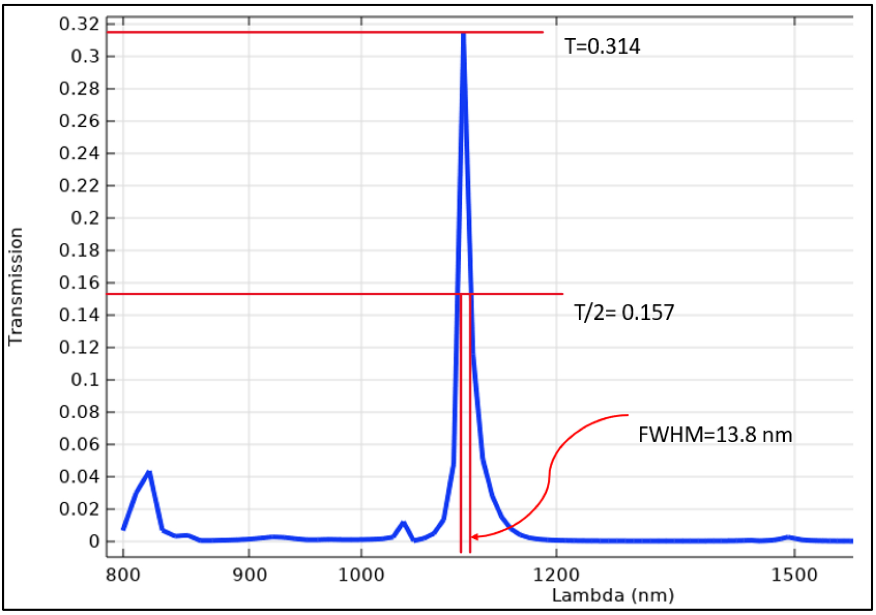

Fig. 4. Optical transmission spectrum of a square ring resonator filter at 1100 NM.

the light waves do not travel in the selfsame direction, and destructive interference occurs. The following equation explains phase mismatch [29, 30].

3. Result and discussion

Figs. 1 to 3 illustrate the basic structure of the optical filter. As mentioned earlier, it is constructed from two layers and contains a square ring resonator. When the SPP wave arrives at the input port in the TM mode, the surface wave travels across the silver-air interface and reaches the nanoresonator. Using the coupling theory, the wave travels to the output port and then reaches the output port throught the response shown in Figs. 4 to 6. A first look at Fig. 4 reveals that the maximum transmission for the suggested filter construction occurred at a response of 0.314 at 1100 nm. To calculate the full-width at half-maximum (FWHM), the response must be divided by a factor of 2. The red line in Fig. 4 then illustrates the process of subtracting the two wavelengths to obtain a full-width at half-maximum(FWHM) of 13.8 nm. The Q factor can be calculated by dividing the resonant wavelength of the 1100 nm response by the peak width of 13.8 nm, yielding a Q factor of 79.7.

As a second step, square-shaped holes were proposed in the periphery of the square ring resonatorThe benefit of this is that by changing the characteristic impedance [24] the response of the proposed optical filter can be shifted to the right side of the graph. The three square holes located near the input and output ports have a side length of 50 nm, and the holes located on either side of the square ring resonator have a side length of 70 nm, as shown in Fig. 5. The highest value for the resonance response is 0.211, at a resonance wavelength of 1650 nm. The full-width at halfe-maximum (FWHM), as shown above, is calculated to be 22 nm. Therefore, the quality factor (Q) is equal to 75.

