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A tunable plasmonic graphene-based optical gate for advanced photonic applications

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Abstract:

This paper presents the design and analysis of a plasmonic graphene-based optical gate with a tunable wavelength selection mechanism, targeting applications in advanced photonic integrated circuits. Graphene, known for its exceptional electrical, thermal, and optical properties, is utilized to develop a compact and efficient optical structure. The proposed mechanism employs thin-layer graphene, dielectric substrates, and an air cavity to achieve tunable resonance at specific wavelengths. Finite-difference time-domain (FDTD) simulations reveal two primary resonance wavelengths at 11000 nm and 7300 nm, demonstrating high transmission efficiency and quality factors of 365 and 400, respectively. The tunability of the mechanism is explored by varying the chemical potential of graphene and the refractive index of the dielectric medium, allowing precise control over the resonance wavelengths. Building on this mechanism, we design a plasmonic graphene-based AND logic gate, which is analyzed for different input states to validate its logical operation. This study underscores the potential of plasmonic graphene-based devices for high-performance, miniaturized photonic systems, with implications for next-generation optical computing and communication technologies.

Keywords: Optical gate; AND; Graphene; Non-linear; Cavity; Quality factor

1. Introduction

In the rapidly evolving field of photonics, the quest for materials and devices that can manipulate light at the nanoscale has led to significant advancements in both fundamental science and practical applications. Among the myriad of materials being explored, graphene has garnered significant attention due to its exceptional properties and potential applications. Graphene is a remarkable two-dimensional material, composed of a single layer of carbon atoms arranged in a honeycomb lattice [1–3]. Renowned for being the thinnest material, graphene exhibits extraordinary flexibility, strength-approximately 200 times stronger than steel-and superior electrical conductivity at room temperature [4], making it a transformative candidate for next-generation electronic and optical devices. These unique characteristics position graphene as a critical player in advancing technologies such as ballistic transistors, integrated circuit components, transparent conductive electrodes, sensors [5], and logic gates.

Plasmonics involves the interaction between electromagnetic waves and free electrons in metals, leading to the excitation of surface plasmon polaritons (SPPs). These SPPs can confine light to sub-wavelength dimensions, allowing for enhanced light-matter interactions critical for applications such as sensing, imaging, and information processing. Traditional plasmonic materials, such as gold and silver, have limitations, including high losses at optical frequencies and a lack of tunability. In contrast, graphene offers a unique solution to these challenges. Its conductivity can be dynamically tuned through electrostatic gating or chemical doping, providing an unprecedented level of control over plasmonic behavior [6].

In recent years, the exploration of SPPs and localized surface plasmon resonances (LSPRs) has accelerated, displaying their utility in both electronic and optical circuits [6, 7]. The simultaneous propagation of electromagnetic waves in these domains, without interference, significantly enhances data transfer capabilities in integrated circuits. Furthermore, plasmonic integrated circuits demonstrate a marked reduction in size compared to traditional optical counterparts, effectively minimizing the diffraction limit and improving transmission and switching speeds. By integrating graphene with dielectric materials and other plasmonic components, it becomes feasible to design plasmonic graphene-based optical waveguides that can be coupled with resonant cavities, enabling innovative optical wavelength selection mechanisms [8].

Optical gates are fundamental components in photonic circuits, analogous to electronic logic gates in traditional computing. They enable the control of light signals, facilitating operations such as switching, modulation, and routing of optical information. The advent of integrated photonics has necessitated the development of compact, efficient, and tunable optical gates that can be seamlessly integrated into photonic circuits.

Tunable plasmonic graphene-based optical gates represent a significant advancement in this area. By leveraging the unique properties of graphene, these devices can achieve high-speed modulation of light, low power consumption, and compact form factors. The integration of graphene with plasmonic structures allows for enhanced light confinement and increased interaction lengths, leading to improved performance metrics compared to conventional optical gates.

The innovative application of graphene, combined with nonlinear refractive index materials, presents a groundbreaking approach to the design of optical logic gates. Graphene's exceptional electrical and thermal conductivity enhances the performance of these gates, allowing for faster processing speeds and greater efficiency. By leveraging the nonlinear optical properties of specific materials, such as silicon carbide or certain organic compounds, researchers can achieve significant improvements in signal modulation and integration density. This synergy not only paves the way for advanced photonic circuits but also holds the potential to revolutionize data processing in various technological domains [9].

The rest of the paper is organized as follows. Related works and background topics are reviewed in section 2. The proposed approach and experimental results are introduced in section 3 and section 4, respectively. The paper concludes with section 5.

2. Background and related works

Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, was first isolated in 2004, and since then, it has garnered immense interest across various fields of research. Its remarkable properties, such as high thermal and electrical conductivity, mechanical strength, and optical transparency, have led to numerous applications in electronics, materials science, and photonics. In the context of plasmonics, graphene stands out due to its ability to support surface plasmons-coherent oscillations of electrons at the surface of a conductor that can be excited at the interface between graphene and dielectric materials [1].

