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Plasmonic Tunable Graphene-Based Circularly Polarized Antenna for 6G Applications

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***Abstract*— Designing efficient antennas for 6G terahertz (THz) communication remains challenging due to the need for wide frequency tunability, circular polarization, and high radiation efficiency—all under compact, low-loss conditions. Conventional metallic antennas suffer from high ohmic losses and limited adaptability, making them poorly suited for dynamic THz environments. This paper presents a graphene-based plasmonic nano-antenna that achieves circular polarization and tunable frequency operation, specifically targeting 6G applications. The antenna employs a multilayer structure comprising a silicon dioxide substrate, gold gate layer, alumina dielectric, and a monolayer graphene radiating patch. Circular polarization is enabled through four symmetrically placed slots in the graphene layer. Simulation results show tunable operation from 3.03 to 3.28 THz, with a 250 GHz bandwidth, peak gain of 3.68 dBi, and up to 70% radiation efficiency. These results demonstrate the antenna's potential for reconfigurable, energy-efficient THz communication in future 6G systems.**

***Keywords*— 6G, Terahertz, Nano-antenna, Graphene, Plasmonic, Circular polarization, Reconfigurable, Electrostatic biasing**

I. INTRODUCTION

The growing demand for ultra-high data rates, low latency, and massive device connectivity is driving the evolution of wireless communication toward sixth-generation (6G) systems. To support emerging applications such as holographic displays, real-time AI processing, and immersive extended reality, 6G targets data rates up to 1 Tbps and latency in the sub-millisecond range [1,2]. Achieving this level of performance is constrained by the already saturated sub-6 GHz and mmWave spectrum [3,4], prompting a shift toward the terahertz (THz) band (0.1–10 THz), which offers significantly larger bandwidth [2,5].

However, operating in the THz range presents major physical-layer challenges, especially for antennas. Traditional metal-based antennas suffer from high ohmic losses at THz frequencies due to the skin effect [6-8], and most are designed for fixed-frequency operation, limiting their adaptability to dynamic 6G environments. To fully leverage the THz spectrum, antennas must offer real-time frequency reconfigurability and high radiation efficiency across a wide band.

Polarization is another critical factor. THz signals are particularly vulnerable to propagation impairments such as reflections, obstructions, and multipath fading. Circular polarization helps address these issues by reducing polarization mismatch and improving link robustness in mobile or non-line-of-sight scenarios [9]. Designing an antenna that simultaneously supports circular polarization and wide frequency tunability, however, remains a significant challenge. Most existing designs compromise between these properties, leading to suboptimal performance.

Graphene has emerged as a promising material for THz antennas due to its two-dimensional structure, high carrier mobility, and tunable surface conductivity via electrostatic biasing [10-12]. These characteristics enable active control over surface plasmon polaritons (SPPs), paving the way for efficient, reconfigurable antennas. Prior work has demonstrated graphene-based antennas with individual capabilities such as frequency tuning [13], polarization switching [14], and beam reconfiguration [15]. Still, a compact antenna

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design that combines wide frequency tunability, circular polarization, and high efficiency under low-voltage bias conditions remains unrealized.

In this context, this paper proposes a multilayer graphene-based plasmonic nano-antenna designed for 6G THz applications. The antenna features a compact architecture that enables wideband frequency reconfigurability through electrostatic gating of graphene. It achieves intrinsic circular polarization to enhance robustness against multipath effects and polarization mismatch in mobile environments. Throughout the tuning range, the design maintains high radiation efficiency while operating under low bias voltages, making it well-suited for energy-constrained devices. The paper presents the antenna's design methodology, analyses key parameters, and validates performance through full-wave simulations, highlighting its potential for integration into next-generation wireless systems.

