IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.066 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 12, Issue 5, May 2025

DOI: 10.17148/IARJSET.2025.12507

AI-Driven Metasurface Assisted Graphene Based Reconfigurable Antenna For Terahertz Communication

Dr. Divya Gudapati[1], G. Sri Raja Rajeswari[2], M. Pavani[3]

Assistant Professor, Department of Electronics and Communication Engineering,

Bapatla Women's Engineering College, Bapatla, A.P, INDIA- 522101[1]

U. G Student, Department of Electronics and Communication Engineering,

Bapatla Women's Engineering College, Bapatla, A.P, INDIA-522101[2,3]

Abstract: This paper presents the performance enhancement of graphene-based pattern reconfigurable antennas for terahertz (THz) applications. An AI-driven metasurface assisted graphene antenna with adaptive beam steering is proposed. Unlike conventional designs that uses bias voltage control for beam reconfiguration, this method integrates a metasurface layer to enhance electromagnetic wave manipulation in the frequency range 4 - 6 THz, improving gain 16 dBi, bandwidth, and directionality. Additionally, an AI-based control system dynamically adjusts the chemical potential of graphene elements in real time, enabling continuous 360° beam steering instead of fixed beam states. The system utilizes Random Forest machine learning algorithm to predict optimal bias voltages based on environmental conditions, ensuring real-time adaptation for enhanced signal strength and reduced interference. This next-generation design provides higher gain, broader coverage, and intelligent beam adaptation, revolutionizing high-speed THz wireless communication for future smart networks.

Keywords: Graphene-based antenna, Pattern Reconfigurable Antenna, Terahertz (THz) communication, Wireless communication systems.

I. INTRODUCTION

Graphene is a semi conducting material that opens up new opportunities in making reconfigurable devices at terahertz frequency ranges [1]**.** The graphene is a 2-dimensional material consisting of a single layer sheet. It has a structure of atomic-scale honeycomb lattice made up of carbon atoms**.** The conductivity of graphene can be effectively controlled by changing the externally applied biasing voltage [2]. Hence, graphene technology has gained the spotlight by growing interest in potential applications including battery current collector, sensor, transistor, detector device, capacitor.
The terahertz (THz) spectrum has attracted considerable interest in numerous fields such as spectroscopy, sensing, imaging, communication, biomedical and space applications over the past few years**.** The THz band (01- 10THz) in the electromagnetic spectrum lies between millimeter and far-infrared (IR) band [3]**.** The THz spectrum attracted more attention in wireless communications due to the large bandwidth and high data rates. The large bandwidth in the order of THz opens the opportunity to transmit high data rate in the order of terabits per second (Tbps)**.** A meta-surface is a two-dimensional (2D) engineered material that can manipulate electromagnetic waves like light, microwaves, or radio wave sin ways that natural materials cannot.

A meta-surface is a specially engineered, ultra-thin material [4] designed to manipulate electromagnetic waves in ways that traditional materials cannot. Composed of arrays of tiny structures often smaller than the wavelength of light meta-surfaces can control the amplitude, phase, and polarization of incoming waves with remarkable precision. These surfaces act as a kind of optical "skin," enabling advanced functions such as beam steering, light focusing, holography, and even cloaking. Unlike conventional optical components [5] like lenses or mirrors, which rely on the gradual bending of light through bulk material, meta-surfaces achieve similar or superior effects on a much smaller scale, making them ideal for compact, lightweight technologies. Their tunability and versatility are paving the way for breakthroughs in fields ranging from imaging and communications to sensors and augmented reality.

A Random Forest Regression model is used to learn the complex mapping between chemical potentials and beam angles so that, when given a desired user direction, the meta-surface can automatically adjust itself to steer the EM beam smartly, efficiently, and in real time evaluated using MSE and R^2 metrics [6]. MSE measures the average of the squares of the errors that is, the average squared difference between the predicted values and the actual values [7]. The

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Impact Factor 8.066 ⅙ Peer-reviewed & Refereed journal ⅙ Vol. 12, Issue 5, May 2025

DOI: 10.17148/IARJSET.2025.12507

proposed AI-driven metasurface operates in the frequency range of 4 to 6 THz. A parametric analysis is conducted on the number of elements in the metasurface, and its performance is evaluated in terms of beam steering in both the E-plane and H-plane. The adaptability of the graphene-based metasurface for indoor and outdoor applications is also investigated. To predict the optimal chemical potential values of graphene at the resonant frequencies and corresponding beam angles toward the user direction, the Random Forest machine learning algorithm is employed, using Mean Square Error (MSE) and R^2 score as performance metrics.

