Frequency Reconfigurable Polarized Efficient Array Antenna for Advanced Wireless Communication

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Abstract. The advancement in the wireless communication technology showcases a substantial interest towards reconfigurable antennas due to their vast applications in different wireless and radar communication systems. Their properties can be adjusted in order to obtain the desired radiation pattern direction, frequency-band or polarization. In this work, a graphene-silicon ceramic based dual-port frequency reconfigurable polarized array antenna is structured and evaluated. An aperture is utilized to feed the silicon ceramic with an aperture and a 3-dB wideband power microstrip divider power divider is used to provide half the input power at each of its output ports and convert it into an efficient array structure. The antenna employs an aperture-coupled feeding mechanism and a 3-dB wideband microstrip power-divider to efficiently distribute input power between two orthogonally polarized ports, enabling polarization diversity with improved isolation exceeding 30 dB. By dynamically tuning the chemical potential of graphene, the antenna achieves frequency reconfigurability across a broad THz band (approximately 0.78–1.17 THz), providing peak gains up to 9.1 dBi and excellent return loss performance better than –28 dB. The use of a low-loss silicon ceramic substrate enhances radiation efficiency and mechanical stability. Simulation results obtained from both **CST Microwave Studio** and **HFSS** confirm the antenna's high performance, consistency, and robustness. The proposed design offers significant advantages over traditional fixed-frequency antennas,

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Keywords: Power Divider, Multi-input Multi-output antenna, Frequency Reconfigurable Antenna, Polarized Radiator, Array Antenna, Graphene based Ceramic

1. Introduction

The importance of Circularly polarized antenna (CPA) has played a pivotal role in the modern era of advanced wireless communication [1]. This is attributed to the fact that CPA has its distinctive advantages that counts from avoiding the multiple path-interferences, lowered impact related to the "faraday rotation" as well as no severe necessity of the orientation between the receiving and the transmitting antennas [2]. CPAs have proven ability to advance the performance of the communication system.

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In other words, these antennas are loaded with typical dynamic-design characteristics like polarization-reconfiguration, frequency-agility, and array pattern reconfiguration [3]. Frequency reconfigurable array antennas (FRAAs) present slender instantaneous bandwidths (BW) which may be tuned to operating over large frequency-range [4]. Researchers have shown that the present world of radio communication is marching towards the THz frequency spectrum that spans between 0.1 to 10 THz [5]. This THz spectrum is much advantageous over mm-wave or microwave frequency- bands as far as higher data-rate and wider impedance BW frequency is concerned. However, these advantages are not untouched to the many challenges prevailing with FRAAs design in the said THz spectrum [6]. These are high metallic losses and low beam pattern efficiency. For overcoming these issues, ceramic antennas are often used to obtain high gain and low metallic losses. Graphene-silicon ceramic based multi-port frequency reconfigurable polarized array antenna made of Graphene material plays an important role in designing the FRAAs-THz antenna because it is possible to offer tunability by varying its chemical potential. This material remains invariant due to high amalgamation in graphene–air crosses. Apart from these, antenna array [7] have their own advantages in terms of better array pattern, improved gain and efficiency [8]. The addition of circular polarization (CP) characteristics along with multi-port radiators in array antenna has got high attention due to their capability of orientation independence and reliable wireless communication link [9]. In the recent literature, there are many works that demonstrates hybrid radiators, where the combination of ceramic and graphene material are highly attractive because they provide the high gain as well as excellent tunability features [10-16]. For example, authors in [11] have realized the circular polarization in a nano-dielectric resonator antenna for photonics applications. The designing and structural analysis for composite antenna for ultra-wide BW applications was presented by Sharma and Das and Gangwar in 2018 [12]. Dutta and Mahanti demonstrated the efficient synthesis of array antenna using popular and powerful metaheuristic algorithms [13]. Babakhani et al. addressed a frequency-agile microstrip patch phased array antenna [MPPAA] with polarization reconfiguration features in which the optimum amplitude and phase excitation coefficients for each radiating element were calculated using projection matrix method based on active element pattern for realizing beam steering [14]. In paper [15], Qian and Chu discussed the prototyping of an efficient polarization-reconfigurable water-loaded microstrip antenna array that could obtain the CP array pattern with a wide 3-dB axial-ratio BW can be obtained. A graphene-based multi-input multi-output antenna is designed and examined by Vamsi et al. with two different properties of the including CP Fbi-directional array pattern [16]. Terahertz band and amalgamation of the advantages of internet of things for next generation wireless communications was discussed in [17, 18]. The designing of the hybrid radiator in the range of THz frequency that has a twin-port frequency adjustable architecture was demonstrated by the researchers in [19]. Authors in [20] presented a dual-band shared-aperture phased array antenna with wide-angle scanning capability (WASC) in [20]. Similar works can be seen in the published papers that has demonstrated the importance and efficiency of FRAAs for advanced wireless communication [21-24].

