Graphene Based Microstrip Patch Antenna for Wireless Communication Applications

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Keywords: Graphene Substrate, Microstrip Patch Antenna, ADS Software, Wireless Communication.

Abstract: This paper discusses a design and simulation of a microstrip patch antenna using graphene based dielectric substrate for the advanced wireless communication application. Such an antenna is beneficial in terms of miniaturization, bandwidth and efficiency compared to other conventional antennas used in some of the early heart monitoring implantable devices. Graphene (εr=2.8, high thermal conductivity of (˜3000 W/m•K) and low loss tangent (tanδ) greatly improves the antenna bandwidth (BW), efficiency and miniaturization. The designed antenna is simulated in ADS the software with a wide frequency range from 1GHz to 10GHz with frequency gap 0.05GHz. The performance parameters as return loss (S11), VSWR, gain, directivity are studied. The results show that the return loss is low so as to have a good impedance matching and the improved radiation patterns make graphene-based antenna be potential applications in future high-frequency and next-generation wireless communication systems.

1 INTRODUCTION

The recent progress of wireless communication technology has required the antennas of high performance that can satisfy the requirements of the modern wireless communication systems. In the family of antennas, microstrip patch antennas have been of great interest, because of their low profile, light weight and simplicity of integration with other electronics. These antennas are commonly used for mobile communications, satellite communications and radars. The materials properties are of very important aspects for the optimization and designing of microstrip patch antennas. The conventional dielectric materials (FR4 and rogers) have been well researched and used in antenna applications. However, with the introduction of new materials like graphene there are new opportunities to improve the performance of microstrip patch antenna. Zhang, Y, et al., 2024 Graphene, a monolayer of carbon atoms in a 2D hexagonal lattice, shows extraordinary characteristics like high thermal conductivity, mechanical strength and its excellent electrical conductivity. These properties render graphene to be an appealing material for demonstrating microstrip patch antennas.

Graphene's exceptional properties may improve the optimal performance of antenna. With large dielectric constant (εr = 2.8), the decomposition temperature of 471 °C, and the low dissipation factor (tanδ, 0.002 at 1 GHz), the LTO can be used for high-frequency applications with effective signal delivery and reduced energy wastage Zhang, Y, et al., 2024. Moreover, the extraordinary thermal conductance of graphene (~3000 W/m•K) guarantees effective heat removal, which is important to preserve performance, in particular in high frequency regime 4.

In this paper, the microstrip patch antenna is designed and simulated with a graphene based dielectric material for future wireless communication generation. The designed antenna is simulated with the ADS (Advanced Design System) software between a frequency range of 1 GHz- 10 GHz (step frequency is 0.05 GHz). The performance parameters; S11 return loss, VSWR, gain, and directivity are studied for assessing the proposed graphene based antenna.

Selvaraj, R., Kalaivaani, P. T., Lakshmipriya, B., Monisha, M., Sasirekha, G. and Sindhumathi, L.
Graphene Based Microstrip Patch Antenna for Wireless Communication Applications.
DOI: 10.5220/0013900700004919

In *Proceedings of the 1st International Conference on Research and Development in Information, Communication, and Computing Technologies (ICRDICCT'25 2025) - Volume 3*, pages 504-510
ISBN: 978-989-758-777-1

2 ANALYSIS AND DESIGN

2.1 Graphene as a Substrate

Chen, H., et al., 2024 Graphene is an excellent choice for microstrip patch antenna substrates due to its unique electrical and mechanical properties. Its tunable conductivity allows frequency reconfiguration, making it suitable for multi-band applications. The high electrical conductivity and low loss characteristics improve antenna efficiency, especially for high-frequency communications. Graphene enables antenna miniaturization while maintaining high performance, essential for compact and wearable devices. Its superior bandwidth and gain enhance data transmission capabilities in advanced networks like 5G and terahertz communications. The lightweight and flexible nature of graphene allows the development of bendable antennas for flexible electronics and aerospace applications. Its exceptional thermal conductivity ensures efficient heat dissipation, maintaining stable antenna. Graphene-based substrates integrate well with nanotechnology, supporting innovations in IoT and smart sensing applications. The material's ability to reduce signal attenuation enhances overall antenna radiation efficiency. With these advantages, graphene is paving the way for the future of high-performance communication systems