II. DESIGN METHODOLOGY

By designing a conventional microstrip patch antenna using a substrate with a preperm dielectric material. Both the ground plane and the patch were modeled using gold. To enhance the antenna's gain, we then introduced a metasurface layer incorporating complementary split-ring resonators (CSRR). Following that, we designed another metasurface layer consisting of patch elements, placed at a distance of 25 micrometers above the original patch antenna. After completing the electromagnetic design, we integrated an AI-driven approach using the Random Forest algorithm. We employed Mean Squared Error (MSE) and R-squared (R^2) as performance metrics to evaluate and predict outcomes. Our model demonstrated that increasing the number of metasurface elements led to an increase in antenna gain and a shift in the resonant frequency toward user direction. The primary objective of this design is to ensure robust signal transmission and reception in both indoor and outdoor environments.

2.1 Design of Patch Antenna

A rectangular patch antenna with dimensions ($L_p \times W_p$) is etched on the grounded Preperm L570 substrate with dielectric constant $\epsilon_r = 5.7$ Gold metal with dimensions ($L_s \times W_s$) acts as the ground for the proposed design. The proposed antenna is depicted in Fig 1 and the dimensions are given in Table I.

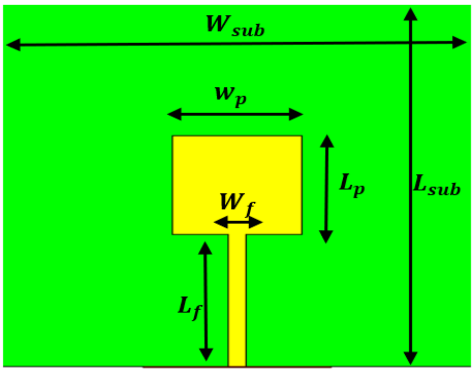

Fig 1: Simple patch antenna

Table 1: Dimensions of Geometrical structure of Patch antenna

Parameter	Description	Diameter (μ_m)
L_p	Length of the Patch	48
W_p	Width of the Patch	48
L_f	Length of the feed	95
W_f	Width of the feed	3.5
L_{sub}	Length of the substrate	192
w_{sub}	Width of the substrate	192
T_{sub}	Thickness of the substrate	5

The metasurface design begins with the selection of a suitable substrate to serve as the foundational layer. In this case, Preperm, a low-loss dielectric material recognized for its stability and excellent performance at high frequencies is chosen. A simple square patch made of graphene is then placed on top of the Preperm substrate. Graphene, a two-dimensional material with exceptional electrical and optical properties, is particularly advantageous for tunable metasurfaces due to its voltage-dependent conductivity.

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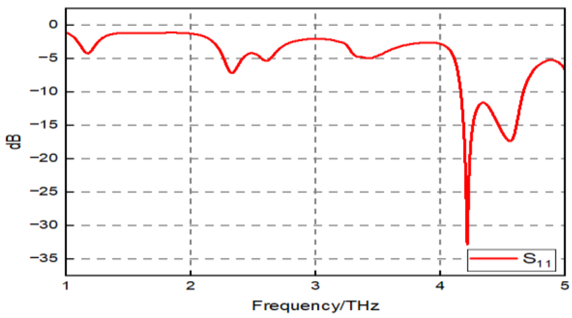
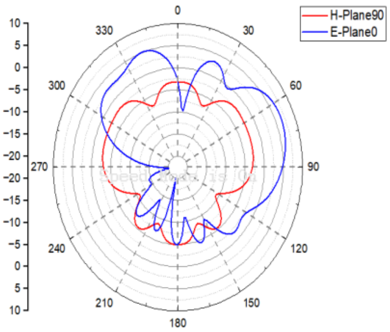