The tunability of graphene's optical properties arises from its unique band structure, which allows for the control of its conductivity through external stimuli. By applying a gate voltage, the Fermi level of graphene can be shifted, thereby modulating its carrier density. This tunability enables the manipulation of the plasmonic resonance frequency, allowing devices to operate across a wide range of wavelengths from the terahertz to the visible spectrum. The ability to dynamically tune the plasmonic response of graphene makes it an attractive candidate for applications requiring real-time modulation of optical signals [2].

The integration of graphene into optical and electronic applications has been the focus of extensive research in recent years, highlighting its unique properties and the potential for innovative device architectures. Several studies have explored the use of graphene-based structures to enhance optical functionalities, particularly through the manipulation of SPPs.

One pivotal study by Dr. Chu [10] demonstrates the design and performance of electrooptical graphene plasmonic logic gates, which leverage the tunability of graphene's plasmonic modes. This research shows that by applying an external gate voltage, it is possible to control the propagation of light within the device, enabling high-speed logic operations. The proposed gates exhibit compact dimensions and improved performance metrics compared to traditional optical logic gates, thus paving the way for their implementation in nano-scale photonic integrated circuits [10].

In addition, Dr. Granpayeh's work [11] has introduced the concept of using graphene-based resonators as band-pass filters operating in the mid-infrared spectrum. The tunability of these filters is achieved by adjusting the chemical potential of graphene, allowing for dynamic control over the resonance wavelength. This feature is crucial for developing wavelength selection mechanisms that can be finely tuned to meet specific application requirements [11].

Other notable contributions to the field include the design of various fundamental logic gates based on plasmonic graphene structures, such as XOR, XNOR, NAND, and NOT gates. These designs not only emphasize the linearity and compact size of the gates but also focus on reducing loss, which is critical for maintaining signal integrity in integrated optical circuits. The compactness of these gates, often less than $\lambda/28$ in size at operational wavelengths, showcases the significant miniaturization potential of plasmonic devices [11].

Recent advancements in numerical simulation techniques, particularly the finite-difference time-domain (FDTD) method, have further enhanced the understanding of the optical behavior of graphene-based structures. This method allows for the detailed analysis of light propagation and resonance phenomena within these devices, providing insights into their performance characteristics and paving the way for optimization in future designs.

Furthermore, various researchers have investigated the effects of dielectric materials and refractive index variations on the optical performance of graphene-based structures [1–3]. Studies indicate that the choice of dielectric medium significantly impacts the resonance wavelengths and overall device functionality. As a result, the exploration of different materials for the air region or cavity layers within these structures remains an active area of research, aiming to improve tunability and operational efficiency [7].

Overall, the body of work surrounding plasmonic graphene devices underscores the material's potential to revolutionize optical and electronic systems. This paper builds upon these foundational studies by presenting a novel wavelength selection mechanism and extending the design to include a plasmonic graphene-based optical AND logic gate, further contributing to the advancement of integrated photonic technologies.

3. Proposed approach

In this section, we outline our proposed approach for designing a plasmonic graphene-based optical gate with a wavelength selection mechanism. Our approach comprises two primary components: the development of a tunable wavelength selection mechanism and the design of an optical AND logic gate. Each component is detailed in the following subsections.

3.1 Wavelength selection mechanism

The first part of our approach is the design of a tunable wavelength selection mechanism based on graphene, which utilizes its ability to support SPPs and LSPRs. The mechanism aims to selectively pass specific wavelengths of light through the structure, making it an essential component for a variety of photonic applications, including optical communication and sensing.

3.2 A) Structural design

The wavelength selection mechanism is designed with a two-layer graphene structure separated by an air cavity, as shown in Fig. 1. The resonant or wavelength selection mechanism is positioned between two graphene waveguides with a gap of 10 nm. The key components of the design include:
Graphene Layers: Two thin layers of graphene, separated by 10 nm, serve as the core of the structure. Graphene's high electrical conductivity and its ability to support plasmonic modes at mid-infrared wavelengths enable the design of an efficient wavelength selector.