II. Design Considerations for Graphene-Based Patch Nano-Antenna

A. *Graphene Permittivity Modeling*

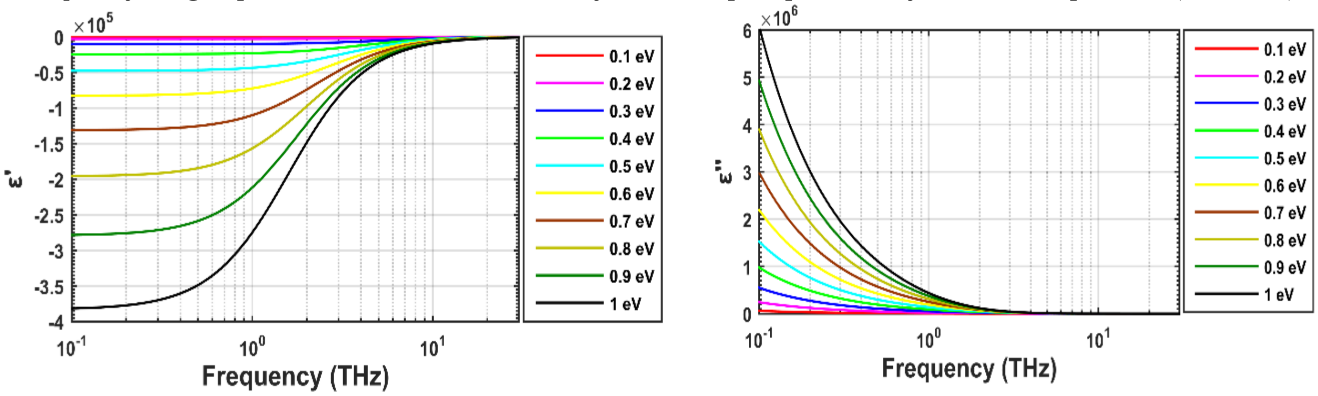
To effectively design graphene-based nano-antennas operating at THz frequencies, accurately modeling graphene's electromagnetic response is essential. This response is primarily governed by its tunable permittivity, enabling dynamic control over its interaction with THz waves.
Using the Kubo formalism, the complex relative permittivity of graphene can be expressed as [16]:

$$\varepsilon_g = \varepsilon_g' + j\varepsilon_g'' = 1 + \frac{\sigma_{intra}}{\omega\varepsilon_0 t_g} \tag{1}$$

Where ε_g' and ε_g'' represent the real and imaginary parts of permittivity, respectively, ε_0 is the vacuum permittivity, and t_g is the nominal graphene thickness (≈ 0.347 nm). The intraband conductivity, σ_{intra}, is given by [11]:

$$\sigma_{intra} = j\frac{q_e^2 K_B T}{\pi\hbar^2(\omega + j\tau^{-1})}\left(\frac{\mu_c}{K_B T} + 2\ln\left(e^{\frac{-\mu_c}{K_B T}} + 1\right)\right) \tag{2}$$

Here qe, K_B, T, $\hbar$, ω, μc, and τ represent the elementary charge, Boltzmann constant, temperature, reduced Planck's constant, angular frequency, chemical potential, and relaxation time in graphene, respectively.
In recent years, Kubo's formalism has been widely used to study the tunability of graphene. However, limited emphasis has been placed on deriving precise solutions to analyze the effect of chemical potential on permittivity in a simplified manner. To address this, a MATLAB code was developed to compute the permittivity expression under different conditions. Assuming μc ≠ 0, the following constants are used: k_B*T = 0.0256 eV, q_e= -1.6 x 10^{-19} C, $\tau = q_e 10^{12}/\mu \times \mu_c$, $\hbar$ =1.054 x 10-34, and ω = 2πf where f represent the frequency. Fig. 1 presents the mathematical analysis of complex permittivity at room temperature (T=300 K).



(a) **(b)**

Fig. 1 Frequency-Dependent Graphene Permittivity for Various Chemical Potentials at 300 K: (a) Real Part and (b) Imaginary Part.