As a third step, it was proposed to change the length for the internal side of the ring square resonator in a zigzag pattern at the corners and midpoints. The reason for this change is to change the characteristic impedance value. This increased variation in the

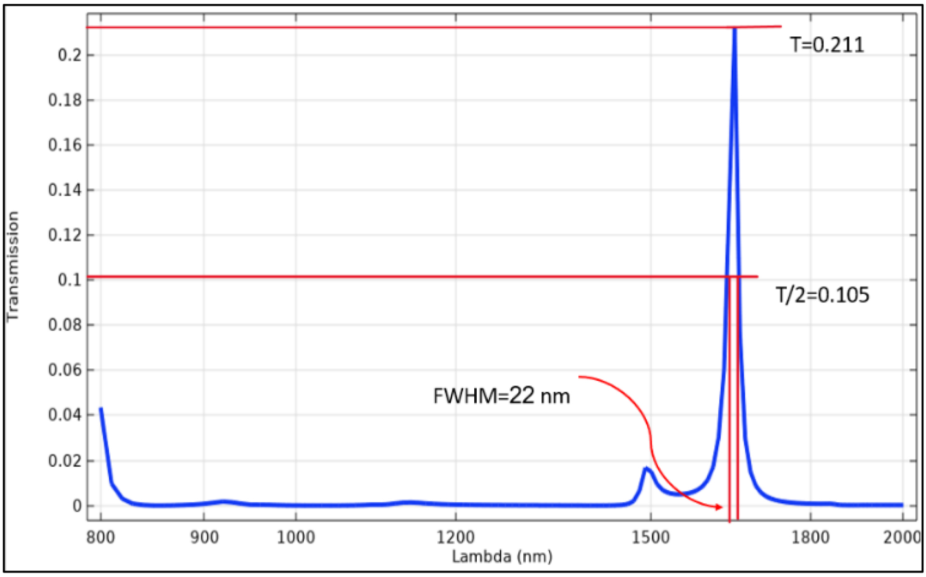

Fig. 5. Optical transmission spectrum of a square ring resonator filter at 1650 NM.

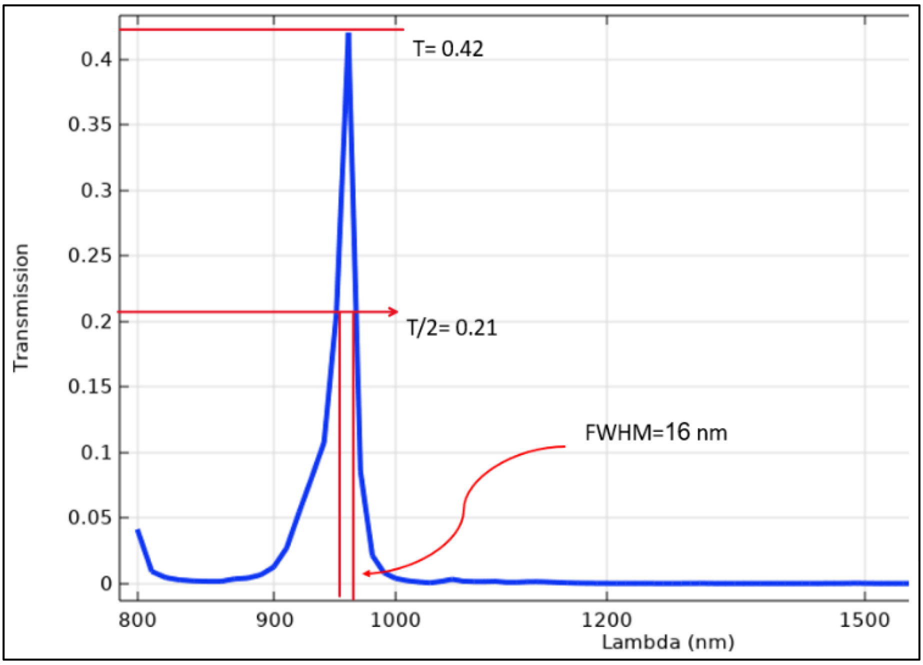

Fig. 6. Optical communication spectrum of a square ring resonator filter 960 NM.

characteristic impedance is attributed to The shift response of the optical filter is proposed on the left side of the graph. The curve is shown in Fig. 6. The maximum value of the resonance curve is 0.42 at the 960 nm resonance response. The maximum peak width (FWHM) value, as shown above, was 16 nm. The quality factor (F - Q) was 60. At this step, the position of the holes in the major resonator was checked.