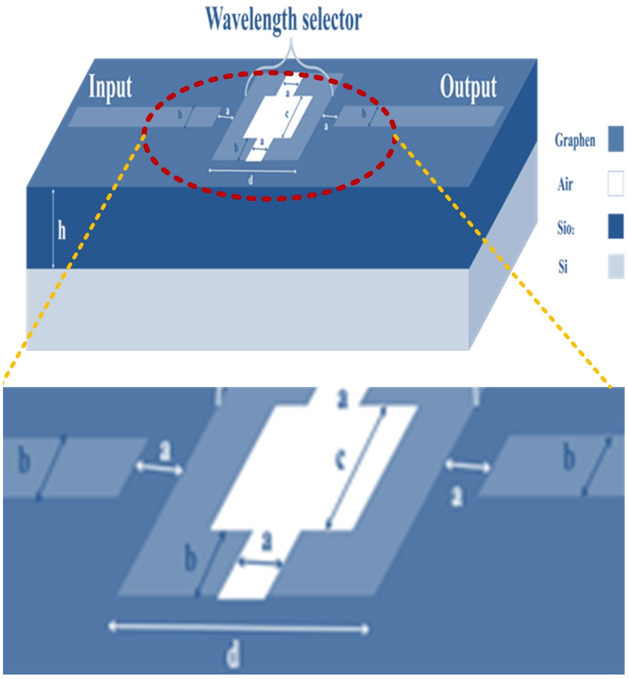

Figure 1. Wavelength selector structure.

Air Cavity: An air layer (white region in Fig. 1), positioned between the graphene sheets, functions as a resonant cavity where light is trapped. The dimensions of the cavity are optimized for resonance at specific wavelengths, typically in the range of 7000 to 14000 nm. The dimensions of the cavity surfaces are defined by the parameters in Fig. 1, with a = 10 nm, b = 12 nm, and c = 40 nm. This cavity configuration ensures that light entering the structure resonates at predetermined wavelengths, which are then transmitted through the graphene layer.
Substrate and Bulk Materials: The structure is placed on a silicon (Si) body, with a silicon dioxide (SiO_2) layer serving as the substrate. The thickness of the SiO_2 layer is set to h = 50 nm. This combination of materials ensures proper wave guiding properties and effective coupling between the input, cavity, and output ports.

3.3 B) Tunability of the wavelength selection mechanism

A key feature of the proposed wavelength selection mechanism is its tunability. The resonance wavelength can be adjusted by altering the chemical potential of the graphene layers, which is achieved by applying an external gate voltage. This voltage modulates the plasmonic properties of graphene, shifting the resonance frequency to higher or lower wavelengths.
The tunability of the structure is explored by varying the chemical potential of graphene and observing the changes in the transmission spectrum. As the chemical potential increases or decreases, the resonance wavelengths shift, offering dynamic control over the wavelength selection. This feature is critical for developing tunable filters and multiplexing devices.

3.4 C) Optical behavior and performance

The optical behavior of the proposed wavelength selection mechanism is analyzed using the finite-difference time-domain (FDTD) method. This method allows for a detailed simulation of the structure's interaction with light, providing insights into the resonance behavior, transmission spectrum, and electric field distribution.
Resonance Wavelengths: The simulations reveal two key resonance wavelengths at 11000 nm and 7300 nm, with normalized transmission amplitudes of 88% and 79%, respectively. These resonant modes are distinct and can be utilized for wavelength selection, depending on the specific application needs.
Electric Field Distribution: Further analysis of the electric field distribution within the structure shows that light at these resonant wavelengths propagates effectively through the graphene layers, confirming the functionality of the design.
The tunable nature of the structure allows for additional flexibility, as the resonance wavelength can be shifted by adjusting the dielectric properties of the materials in the cavity region, further enhancing the control over the selection process.
Fig. 2 depicts the refractive index distribution of the proposed structure from a top view. According to this figure, the refractive index of the substrate is approximately 1.5, while the graphene sheets have a refractive index of 0.0084,

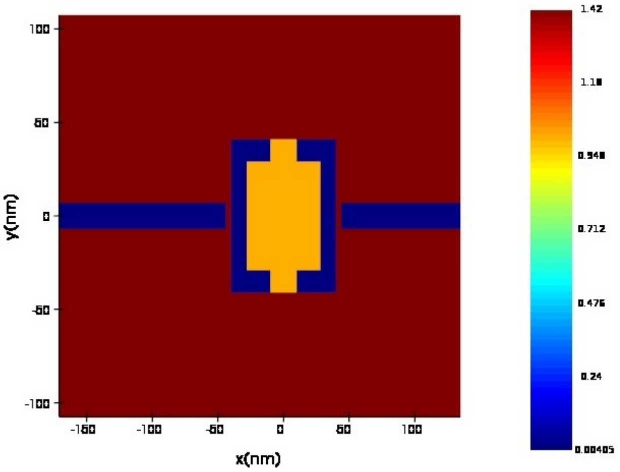

Figure 2. The refractive index distribution of the pro-posed structure (top view).