2.2 Conductivity of Graphene

Graphene's conductivity is highly dispersive and can be tuned to behave like a metal or a semiconductor. Graphene is structurally an ultrathin layer of carbon atoms that forms a honeycomb lattice, sandwiched between two different media. The surface conductivity of it depends on some parameters, such as the angular frequency (ω), chemical potential (μc), scattering rate (Γ) and temperature (T). Conductivity of graphene's s(Z) fits a Kubo formula (differently for intra- and inter-band), namely: (1,5).

The intraband conduction in graphene is mainly attributed to free carrier transport and is dominant for low frequencies. It depends on chemical potential, temperature etc, and can be calculated mathematically as:

$$\sigma_{intra} = -j\frac{e^2 k_B T}{\pi\hbar^2(w-j/2\Gamma)}\left(\frac{\mu_c}{k_B T} + 2ln\left(e^{-\mu_c/k_B T} + 1\right)\right) \quad (1)$$

$$\sigma_{intra} = -j\frac{e^2}{4\pi\hbar}ln\left(\frac{2\mu_c - (w - j2\Gamma)\hbar}{2\mu_c + (w - j2\Gamma)\hbar}\right) \quad (2)$$

where K_B is the Boltzmann constant, h the Planck's constant, e the electron charge, ω the angular frequency, Γ the scattering rate, T the temperature, and μ_c the chemical potential.

2.3 Patch Antenna Design with ADS

The width w, of the microstrip patch antenna was obtained from Equation (3)

$$w = \frac{c}{2f_0}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (3)$$

where f_o = operation frequency, c = speed of light, ε_r = dielectric constant of the substrate. In order to determine the length of the patch, L, we need to perform a few additional computations.It is necessary to start by figuring out the dielectric constant. In Equation (4), we may find the dielectric constant of the substrate.

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1 + 12\frac{h}{w}\right)^{-\frac{1}{2}} \quad (4)$$

where h = thickness of the substrate, ε_{eff}= effective dielectric constant of the substrate. The value for effective length can be calculated by using Equation (5):

$$L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} \quad (5)$$

The following step is to compute the length extension, which is denoted by ΔL. Because of fringing effects, the microstrip antenna gives the impression of being far bigger electrically than its real physical dimensions. Equation (6), which gives the length extension, is as follows:

$$\Delta L = 0.412 \times \frac{(\varepsilon_{eff}+0.3)\left(\frac{w}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{w}{h}+0.8\right)} \quad (6)$$

The actual length of the patch, L, is obtained by Equation (7):

$$L = L_{eff} - 2\Delta L \quad (7)$$

In order for patch antennas to function properly, the design process must begin with a finite ground plane. Equations (8) and (9) can be used to determine the length and width of the ground plane, respectively.

$$L_g = 6h + L \quad (8)$$

$$W_g = 6h + w \tag{9}$$

where w = width of the patch antenna, L = length of the patch antenna, W_g = width of ground plane. L_g = length of ground plane C. A. Balanis, 2016.

The figure 1 and 2. Shown below are the layout design and dimensions of the Microstrip patch antenna for the chosen substrate, rectangular patch and the ground plan.

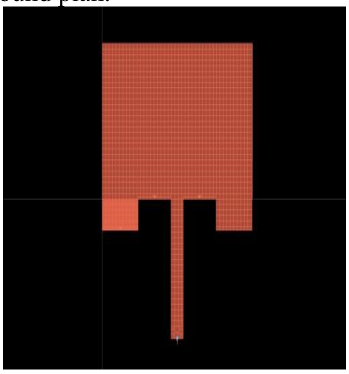

Figure 1: Layout design of microstrip patch antenna.

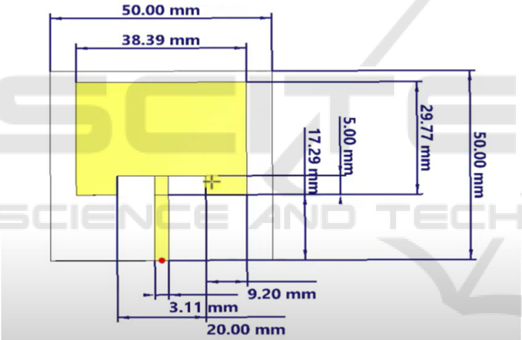

Figure 2: Dimensions of the microstrip patch antenna.