As shown in Fig. 1a, the real part of graphene permittivity is negative, a key criterion for the propagation of surface plasmon polaritons in nanomaterials. Fig. 1a further illustrates that this negativity is more pronounced at lower THz frequencies and gradually decreases as the frequency increases. Additionally, the significant imaginary component of permittivity indicates considerable ohmic loss in the graphene material as shown in.

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Fig. 1b. These losses remain substantial up to approximately 2 THz, beyond which they decrease, suggesting improved performance of the graphene material at higher frequencies.

B. *Design of the Proposed Plasmonic Nano-Antenna*

This section outlines the design of a frequency-reconfigurable, graphene-based plasmonic nano-antenna tailored for 6G communication systems. Fundamentally, the design utilizes electrostatic gating to fine-tune graphene's chemical potential (μc), allowing dynamic control over the antenna's resonant frequency and radiation properties. Furthermore, to minimize intrinsic losses associated with graphene at lower frequencies, the nano-antenna is designed to operate above 2 THz, a range where graphene generally exhibits superior conductive performance.

Structurally, the proposed antenna, illustrated in Fig. 2, features a multilayer configuration. It is built on a 16 µm thick silicon dioxide (SiO_2) substrate, selected for its low-loss characteristics and compatibility with standard semiconductor manufacturing techniques. Integral to the reconfigurability is the electrostatic gating mechanism. This is physically implemented by incorporating a 50 nm gold layer as the gate electrode, deposited directly onto the substrate. Above this gold layer, an 85 nm thick alumina (Al_2O_3) layer serves as the gate dielectric. Al_2O_3 was chosen for its high dielectric constant and low loss properties, both critical for achieving effective modulation of graphene's chemical potential at practical voltage levels.

Functionally, the chemical potential of graphene is directly influenced by the applied gate voltage (Vg) and can be expressed as [21]:

$$\mu_c = \sqrt{\frac{(V_g - V_{Dirac})\varepsilon_0 \varepsilon_d \pi \hbar^2 V_f^2}{t_d q_e}} \qquad (3)$$

where, ε_d and t_d represent the relative permittivity and thickness of the gate dielectric layer, respectively, while V_{Dirac} is the voltage-dependent offset. By adjusting Vg, the carrier concentration in graphene, and consequently its chemical potential, can be dynamically controlled.

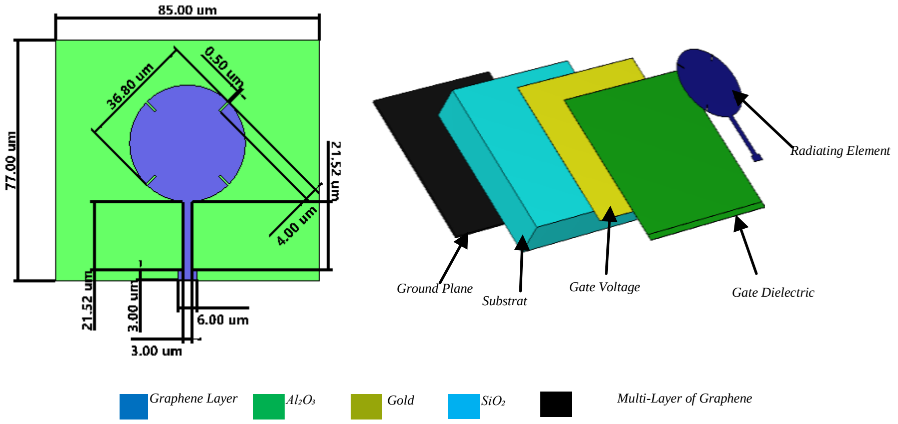

Fig. 2 Detailed geometry of the proposed nano-antenna.

This element consists of a monolayer graphene sheet with a nominal thickness of 0.347 nm. Moreover, to enhance performance in complex wireless environments often encountered in 6G scenarios, the patch incorporates four strategically placed slots designed to generate circular polarization. Finally, the ground plane is implemented using a 1 µm thick multilayer graphene structure situated on the bottom surface of the SiO_2 substrate.