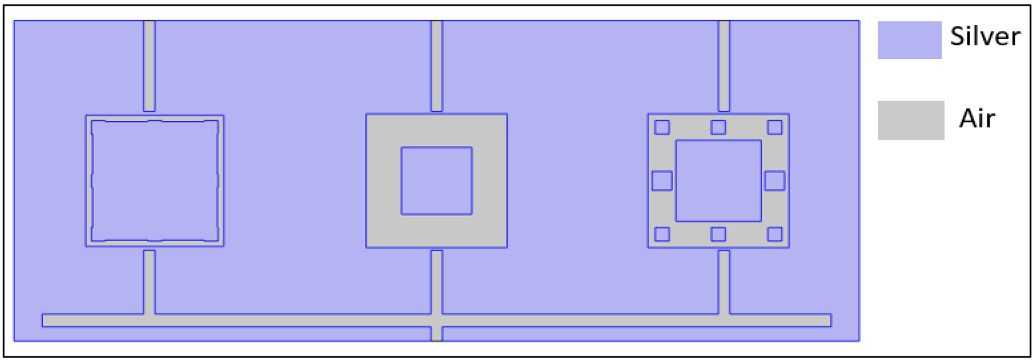

Fig. 7. 1 × 3 Optical demultiplexer.

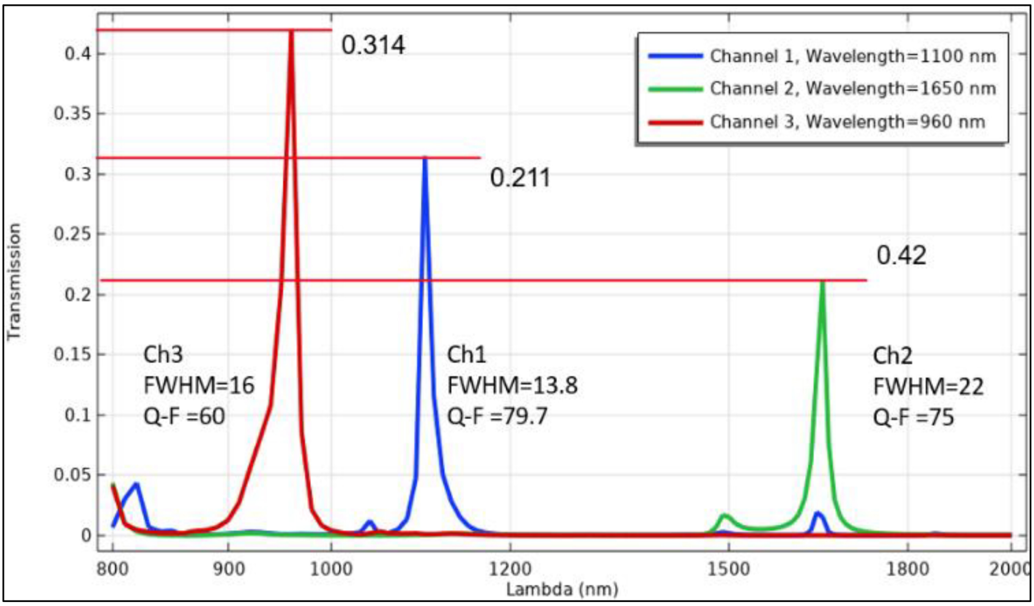

Fig. 8. Optical transmission spectrum of a plasmonic demultiplexer 1 × 3 at 1100 NM, 1650 NM, and 960 NM.