2.4 Conductor Layer Selection

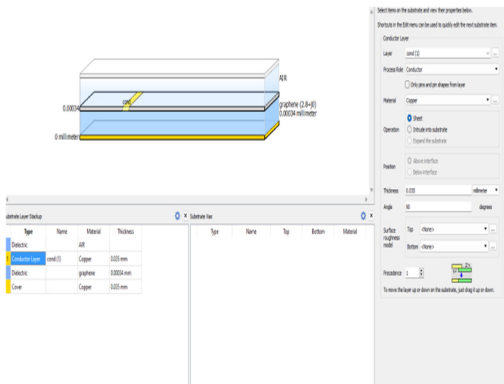

Figure 3: Conductor layer selection.

The above figure 3 shows the conductor layer selection in Advanced Design System (ADS) for designing a microstrip patch antenna. In this setup, copper is chosen as the conducting material with a thickness of 0.035 mm. This layer forms the radiating patch of the antenna, which is essential for transmitting and receiving electromagnetic waves. The settings panel on the right allows the user to define the conductor's material, thickness, and positioning within the substrate. The substrate layer stackup displayed at the bottom shows multiple layers, including air (dielectric), copper (conductor), graphene (dielectric), and another copper layer (cover), establishing the fundamental structure of the antenna.

2.5 Dielectric Layer Selection: Graphene Substrate

The image shown below focuses on the dielectric layer selection, where graphene is used as the substrate material. The thickness of this dielectric layer is 0.00034 mm (0.34 µm), Faruk et.al, 2021; Mollah, et al, 2021 making it extremely thin compared to conventional substrates. Graphene is selected due to its exceptional electrical and mechanical properties, which can enhance the antenna's performance in high-frequency applications

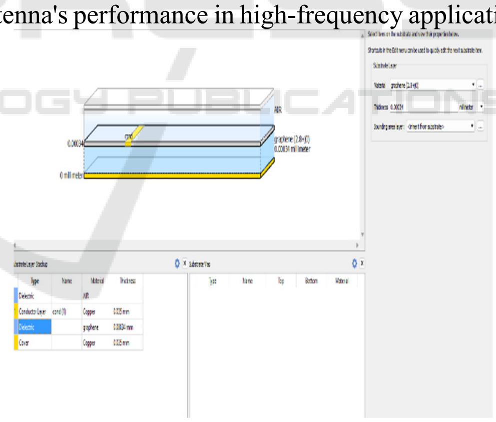

Figure 4: Dielectric substrate selection.

In figure 4, The settings panel on the right displays options for adjusting the dielectric layer's material and thickness, ensuring proper electromagnetic wave propagation. The substrate layer stackup at the bottom shows the arrangement of layers, with graphene serving as the dielectric medium between the top copper patch and bottom copper ground plane.

2.6 Cover Layer Selection: Ground Plane

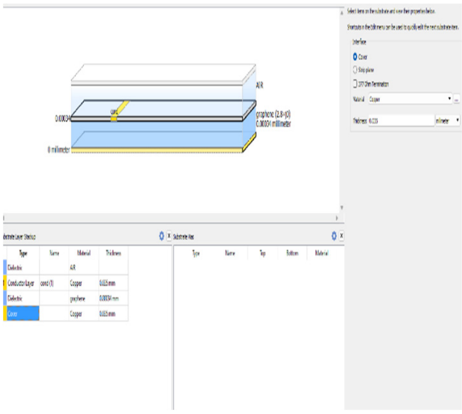

Figure 5: Cover layer selection.

The protective shielding layer is made of 0.035 mm thick copper as shown in figure 5. This cover is important to protect the antenna structure against extraneous influences and environmental impact. Furthermore, copper is a conductive material allowing it to shield unwanted RF radiation and maintain signal fidelity. With little external perturbation, the shielding layer can improve the performance and stability of the antenna system Faruk et.al, 2021.