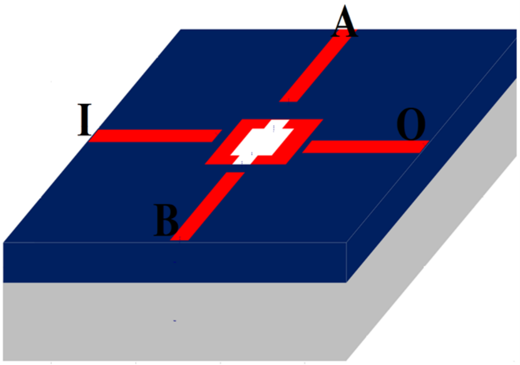

Figure 3. The proposed AND structure.

and the air layer's refractive index is about 1. The boundary conditions are such that both the input (where light enters) and the output (where light exits) are covered with dielectric layers or perfectly matched layers (PMLs). The top and bottom of the structure, through which light does not travel, are considered metallic. It is noteworthy that these boundary conditions are specific to graphene and are commonly used in optical performance studies of graphene-based structures, particularly in designing optical devices.

3.5 Design of the plasmonic graphene-based and gate

In addition to the wavelength selection mechanism, our approach extends to the design of a plasmonic graphene-based AND logic gate. This gate performs logical operations on optical signals and is built using the same plasmonic graphene structure with slight modifications. The AND gate uses the wavelength selection mechanism as a foundation and introduces logic inputs and a bias input to create a functional optical gate.

By convention, an input or output is considered "on" when light is present, and "off" when light is absent. The presence and absence of light in a port correspond to logical values of 1 and 0, respectively. In other words, when a port is on, it is in a logical high state (1), and when off, it is in a logical low state (0). It is important to note that the material composition and height of the designed structure are consistent with the wavelength selection mechanism.

3.6 A) AND gate structure

The AND gate structure is composed of three primary inputs: two logical inputs A and B and a bias input I, as shown in Fig. 3. The bias input ensures that the gate remains in a continuously active state, analogous to a DC bias in digital circuits. The two primary inputs A and B are responsible for the logic operation, with the gate output determined by the interaction of light from these inputs.

Primary Inputs: Inputs A and B are the main sources of light that will be used to trigger the AND logic operation. When either input is "off" (no light), no change occurs in the output.

Bias Input: The bias input is continuously active, ensuring that the system remains in an operational state. Its role is to facilitate the transmission of light from the input ports when both primary inputs are active.

Output: The output (O) is determined by the logical operation between inputs A and B. The output is "on" (logical 1) only when both inputs are "on", in accordance with the logical definition of the AND gate.

3.7 B) Operational states and logic analysis

The optical AND gate operates in four possible states, based on the logical values of inputs A and B:

State 00: Both inputs A and B are in a logical 0 state (no light). As a result, no light is transmitted to the output, and the output remains in a logical 0 state.

State 10: Input A is active (logical 1), while input B is inactive (logical 0). Due to the insufficient light intensity from a single active input, no change occurs in the output, which remains in a logical 0 state.

State 01: Input B is active (logical 1), while input A is inactive (logical 0). Similar to the previous state, the output remains at logical 0 due to insufficient intensity from input B.

State 11: Both inputs A and B are active (logical 1), providing enough light intensity to induce a nonlinear refractive index change in the cavity region. This enables light from the bias input to propagate and reach the output port, resulting in a logical 1 output.

4. Experimental results and discussion

This section presents the experimental results and simulations conducted to validate the design of the plasmonic graphene-based optical gate with the wavelength selection mechanism. To evaluate the performance of the proposed structure, a series of simulations were performed using the finite-difference time-domain (FDTD) method. The simulations focus on two key aspects: the wavelength selection mechanism and the functionality of the plasmonic graphene-based AND gate. The parameters and associated values for conducting tests of the proposed structure are depicted in Table 1.

4.1 Wavelength selection mechanism: simulation results

The first set of experiments aimed at validating the wavelength selection mechanism involved simulating the transmission properties of the structure for different resonance

Table 1. The parameters and associated values for testing the proposed structure.

Value	Title
11000 nm	Simulation wavelength
270 nm	Bandwidth
1.4	Nonlinear refractive index of cavity
0.35	Chemical potential of graphene
40	Quality factor
85	Transmission range
All four gate states	Examined states

wavelengths. The structure was modeled using the parameters described in the structural design of section 3.1, including the two graphene layers, the air cavity, and the silicon substrate.

4.2 A) Transmission spectrum

The transmission spectrum of the wavelength selection mechanism was simulated for a variety of resonance wavelengths. The results, shown in Fig. 4, reveal two prominent resonance peaks at 11000 nm and 7300 nm, with corresponding transmission amplitudes of 88% and 79%, respectively. These peaks correspond to the resonance wavelengths at which light is efficiently transmitted through the graphene layers.

Resonance at 11000 nm: The resonance at 11000 nm has a transmission amplitude of 88%, with a bandwidth of 400 nm. This mode exhibits high transmission efficiency, making it suitable for applications that require higher light intensity.

Resonance at 7300 nm: The resonance at 7300 nm has a transmission amplitude of 79% and a narrower bandwidth of 200 nm. Although the transmission amplitude is lower than that of the 11000 nm resonance, the quality factor of this mode is higher, making it ideal for applications where a sharper wavelength selection is needed.