The geometric proposal of a 1 × 3 plasmonic optical demultiplexer by one input to three outputs consists of three square ring resonators. The three resonators differ from each other in terms of the dimensions of the inner resonator perimeter and the presence of small square gaps in the perimeter, as in the filter on the right of the structure. This is The structure is built using a MIM plasmonic structure with silver as the conductor and air as the insulator, as shown in Fig. 7. This aims to obtain three responses at different impedance values, which allows for optimized resonance wavelengths of 1100, 1650, and 960 nm, respectively. The section following A splitter is a waveform input port, which divides the signal of interest in three equivalent segments that pass done each resonator.

After the splittre part, the result was an optical spectrum with three de-multiplexing responses. Fig. 8 shows the three response curves. The highest amount of the resonance curvature for the first response at the resonance wavelength of 1100 nanometer is 0.314. The full width at the peak (FWHM) amount was calculated to be 13.8 nanometer, and The quality factor is 79.7. The maximum amount of the resonance curve is 0.211 in the

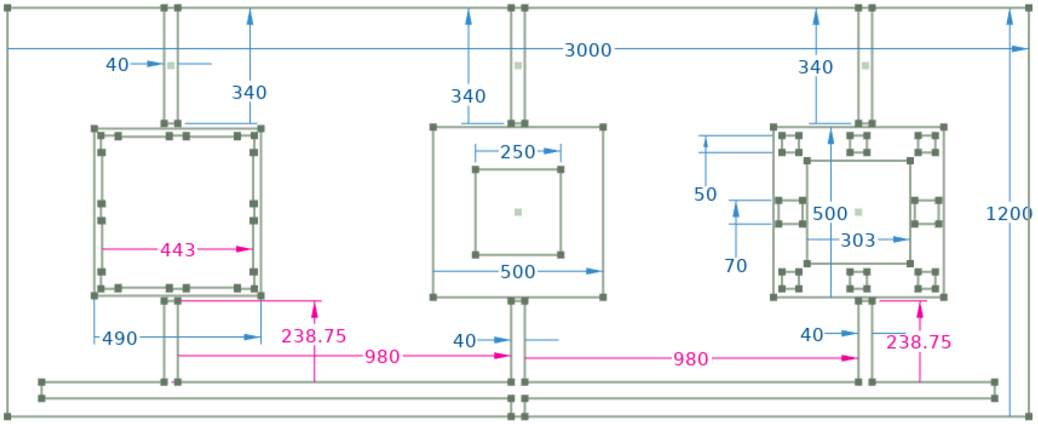

Fig. 9. General system dimensions.

second response at a resonance wavelength of 1650 nanometer. The full width at the peak (FWHM) value was calculated to be 22 nanometer, and the Q factor is 75. Finally, the third response, the full width at peak (FWHM) value was calculated to be 16 nanometer at its highest value for the resonance curve of 0.42 at a resonance wavelength of 960 nanometer. Then the Q factor remains 60. At this point, the position of the three pits is in resonators is checked.

Fig. 9 shows the design with the main structure measuring 1200 nanometer in height and 3000 nm in width, and a substructure It is made up of air as well dielectric and Silver is a metal. Three square ring resonators, as shown in Figs. 2 to 4, are used with an input divider measuring 2800 nanometer in width and 42.7 nanometer in height. The inlets and outlets of the three filters are spaced 980 nm apart, with the filter centers spaced 1000 nm apart, and the filter centers are spaced 10 nm apart. The dimensions and shapes of the three filter resonators vary, as do the presence or absence of notches, and the internal diffuser dimensions of this square ring resonator are changed relative to the filter to Located on the left sideways of the major structure, representinginsulator (air). Meanwhile, silver inhabit the residual part of the nanostructure. This design creates three channels of 40 nanometer wide and 340 nanometer high, separated by 980 nanometer, and three responses are obtained at $\lambda 1 = 1100$, $\lambda 2 = 1650$, and $\lambda 3 = 960$ as shown in Fig. 8.