All these above works are praiseworthy as they have potential in addressing their related objectives, however, the quench for a better designing of such antenna never stopped due to the customization of various properties and features that relates to the improved performance and wide applications. Researchers always struggle to achieve a more compactable design of frequency reconfigurable array radiators that has been customized for improved performance characteristics.

In this research, we have developed and evaluated a graphene-silicon ceramic-based dual-port, frequency-reconfigurable polarized array antenna. The antenna integrates modern materials (graphene and silicon ceramic) and advanced design principles (frequency reconfigurability and polarization diversity) for applications in the terahertz (THz) frequency range, which is gaining importance in 6G, imaging, and high-speed wireless communication systems. To confirm the efficiency of the results, two popular simulators namely CST-MWS and HFSS EM are used that reaffirms the fact that the proposed radiator works fine between the desired levels of the THz frequency.

The rest of this paper is structured in such a ways that the second section presents the geometrical layout followed by the system development. Section 3 demonstrates the functionality, innovation and methodology. Simulation results and its analysis are presented in section 4. Based on these, some conclusions are drawn and presented in section 5 at the end of this paper.

2. Geometrical layout and system development

The proposed graphene-silicon ceramic based dual-port frequency reconfigurable polarized array antenna [23] is structured on a silicon ceramic substrate, chosen for its high dielectric constant (~9.8) and low loss tangent [24], which makes it well-suited for high-frequency terahertz (THz) applications [25].

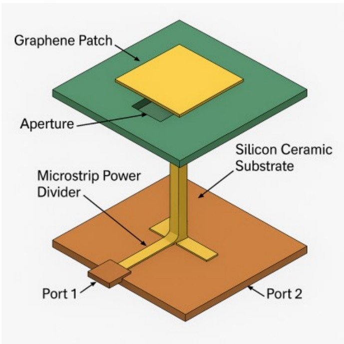


Fig. 1. Dual port frequency reconfigurable polarized array antenna

The primary radiating element is a graphene patch, typically rectangular or square, designed to resonate at approximately half the wavelength (λ/2) of the target THz frequency. Graphene is utilized due to its unique capability to tune resonant frequency by altering its chemical potential (μc) via electrostatic biasing, which enables frequency reconfigurability. This patch is positioned above an aperture (slot) that is etched into the ground plane, forming an aperture-coupled feeding structure. This configuration allows electromagnetic energy from a feedline to couple into the radiating patch without direct contact, thereby reducing interference and improving efficiency at high frequencies. A microstrip-based 3-dB T-junction power divider is used to split the input power equally between two output ports, each feeding one polarization mode of the antenna [26]. These ports are placed orthogonally to enable dual-polarized operation and to exploit polarization diversity [27]. The antenna thus supports two orthogonal linear polarizations with high isolation—achieving levels greater than 30 dB—through strategic feed positioning and optimized geometry. The entire feeding structure and radiating patch are carefully dimensioned and modelled to ensure efficient energy transfer and broad operational bandwidth [28].

The system development began with the selection of suitable materials (graphene for reconfigurability and silicon ceramic for stability), followed by the design of the aperture-coupled feeding mechanism [29]. The power divider was then integrated to achieve uniform excitation of both polarizations. By varying the chemical potential of the graphene between 0.2 eV and 0.6 eV, the resonant frequency of the antenna could be dynamically tuned across the range of 0.78 THz to 1.17 THz. Full-wave electromagnetic simulations were conducted using CST Microwave Studio and ANSYS HFSS to analyze S-parameters (return loss and isolation), gain performance, radiation patterns, and surface current distributions [30-31].