4.3 B) Electric field distribution

To further investigate the behavior of the resonant modes, the electric field distribution within the structure was analyzed for the two resonance wavelengths. Fig. 5 and Fig. 6 illustrate the propagation of optical waves within the structure for light at 11000 nm and 7300 nm, respectively. In both cases, the electric field is confined within the cavity and propagates efficiently towards the output port, confirming the effectiveness of the wavelength selection mechanism.

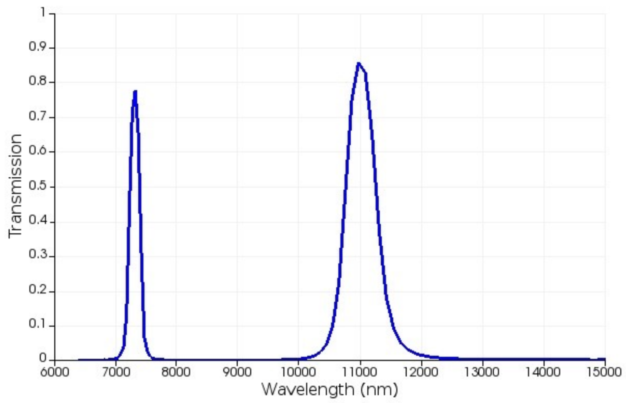

Figure 4. The transmission spectrum of the wavelength selection mechanism.

4.4 C) Tunability of the wavelength selection mechanism

One of the critical features or advantages of any wavelength selection mechanism is its tunability, allowing the resonance wave-length to be adjusted by modifying certain characteristics of the mechanism as needed. In this paper, we aimed to design a wavelength selection mechanism with inherent tunability. As previously mentioned, graphene possesses a chemical potential that can be modulated by applying a voltage. By altering this chemical potential, the resonance

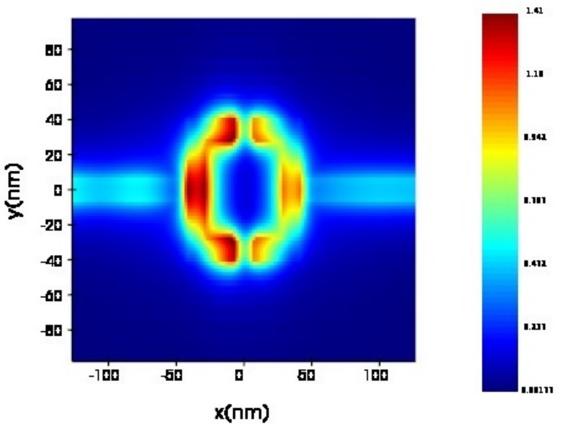

Figure 5. Optical propagation at 11000 nm.

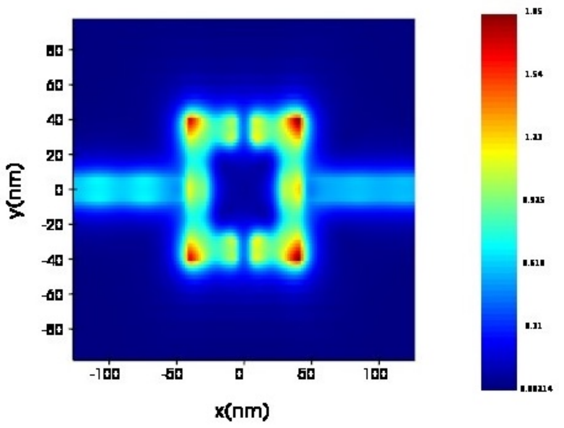

Figure 6. Optical propagation at 7300 nm.

wavelength of graphene can be shifted accordingly. The output spectra of the proposed wavelength selection mechanism for different chemical potential values are shown in Fig. 7. The figure demonstrates that as the chemical potential increases or decreases, the resonance modes at 11000 nm shift to higher or lower wavelengths, respectively. Notably, the transmission amplitude remains constant across various chemical potential values. Detailed specifications of the resonance modes for different chemical potentials are provided in Table 2.

Another crucial parameter influencing the tunability of the structure is its dependence on the material or refractive index of the dielectric medium used within the structure. This dielectric material corresponds to the air region depicted in Fig. 1. The output spectra of the proposed wavelength selection mechanism for various refractive index values of this region, with a chemical potential of 0.45 eV, are presented in Fig. 8. This Figure shows that increasing the refractive index of this region shifts the resonance wavelength toward higher values. The transmission amplitude remains unchanged across different refractive indices. Comprehensive details of the resonance wavelengths for various substrate refractive indices are listed in Table 3.