In 2024, researchers Alireza Ekrami Kivaj et al. presented a new design for a three-channel plasmonic optical demultiplexer founded on(MIM) waveguides.The design is based on nanocavities composed of interconnected metallic discs and rings capable of transmitting specific wavelengths in the telecommunications and visible wavelength ranges. Numerical results using the FDTD method in Lumerical software showed that the full bandwidth at half-intense (FWHM) is approximately 18 nm, and the transmission spectra can be simply tuned by varying the geometric dimensions or the refractive index. It was also observed that increasing the refractive index leads to a move of the spectrum to lengthier wavelengths with a decrease in amplitude due to internal losses. The channels feature two sharp resonant modes caused by the propeller resonance phenomenon, with a low quality factor, ranging from 60 to 67, and a minimum FWHM of 18 nm [31].

In 2021, Morteza Mansouri et al.suggested a tunable plasmonic demultiplexer structure founded on surface plasmon nanoresonators. A modulated-interface (MIM) waveguide structure was technologically advanced using metals such as gold and silver to attain high performance in the optical communications range. The device has a 1 × 3 configuration

Table 1. Comparison of the results for the suggested design with the results of previous articles.

Criteria	This Work	[31]	[32]	[33]	[34]	[35]
Method	FEM	FDTD	FDTD	FDTD	FDTD	FDTD
Structure	MIM-3 ring square resonators	based on nanodisk/ nanoring resonators (MIM)	MIM circular Resonator	MIM groove-shaped guides	MIM waeguide and nanodisk resonators	MIM multi-teeth-shaped
Dimension	3000 × 1200 nm^2	2000 × 2000 nm^2	2500 × 1000 nm^2	4200 × 2000 nm^2	5000 × 2500 nm^2	2000 × 1000 nm^2
Outputs	3	3	3	3	3	3
λ	960 nm, 1100 nm, 1650 nm	1213 nm, 1142 nm, 1080 nm	1456 nm, 1219 nm, 1133 nm	650 nm, 850 nm, 1060 nm	1517 nm, 1320 nm, 1187 nm.	1550 nm, 1500 nm, 1600 nm
Dielectric	Air	Air	Air	Silica	Air	Air
Metal	Ag	Ag	Au	Ag	Ag	Ag
Gauge	FWHM, Q-Factor	FWHM, Q-Factor	FWHM, Q-Factor	FWHM, Q-Factor	FWHM, Q-Factor	FWHM, Q-Factor
Q-Factor	79.7, 75 and 60	_ _ _ _	58, 45 and 37.7	38, 44.7 and 53	60, 40 and 45	50, 51.7 and 53
FWHM	13.8 nm min	18 nm min	25 nm, 27 nm, 30 nm	17 nm, 19 nm, 20 nm	25 nm, 33 nm 29.5 nm	31 nm, 29 nm, 30 nm

and a demultiplexer, Consecutive. Arithmetical results using FDTD established that the transmission features can be controlled through the ring radius and refractive index. The design is compressed and compact, but its quality factor is comparatively low and does not encounter the supplies for efficient multiplexing [32].

In 2024, Seyed Morteza Abadi et al. suggested the design and simulation of a 1 × 3 plasmonic optical multiplexer founded on waveguides (MIM). Circular cavities linked to the main waveguide were used to obtain three production channels with different wavelengths. Simulation results using the FDTD method established high parting efficiency with a tall quality factor, allowing the output wavelengths to be attuned by changing the cavity radius or refractive index. The design goals to attain high performance in integrated optical communication systems and nanosensors, owing to its small size and high spectral resolve, with an very small quality factor [33].

In 2021, Arman Amiri-Faghani et al.designed a innovative wavelength demultiplexer founded on a(MIM) waveguide with nano-resonators decided in a pair of three-channel disc-shaped glass. The design attains three-wavelength parting with a high transmission efficiency of up to 82% and low interference of less than –23 dB. Two-dimensional FDTD simulations were used to study the transmission appearances and the effect of geometric variables and refractive index on presentation. The results presented that the resulting wavelengths can be adjusted by adapting the disc radius and spacing, and with a higher FWHM, this principals to a decrease in the quality factor of the three responses [34].