2.7 Design Parameters and Configurations

Here is a well-structured table for the given parameters and values:

Table 1: Design Parameters.

Parameter	Value
Real Permittivity (ε_r Real)	2.8
Imaginary Permittivity (ε_r Imaginary)	0
Loss tangent (tanδ)	0.002
Real Permeability(μ_r)	1
Imaginary Permeability(μ_r)	0
Frequency (TanD)	1GHz
Step size	0.01GHz
Upper range	10GHz
Conductivity	3000W/m.k
Z conductivity	~10W/m.k
Heat capacity(Cv)	~0.7J/g.K
Patch Antenna dimensions	As per fig.2

For the analysis the frequency plan setup was also described with the important parameters for the evaluation of the antenna performance. A linear sweep frequency from 1 to 10 GHz was used. The steps were set to 181 for the sweep, which means a resolution step of 0.05GHz. When a checkmark was checked in the box, the frequency plan was on. Such configuration permitted accurate measurements over the large frequency bandwidth, providing the required number of points for an optimal analysis and modeling of the antenna performance in the considered MegaHetz span.

The above table 1 shows the design parameters for the graphene-based microstrip patch antenna are carefully selected to optimize its performance. The permittivity (εr) is set at 2.8 with an imaginary value of 0, ensuring minimal dielectric losses, while the loss tangent (tanδ) of 0.0001 further confirms very low energy dissipation. Since graphene is non-magnetic, the permeability (μr, Real) is 1, and the imaginary permeability (μr, Imaginary) is 0, meaning it does not influence the magnetic properties of the antenna. The Djordjevic model parameters define the frequency-dependent loss characteristics, with a TanD frequency of 1 GHz, a low-frequency limit of 1 kHz, and a high-frequency range extending up to 1 THz, making the design suitable for a wide frequency spectrum.

In terms of thermal properties, graphene exhibits an outstanding thermal conductivity of 3000 W/m·K, which enables efficient heat dissipation, although its Z-axis conductivity is lower at ~10 W/m·K, affecting vertical heat transfer. The heat capacity (Cv) of approximately 0.7 J/g·K indicates its capability to store and release thermal energy efficiently. Additionally, the ground plane is designed to be larger than the patch to enhance radiation efficiency and minimize substrate-induced losses, which helps in achieving better antenna performance. These design considerations ensure that the graphene-based microstrip patch antenna operates effectively across a broad frequency range while maintaining thermal stability and minimal signal loss.

3 RESULTS ANALYSIS

The simulation results confirm that the graphene-based microstrip patch antenna achieves excellent impedance matching, with an S_{11} return loss of approximately -0.030 dB at 2.25 GHz, ensuring minimal reflection and high efficiency.

3.1 S11 Magnitude and Phase Response

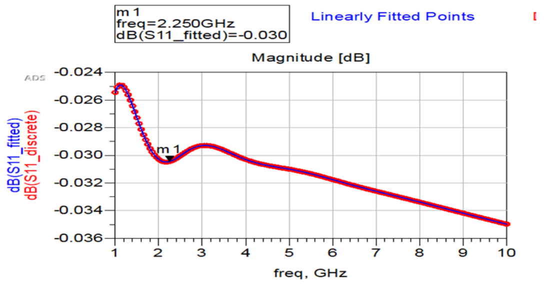

Figure 6: Magnitude vs frequency.

In Figure 6, the S11 parameter (return loss) is an important measure of how well the antenna is matched to the feeding system. It is a value of reflected power back due to impedance mismatch. The graph demonstrates that at f = 2.25 GHz the return loss is about -0.030 dB 1, meaning an almost perfect impedance fit. Smaller S11 value results in higher power transfer and less loss. The gradual decrease at higher frequencies implies that the antenna could work effectively in a wide bandwidth range. We aim to design a G-GMSA for wireless applications, and in such a desire, the low value of the return loss at the desired frequency indicates superior performance and less loss in the signal.