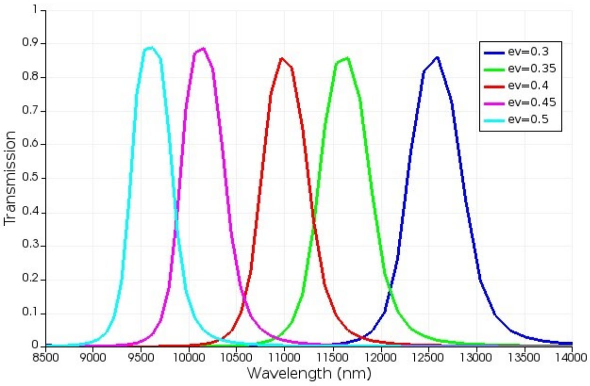

Figure 7. Resonance mode dependency on chemical potential.

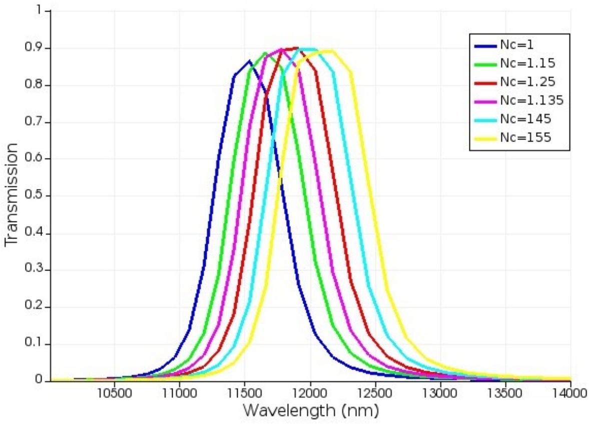

Figure 8. Resonance mode dependency on the refractive index of the dielectric.

It should be noted that the impact of these parameter changes on the resonance wavelength has been examined within the range of 10000 nm to 14000 nm. Due to a reduction in amplitude within the range of 7000 nm to 8000 nm, this range has been excluded from the analysis. Additionally, when examining the optical behavior of dielectric materials, the material's nature is determined solely by its refractive index. In other words, the refractive index defines the material's identity.

4.5 Plasmonic graphene-based and gate: simulation results

The second set of experiments focused on the design and validation of the plasmonic graphene-based AND gate. The structure was modified to include three inputs (two logic inputs and a bias input) and one output, as described in the design section. The simulation analyzed the output behavior under various input combinations to determine the gate's logical functionality.

Table 2. The effect of chemical potential on resonance mode.

eV (V)	λ (nm)	Transmission efficiency (%)	BW (nm)	$Q = \lambda/BW$
0.3	12100	88	300	40
0.35	11600	88	310	37
0.4	11000	88	300	36
0.45	10100	89	300	33
0.5	9600	89	310	31

Table 3. The effect of the refractive index of the dielectric on resonance mode.

Nc	λ (nm)	Transmission efficiency (%)	BW (nm)	$Q = \lambda/BW$
1	11550	88	500	23
1.15	11650	89	500	23.3
1.25	11750	90	500	23.5
1.35	11850	90	520	22
1.45	12000	99	540	22
1.55	12150	90	550	22

4.6 A) State analysis and output behavior

The AND gate was analyzed under the four possible input combinations for A and B (i.e., 00, 10, 01, and 11). The results for each state were as follows:

State 00: When both inputs A and B are in the logical low state (no light), no light reaches the output, Fig. 9. The output remains in a logical low state (0), confirming the correct behavior for this input condition.

State 10 and 01: In both these states, only one of the inputs is active. The input light is insufficient to induce a change in the nonlinear refractive index of the air cavity. As a result, no light reaches the output, and the output remains in a logical low state (0), Fig. 10 and Fig. 11.

State 11: When both inputs A and B are active, the combined light intensity is sufficient to induce a change in the refractive index of the cavity region. This allows light from the bias input to propagate through the structure, reaching the output and setting it to a logical high state (1).

The output behavior for each state matches the expected logical behavior of an AND gate, as shown in the Fig. 9 to Fig. 12.

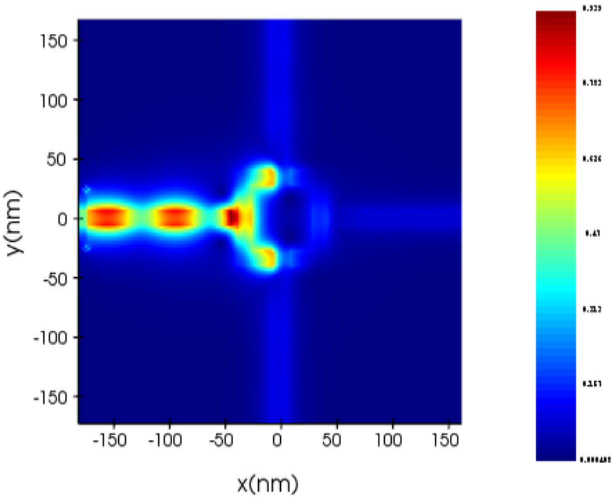

Figure 9. State 00.