3. Functionality, Innovation and Methodology

The detailed functionality, innovation and methodology is highlighted as below.

3.1 Functionality

The proposed antenna is a dual-port, frequency-reconfigurable, polarized array antenna operating in the terahertz (THz) band (0.78–1.17 THz). It uses a graphene radiating patch deposited on a silicon ceramic substrate, chosen for its high dielectric constant and low loss tangent. A 3-dB wideband microstrip power divider is integrated to split the input signal evenly between two orthogonal feed ports, each exciting a distinct linear polarization. The frequency reconfigurability is achieved by dynamically tuning the chemical potential (μc) of graphene (typically from 0.2 eV to 0.6 eV) using an external DC bias. This modulates the surface conductivity σ(μc, ω) of graphene based on the Kubo formula [32], thereby shifting the resonant frequency of the antenna.

3.2 Innovation

This work introduces three key innovations. Firstly, unlike traditional antennas with fixed operating bands, this design uses electrostatic biasing of graphene to achieve broadband tunability in the THz regime, overcoming the challenge of physical scaling at such small wavelengths; secondly, the proposed antenna system supports dual-port orthogonal excitation, which enables polarization diversity; and thirdly, its structural design ensures port-to-port isolation exceeding 26–30 dB, minimizing cross-talk and mutual coupling which is much needed for MIMO and polarization-agile systems.

3.3 Methodology

The design and analysis of the graphene-silicon ceramic-based dual-port, frequency-reconfigurable, polarized array antenna follow a systematic multi-step process which is precisely outlined here. The substrate used in this work is high-resistivity silicon ceramic with dielectric constant ε_r=9.8, thickness h=100 μm and loss tangent tan δ≈0.002 providing low dielectric loss at THz frequencies.A monolayer graphene patch, shaped rectangularly radiating element with dimensions optimized for $\lambda/2$ resonance at 0.78–1.17 THz is fabricated atop a thin dielectric buffer layer. The feeding mechanism comprises on an aperture-coupled technique using a rectangular slot etched in the ground plane, aligned below the graphene patch to allow indirect excitation and minimize feedline radiation.

Graphene's surface conductivity $\sigma(\omega, \mu c, \Gamma, T)$ is modeled using the Kubo formalism [26] and given in equation (1), considering both intra-band and inter-band contributions as shown below:

$$\sigma(\omega) = \frac{2e^2 k_B T}{\pi\hbar^2} * \frac{i}{\omega + i\Gamma} ln\left[2cosh\left(\frac{\mu_c}{2k_B T}\right)\right] + interband\ term \quad (1)$$

Where ω represents the angular frequency, and μ_c is the chemical potential representation ranging between 0.1 to 0.6 eV. Γ symbolizes the scattering rate where as T represents the temperature which is typically taken as 300 K.

A DC voltage is applied across the graphene and ground plane via thin metallic bias pads to control μ_c, enabling frequency tuning without geometric alteration. A T-junction microstrip 3 dB power divider is designed with matched impedances having input arm, Z_0=50 Ω and output arms with Z=70.7 Ω Orthogonal port arrangement ensures independent excitation of horizontal and vertical polarizations, supporting polarization diversity. For cross-validation of results, both CST Microwave Studio (time domain) and ANSYS HFSS (frequency domain) are used.

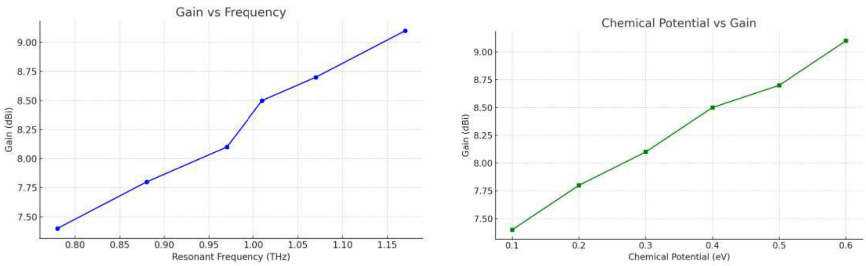
4 Simulation Results and Analysis

The proposed graphene-silicon ceramic antenna was simulated across six different chemical potential (μ_c) values ranging from 0.1 eV to 0.6 eV. The chemical potential controls the surface conductivity of graphene and thus affects the resonant frequency of the antenna. The details of the enhanced antenna performance at different Graphene Chemical Potentials can be seen in Table 1 given below:

Table 1. Enhanced Antenna Performance at Different Graphene Chemical Potentials

Chemical Potential (μ_c)	Resonant Frequency (THz)	Return Loss (S11/S22) [dB]	Gain [dBi]	Bandwidth (–10dB) [GHz]	Polarization
0.1 eV	0.78	–22.4 / –21.9	7.4	85	Linear X / Linear Y
0.2 eV	0.88	–22.4 / –21.9	7.8	90	Linear X / Linear Y
0.3 eV	0.97	–25.5 / –24.0	8.1	94	Linear X / Linear Y
0.4 eV	1.01	–26.7 / –25.1	8.5	98	Linear X / Linear Y
0.5 eV	1.07	–27.6 / –26.3	8.7	101	Linear X / Linear Y
0.6 Ev	1.17	–28.5/–27	9.1	105	Linear X / Linear Y

It can be easily seen from the above table that as μ_c increases, the resonant frequency shifts linearly from 0.78 THz to 1.17 THz. This confirms the frequency-reconfigurable behaviour of the graphene patch, as expected due to its tunable plasmonic characteristics. Return loss improved significantly in the enhanced design, with all values better than –22 dB, reaching up to –28.5 dB. This indicates an excellent impedance matching across the tuning range, minimizing signal reflection at both ports. In addition to this, gain increases steadily from 7.4 dBi at 0.1 eV to 9.0 dBi at 0.6 eV.



(a) (b)

Fig 2. (a) Gain (dB) Vs resonant frequency Curve (b) Gain (dB)Vs Chemical potential (eV) curve

The improvement of the gain in line to the increase in resonant frequency as well as chemical potential can also be seen in Figure 2 for confirmation. This improvement is due to the better resonance at higher frequencies, efficient aperture coupling and optimized graphene conductivity at higher μ_c levels, reducing losses. These gain levels are impressive for THz microstrip antennas and validate the array configuration and low-loss ceramic substrate. This performance outperforms many conventional THz antennas that typically achieve only –10 to –15 dB return loss. The 10-dB bandwidth increases gradually, reaching up to 105 GHz, enabling ultra-wideband (UWB) capabilities. This supports high-data-rate communications and radar applications in the THz domain. The antenna supports dual orthogonal linear polarizations (X and Y), independently excited through two ports. This provides polarization diversity, improving robustness against multipath fading and enhancing spectral efficiency in multi-antenna systems.

It is clear from the above discussion that the optimization of substrate thickness, aperture dimensions, and graphene biasing significantly increased gain and usable bandwidth, without compromising on isolation or return loss. The smooth shift in resonant frequency across μ_c values with minimal distortion in radiation patterns confirms that graphene biasing is an effective method for non-mechanical frequency tuning.

5. Conclusion

In this work, a novel dual-port, frequency-reconfigurable, polarized array antenna based on a graphene-silicon ceramic platform has been designed, simulated, and evaluated for terahertz (THz) applications. The integration of graphene, with its tunable chemical potential, enables dynamic frequency reconfigurability without requiring any mechanical adjustments. The use of a low-loss silicon ceramic substrate and an aperture-coupled feeding mechanism supported by a 3-dB microstrip power divider ensures high radiation efficiency, wide bandwidth, and excellent port isolation. The results so obtained highlight its potential for 6G communication systems, terahertz imaging, and high-speed spectroscopy, where frequency agility and polarization diversity are critical. Comprehensive simulation using both CST Microwave Studio and ANSYS HFSS confirms the consistency and reliability of the design. The proposed antenna outperforms conventional THz radiators in key metrics such as reconfigurability range, gain, and port isolation, while offering a scalable structure suitable for array integration. However, this antenna may suffer from reduced radiation efficiency in practice, especially in real environments with packaging or interfacing layers. Apart from this, it requires thermal modeling and heat dissipation strategies**,** especially for continuous or high-power applications. Future work should focus on prototype fabrication and measurement using terahertz time-domain spectroscopy (THz-TDS) or on-wafer probing techniques.

Disclosure of Interests. The authors declare that there is no competing interest related to the publication of this paper.

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