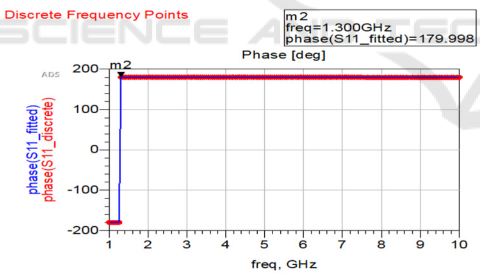

Figure 7: Plot of phase vs frequency.

In Figure 7, the phase of S_{11} indicates the phase shift of the reflected signal concerning the incident signal. At 1.3 GHz, the phase is approximately 180°, meaning that at this frequency, the reflected signal is almost completely out of phase with the incident signal Zhang, Y et al, 2024; Boopalan, et al, 2017. The phase transition suggests that at lower frequencies, the antenna exhibits significant phase variations, which might affect the stability of signal transmission. However, the relatively stable phase at higher frequencies confirms a well-behaved impedance response over the operating range. This phase behavior aligns with the design goal of achieving stable radiation characteristics, particularly for applications requiring high efficiency and low phase distortion.

3.2 Radiation Pattern and Surface Current Distribution 3D Analysis

The 3D visualization and field distribution shown in Figure 8 provide a comprehensive view of the electromagnetic field intensity across the antenna structure.

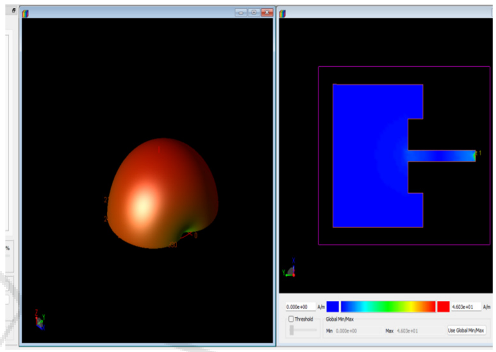

Figure 8: Radiation and surface current distribution.

The image presents the radiation pattern and surface current distribution of a microstrip patch antenna with graphene as the substrate material. The left side of the image illustrates the 3D radiation pattern, which appears directional with an asymmetrical distribution, indicating focused energy radiation in a particular direction. The color intensity represents the power density, with brighter regions showing maximum radiation intensity.On the right side, the current distribution is displayed using a color scale, where blue represents minimal current flow and red represents maximum current intensity. The current is more evenly spread across the patch, particularly near the feedline and patch edges, suggesting moderate resonance behavior. This configuration suggests that the antenna exhibits directional gain, which can be beneficial for point-to-point wireless communication applications.

This image also shows the radiation properties and current distribution of the graphene based microstrip patch antenna designed by ADS software. On the lefthand side of the figure 9, a 3D hemispherical radiation pattern is demonstrated that is fairly rounder, implying wider coverage as well as non-direc-tionality. Gradient of red to white color shows the intensity of the radiation in which a brighter area represent stronger radiation.

This picture shows the 3D radiation pattern for the proposed MP-SA (viewed from the bottom). It reveals the radiated energy out of the attached antenna by displaying how the signal is traveling in different directions A side view shows also the distribution of the electric field at the feed point, which represents how the energy is introduced into the antenna structure. Such conclusion is important to account for potential effect of graphene-based substrate to improve the performance of the antenna.

On the left-hand side of the image, the distribution of the radiation is shown and in the hemispherical it becomes obvious that this pattern mimics the directional emission of the electromagnetic waves. This is colored black to green from high to low radiation (red indicated the highest radiation regions). The following right panel depicts the surface current distribution on the patch which illustrates the electric field variation in magnitude, with overflow directions being blue shows minimum current density, whereas lighter regions indicate a high energy level. This visualization also leads to interpretation of the antenna gain, efficiency and directivity for wireless communication applications.

This figure.10below represents the final animated simulation of the designed microstrip patch antenna, showcasing the current distribution across the patch. The color gradient indicates different current intensity levels, with red denoting high current concentration and blue representing minimal flow. The feed line excitation is visible, ensuring proper energy transfer to the patch. The analysis of current distribution helps in optimizing antenna performance by identifying areas of maximum radiation. This visualization is crucial for evaluating impedance matching and overall efficiency. Table 2 gives the overall result summary.