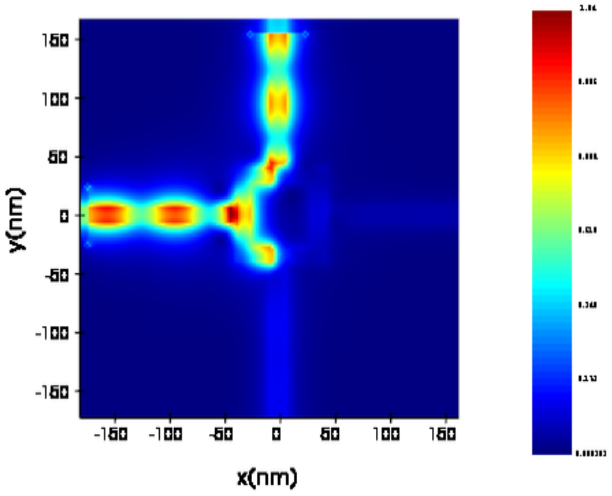

Figure 10. State 01.

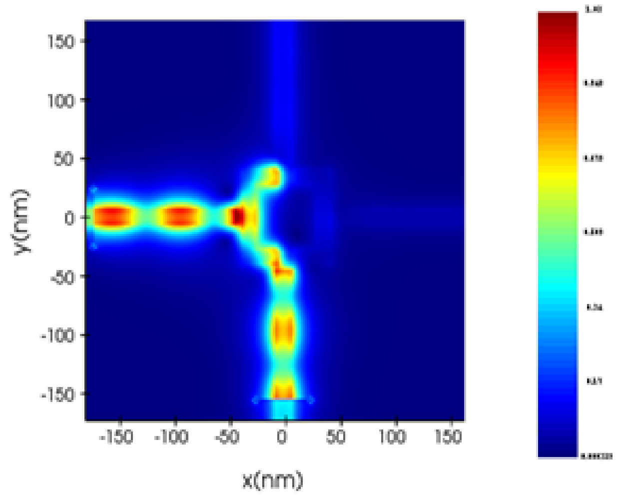

Figure 11. State 10.

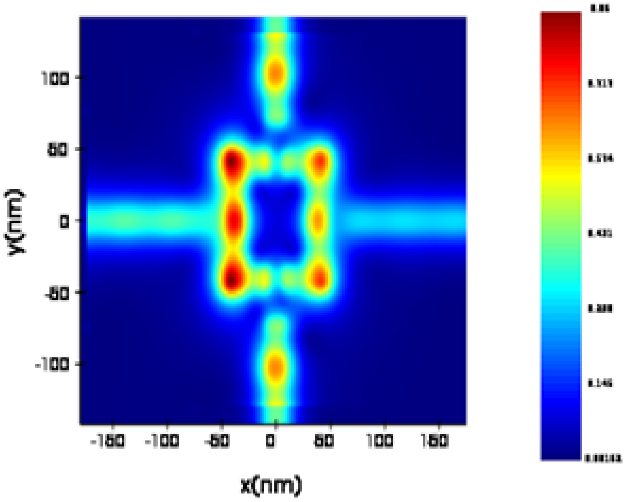

Figure 12. State 11.

4.7 B) Performance evaluation

The performance of the AND gate was quantitatively assessed using the output states for each input combination. The results are summarized in Table 4, where it is evident that the structure correctly implements the AND logic function. The logical states of the output for each combination of input states (00, 10, 01, and 11) align with the expected behavior of an optical AND gate, Table 4.

Table 4. The performance of the AND gate according to simulations.

A	B	O
0	0	0
0	1	0
1	0	0
1	1	1

4.8 Comparison with the state-of-the-art works

The proposed structure and approach are compared with the state-of-the-art works. Results are shown in Table 5.

Table 5. Comparison with the existing works.

Approach	Year	Quality factor (Q)	Structure size (μm)	Bandwidth (nm)	Transmission percentage (%)
[12]	2024	3	0.33	330	70
[13]	2022	103	0.2295	-	80
[14]	2020	6.3	0.71 *0.618	107	51
[15]	2015	27	0.6 * 0.65	600	78
[16]	2023	28	1.4*1.7	50	72
[17]	2017	27	-	500	55
This work	-	40	2.5 * 2.5	275	85

4.9 Comparison with conventional optical logic gates

To further validate the performance of the proposed plasmonic graphene-based AND gate, we compared its performance with conventional optical logic gates based on silicon and other plasmonic materials. The comparison was based on several factors, including:

Size and Compactness: The plasmonic graphene-based AND gate design is significantly more compact than traditional optical gates, allowing for higher integration densities in photonic circuits.

Tuning Range: The ability to tune the wavelength selection mechanism using the chemical potential of graphene gives the proposed design a clear advantage over conventional designs that lack such tunability.