Simulation and optimization of the proposed nano-antenna were performed using the frequency solver in CST Studio Suite. Key performance metrics, including return loss, gain, efficiency, and polarization characteristics, were evaluated under different bias conditions and are presented in the following section.

III. Results and Analysis

A. *Frequency Reconfigurability*

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The frequency tuning capability of the proposed nano-antenna is demonstrated through return loss (S11) simulations, as shown in Fig. 3. The results clearly validate the effectiveness of electrostatic tuning via graphene's chemical potential, with a noticeable shift in resonant frequency as the gate voltage (Vg) changes. At Vg = 0V, the antenna resonates at approximately 3.03 THz, achieving a strong return loss of -35 dB, which indicates excellent impedance matching and a bandwidth of 18 GHz. As Vg increases, the resonance gradually shifts to higher frequencies, reaching 3.28 THz at Vg = 30 mV, with a return loss of -32 dB while maintaining a consistent 18 GHz bandwidth. This results in a tuning range of 250 GHz, demonstrating the wide frequency agility of the proposed design.

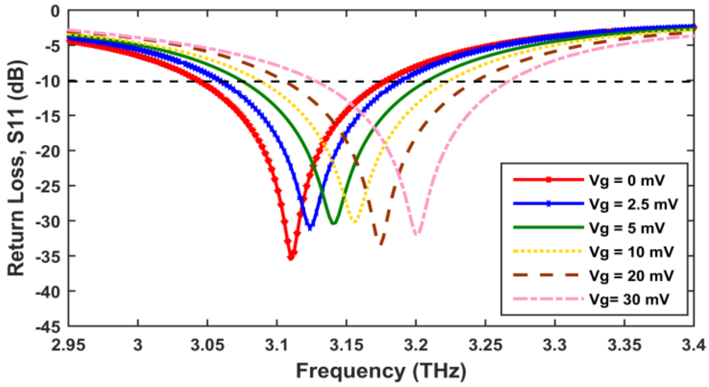

Fig. 3 Return loss simulations of the proposed graphene nano-antenna under different gate voltages.

These findings validate the proposed nano-antenna's suitability for dynamically reconfigurable 6G communication systems, where tunability within the THz spectrum is essential for adaptive frequency allocation and efficient low-power operation.

B. Polarization Characteristics

The polarization performance of the proposed nano-antenna is evaluated using the axial ratio (AR), as shown in Fig. 4. An AR below 3 dB signifies effective circular polarization generation. The simulation results confirm that the designed antenna maintains AR < 3 dB across its operational tuning range, particularly around the resonant frequencies corresponding to different gate voltage values.

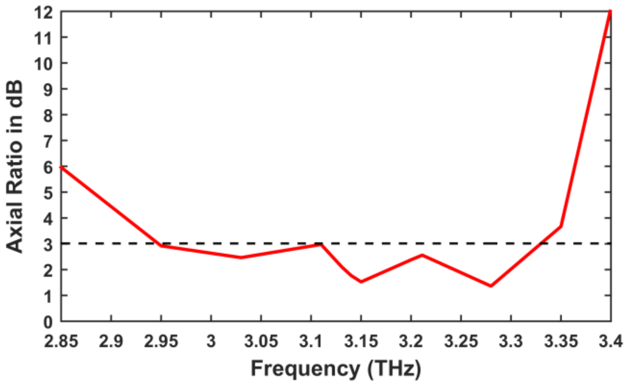

Fig. 4 Axial ratio performance of the proposed nano-antenna across the operational frequency range.

C. Gain and Radiation Efficiency

Fig.5 presents the simulated gain and radiation efficiency as functions of frequency. The antenna demonstrates high realized gain across the tunable frequency range, varying between 3.2 dBi and 3.68 dBi, with a peak value of 3.68 dBi at 3.13 THz. Additionally, the radiation efficiency remains above 60% throughout the operational band, reaching a maximum of 70% around 3.13 THz. These results confirm that the proposed nano-antenna achieves efficient radiation performance, balancing gain and efficiency within the challenging THz regime. While not explicitly plotted, variations in the graphene chemical potential also influence the radiation pattern, enabling potential beam reconfiguration for adaptive THz communications.