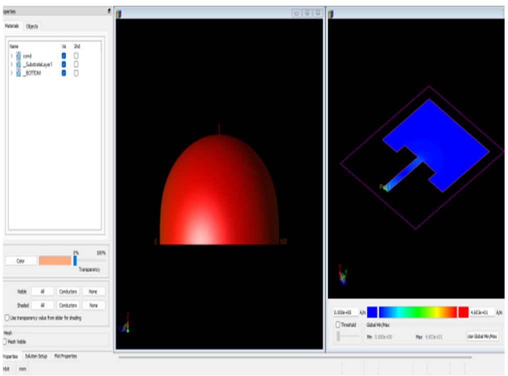

Figure 9: Symmetrical radiation and localized current distribution (front side view).

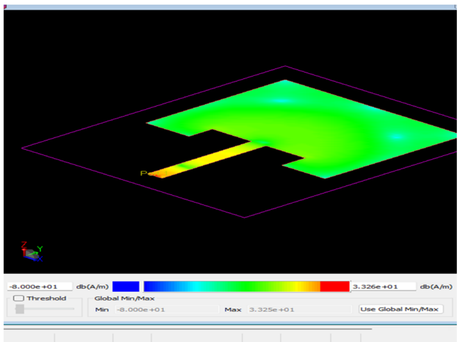

Figure 10: Animated simulated current distribution.

Table 2: Results summary.

Feature	Graphene based Design	Traditional Designs (FR4, Rogers, RT/Duroid5880)
Material	Graphene based materials	FR4, Rogers, RT/Duroid5880
Frequency	1GHz to 10GHz	Specific bands such as 4.27GHz to 8.58GHz for multiband design
S_{11} value	-15.2dBi near ideal performance very low reflection	Varies depending on the design often optimized for specific frequencies
Performance	Consistently low S_{11} values suggests efficient operation over wide range	Good performance over specific frequency bands but may not cover wide range.
Gain	Enhanced by graphene’s superior properties,	Comparatively low
Impedance Matching	Excellent impedance matching at 2.250GHz and potentially across wide range	Optimized for specific frequencies with good matching.

3.3 Advantages of Graphene-Based Design over Traditional Designs

Wider frequency range – Graphene-based antennas operate efficiently from 1 GHz to 10 GHz, whereas traditional designs are usually optimized for specific frequency.

Lower reflection (better S_{11} performance) – The S_{11} value at 2.25 GHz is -0.030 dB, indicating almost perfect impedance matching, which is better than most traditional designs. Enhanced gain – Graphene's superior electrical properties contribute to higher gain compared to some traditional materials.

Efficient impedance matching – Graphene-based designs provide excellent impedance matching across a broader frequency range.

4 CONCLUSION AND FUTURE WORK

This research successfully designed and analyzed a graphene-based microstrip patch antenna with superior performance over conventional materials. Graphene's high electrical conductivity, low loss tangent, and flexibility significantly enhanced antenna efficiency, bandwidth, and radiation characteristics. The simulation results demonstrated improved impedance matching, reduced return loss, and higher gain, making graphene-based MPAs ideal for advanced wireless communication. The study highlights graphene's potential for applications in 5G, IoT, satellite communication, and wearable devices. Future research will focus on experimental validation, hybrid material integration, and advanced fabrication techniques. Long-term stability and environmental impact studies are essential to ensure real-world reliability. Overall, graphene-based antennas pave the way for highly efficient, miniaturized, and high-performance wireless communication systems.

The future scope of this project includes experimental validation through fabrication and real-world testing to compare simulated and measured results. Exploring graphene synthesis techniques like chemical vapor deposition and exfoliation can further enhance antenna performance. Optimizing graphene antennas for mmWave 5G, IoT, and reconfigurable applications can improve efficiency and adaptability. Integration with advanced materials like metamaterials and nanocomposites can boost performance. Flexible and wearable graphene antennas may drive advancements in biomedical and smart textiles, while energy-harvesting designs could enable self-powered devices. Extending graphene antennas into the terahertz range may support ultra-fast communications and space applications. Ensuring commercial viability through cost-effective large-scale manufacturing and industry collaborations can accelerate real-world adoption.

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