In 2021, O. Abbaszadeh-Azar et al. The investigators proposed a design for a demultiplexer founded on a (MIM) plasmonic waveguide in the form of multiple teeth, using (FDTD) numerical simulation technique. They established that variable geometric dimensions, such as the deepness or width of the multiple teeth, leads to additional exact control of the transmitted wavelengths [35].

Three- and four-channel designs were proposed, and the results showed that each channel has a distinct wavelength that can be easily controlled. This design is simple and small in size, but its efficiency is not high, as the quality factor is low by approximately 50, which is not good.

Based on the comparison between this paper and previous works, it can be noted that all studies focused on improving the performance of plasmonic filters and demultiplexers based on metal-insulator-metal (MIM) guides, but the distinction in this research lies in achieving a high Q-factor with a small FWHM thanks to the design based on three square resonators. While Ekrami (2024) used coupled disc and ring resonators to improve spectral selectivity, Truong (2021) adopted Fabry–Perot cavities to improve efficiency, and Medina (2022) focused on multichannel capability over a wide bandwidth (500–2100 nm), this paper achieves outstanding performance within a compact, small-scale design (3000 × 1200 nm^2) at wavelengths of 960, 1100, and 1650 nm.

The main advantage of this paper over previous studies is its higher quality factor (79.7, 75, 60) compared to previous works, which typically did not exceed 60, in addition to the use of the finite element method (FEM) instead of the traditional FDTD, which provides higher accuracy in electromagnetic field calculations. This makes it a viable development towards the fabrication of high-performance, miniaturized plasmonic demultiplexers that can be integrated into modern optical integrated circuits.

4. Conclusions

Optical demultiplexers are one of the greatest common mechanisms in optoelectronics. The 1 × 3 plasmonic demultiplexer is planned founded on MIM plasmonic waveguides. The transmittance at the output executor can be controlled based on the phase of the light incident on the input port and the control port, thanks to the evenly arranged ports.The structure consists of two regions, with the gray region representing air and the blue region representing silver, a material known for its strong plasmonic properties. It contains three square-ring resonators. The input signal is split into three channels through square-ring structures. These structures performance as wavelength-selective filters.This change in shape and location results in the chosenof exact wavelengths for each channel. When the signal is insertion into the input port, it is distributed founded on its wavelength, with each exact wavelength absorbed toward a exact channel (CH1, CH2, CH3). Three responses were got (1100 nm, 1650 nm, and 960 nm). The best response was at 1100 nm, with a quality factor of 79.7. This is a good response associated to preceding work in terms of size, ease of design, type of material used, and quality factor. This be contingent on the plasmonic resonance designs in the square-ring structures, which differ depending on their design.

Despite its talented performance, the suggested design still has numerous limitations. First, the construction relies on silver, which suffers from intrinsic optical losses that can decrease efficiency in practical implementations. Second, just TM-polarized SPP modes were analyzed, whereas real-world devices may necessitate polarization-insensitive or dual-polarization processes. Finally, fabrication of very narrow features (40 nm ports and 50–70 nm slits) stances technological challenges that may present deviations from the ideal numerical results.In the Future, work can address these limits through several guidelines.

Material optimization, through replacing silver with low-loss plasmonic materials could reduce absorption losses and enhance transmission efficiency(e.g., aluminum-doped zinc oxide, titanium nitride, or graphene-based plasmonics).

Expanding channel count: The offered design can be configured by modifying the resonator geometry or introducing cascaded multi-resonator structures extended to 1 × 4 or 1 × N.

In conclusion, the suggested plasmonic 1 × 3 demultiplexer provides in height spectral resolution, a dense footprint, and robust potential for integration into next generation on chip optical communication systems, with numerous occasions for further improvement and optimization.

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The final research article has been approved by all authors.

Disclosures

The authors state no rival interests.

Data availability

The corresponding author will provide datasets and curves produced during the present investigate upon request.

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