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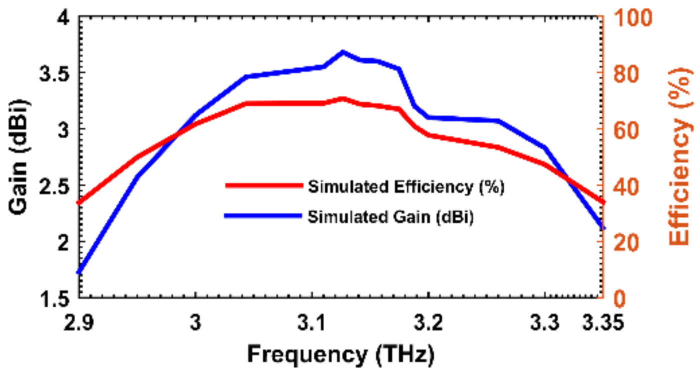

Fig. 5 Simulated gain and radiation efficiency of the proposed nano-antenna across the tunable frequency range**.**

D. Performance Summary and Comparison

Overall, the simulation results demonstrate a plasmonic graphene-based nano-antenna design that successfully integrates wide frequency tunability equal to 250 GHz with efficient circular polarization and respectable gain around 3.68 dBi and radiation efficiency > 60% in the THz band around 3-3.3 THz. The ability to dynamically adjust the operating frequency via low electrostatic voltage gating is a key enabler for future adaptive 6G networks. A comparison with existing graphene THz antenna designs, summarized in Table I, highlights the competitive performance metrics achieved by the proposed structure, particularly the combination of frequency tuning range, circular polarization, and efficiency. These combined characteristics position the antenna as a viable and promising component for advancing THz communications towards 6G implementation.

TABLE I
COMPARISON OF THE PROPOSED NANO-ANTENNA WITH EXISTING WORK IN THE LITERATURE

Ref	Structure	Substrate	Material	Frequency (THz)	Bandwidth (GHz)	Efficiency (%)	Gain (dBi)	Polarization	Features
[22]	Planar	SiO2	Graphene	2.48 and 3.35	140	53.5 - 87.3	2.7 -6.03	Linear	THz Application
[23]	Planar	PTFE	Graphene	0.45	110	NR	6.71 (Reported as Directivity)	Linear	Frequency Reconfigurable
[24]	Planar	SiO2	Copper, Graphene	1.8	117	77	5	Linear	Frequency Reconfigurable
[25]	Planar	SiO2	Graphene	0.92	300	45.6	6.9 (Reported as Directivity)	circular	Frequency Reconfigurable
[26]	SIW	SiO2	Graphene	1	200	50	4.6	Linear	Frequency Reconfigurable
[27]	Planar	SiO2	Graphene	0.82–1.07	250	16-40	5 (Reported as Directivity)	Circular	Frequency and Polarization Reconfigurable
THIS WORK	Planar	SiO2	Graphene	3,03-3,28	250	62-70	3.68	Circular	Frequency Reconfigurable

IV. CONCLUSIONS

This paper has introduced a novel plasmonic graphene-based circularly polarized antenna designed for future 6G applications. By leveraging the exceptional properties of graphene, the proposed antenna achieves enhanced frequency reconfigurability, miniaturization, and efficient plasmonic wave propagation. The numerical analysis, conducted using CST Studio Suite, has validated the antenna's capability to operate within the frequency range of 3.03-3.28 THz, demonstrating a bandwidth of 250 GHz, a peak gain of 3.68 dBi, and a peak efficiency of 70%. The introduction of strategically placed slots in the radiating patch ensures circular

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polarization, making the antenna robust against polarization mismatches and well-suited for high-speed data transmission in dynamic wireless environments.

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