Switching Speed and Loss: The plasmonic graphene-based design is capable of faster switching times due to graphene’s high carrier mobility. Moreover, the losses in the structure are minimized due to the efficient coupling between the graphene layers and the resonant cavity, resulting in lower power consumption compared to traditional optical gates.

4.10 Experimental setup and materials

While the results presented in this section are based on simulations, the proposed design has been optimized for experimental validation. The materials used in the structure, including graphene, silicon, and silicon dioxide, are commercially available and suitable for fabrication using standard nanofabrication techniques such as electron-beam lithography.

5. Conclusion

In this paper, we proposed a plasmonic graphene-based optical gate with an integrated wavelength selection mechanism, aiming to leverage the unique properties of graphene for next-generation photonic circuits. The design incorporates graphene’s remarkable tunability through chemical potential modulation, enabling precise control over resonance wavelengths for wavelength selection purposes. Additionally, we introduced a plasmonic graphene-based AND gate that employs a three-input configuration, demonstrating the feasibility of using graphene in complex optical logic operations.

The proposed plasmonic graphene-based optical gate offers significant promise for photonic integrated circuits, particularly in the mid-infrared range, where graphene’s plasmonic properties can be fully exploited. The tunability of the wavelength selection mechanism provides additional flexibility, making the design adaptable to various applications that require dynamic wavelength filtering and logic gate operations.

Authors contributions
Authors have contributed equally in preparing and writing the manuscript.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Rhee. Kyong Yop. “Electronic and thermal properties of graphene.”. *Nanomaterials*, 10.5, 2020.

[2] Osman. Amr et al. “A comprehensive review on the thermal, electrical, and mechanical properties of graphene-based multi-functional epoxy composites.”. *Advanced Composites and Hybrid Materials*, 5.2:547–605, 2022.

[3] Qiao. Hui et al. “Tunable electronic and optical properties of 2d monoelemental materials beyond graphene for promising applications.”. *Energy & Environmental Materials*, 4.4:522–543, 2021.

[4] Sharotri. Nidhi et al. “Fundamental of graphene nanocomposites.”. *Handbook of Polymer and Ceramic Nanotechnology*, pages 1161–1184, 2021.

[5] Markarian. Haybert and Sedigheh Ghofrani. “Randomness, coherence and noise robustness in compressive sensing.”. *Signal Processing and Renewable Energy*, 4.1:63–76, 2020.

[6] Indutnyi. Ivan et al. “Plasmon-enhanced photostimulated diffusion in a thin-layer ag-gese2 structure.”. *Journal of Non-Crystalline Solids*, 618:122513, 2023.

[7] Roy. Sourov et al. “A comprehensive review on rectifiers, linear regulators, and switched-mode power processing techniques for biomedical sensors and implants utilizing in-body energy harvesting and external power delivery.”. *IEEE Transactions on Power Electronics*, 36.11:12721–12745, 2021.

[8] Raghuwanshi, Sanjeev Kumar, Santosh Kumar, and Yadvendra Singh. “2D materials for surface plasmon resonance-based sensors.”. *CRC Press*, 2021.

[9] Xia. Fengnian, Hugen Yan, and Phaedon Avouris. “The interaction of light and graphene: basics, devices, and applications.”. *Proceedings of the IEEE*, 101.7:1717–1731, 2013.

[10] Ooi. Kelvin JA et al. “Electro-optical graphene plasmonic logic gates.”. *Optics letters*, 39.6:1629–1632, 2014.

[11] Asgari. Somayyeh, Nosrat Granpayeh, and Zahra Ghattan Kashani. “Plasmonic mid-infrared wavelength selector and linear logic gates based on graphene cylindrical resonator.”. *IEEE Transactions on Nanotechnology*, 18:42–50, 2018.

[12] Ebadi. Seyed Morteza, Shiva Khani, and Jonas Örtegren. “Design of miniaturized wide band-pass plasmonic filters in mim waveguides with tailored spectral filtering.”. *Optical and Quantum Electronics*, 56.5:1–24, 2024.

[13] Khani. Shiva and Mohsen Hayati. “Optical sensing in single-mode filters base on surface plasmon h-shaped cavities.”. *Optics Communications*, 505:127534, 2022.

[14] Hasan. Mehedi et al. “Plasmonic corrugated waveguide coupled to a rectangular nano-resonator as an optical filter.”. *OSA Continuum*, 3.12:3314–3323, 2020.

[15] Zhuang. Huawei et al. “Plasmonic bandpass filter based on graphene nanoribbon.”. *Applied Optics*, 54.10:2558–2564, 2015.

[16] Cui. Pengfei et al. “Band-stop filter and narrow band-pass filter based on metal-insulator-metal waveguide.”. *Micro and Nanostructures*, 175:207503, 2023.

[17] Asgari. Somayyeh and Nosrat Granpayeh. “Tunable plasmonic dual wavelength multi/demultiplexer based on graphene sheets and cylindrical resonator.”. *Optics Communications*, 393:5–10, 2017.