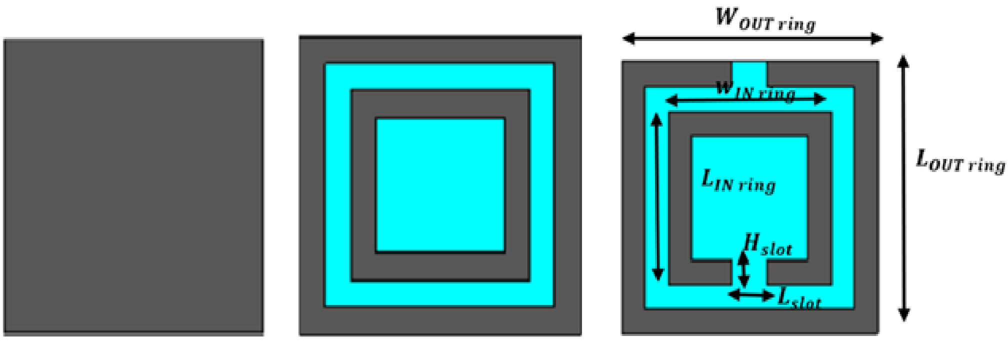
Fig(a): Return loss



Fig(b): Radiation Pattern

2.2 Evolution Stages of Metasurface Unit Cell

In the second stage of the design, a smaller square section is subtracted from the center of the graphene patch, resulting in a square ring structure. This transformation enhances the resonant behaviour of the unit cell by introducing stronger field confinement and sharper resonance. In the third stage, narrow slots are etched into the ring, forming a Complementary Split Ring Resonator (CSRR) configuration, shown in Fig 2. The CSRR not only enables precise control over the resonance characteristics and beam steering performance but also offers several key advantages: compact size, high Q-factor, strong electric field localization, and the ability to achieve negative permittivity. These features contribute to improved frequency selectivity, tunability, and enhanced electromagnetic response, making the metasurface highly suitable for advanced wave manipulation applications.



(a) Stage-1 (b) Stage-2 (c) Stage-3

Fig. 2. Evolution stages of metasurface unit cell

The dimensions of the unit cell are tabulated in Table II.

Table II: Dimensions of Evolution Stages of Meta-surface Unit Cell

Parameter	Description	Dimensions in (µm)
$L_{OUT\ ring}$	Length of outer ring	44
$W_{OUT\ ring}$	Width of outer ring	44
$L_{IN\ ring}$	Length of inner ring	28
$W_{IN\ ring}$	Width of inner ring	28
L_{slot}	Length of the slot	6
H_{slot}	Width of the slot	4

2.3 Evolution Stages of Graphene based Meta-Surface:

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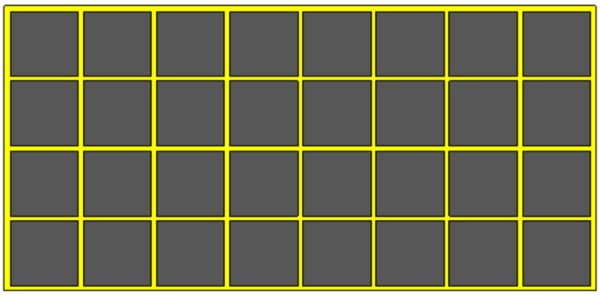
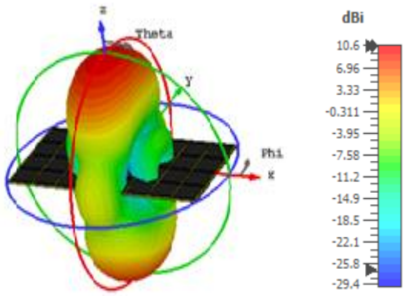
A complementary split-ring resonator (CSRR) is the negative (complementary) structure of a split-ring resonator (SRR), typically etched above the substrate. Complementary Split-Ring Resonators (CSRRs) are widely used in meta-surfaces because they offer precise control over the interaction between electromagnetic waves and engineered surfaces. CSRRs act as electrically resonant structures [8] that can produce negative effective permittivity at specific frequencies. This property allows meta-surfaces with CSRRs to manipulate electromagnetic waves in highly controlled ways, such as bending, filtering, absorbing, or redirecting them [9]. In a fully metallic metasurface design, the entire array is composed of metallic patches, removing the need for tunable materials like graphene. The design shown above features a periodic 2D array of square metallic patches, uniformly arranged on a dielectric substrate. A low-loss dielectric such as Preperm is used as the foundational layer, selected for its mechanical stability and reliable performance across microwave to millimeter-wave frequencies.

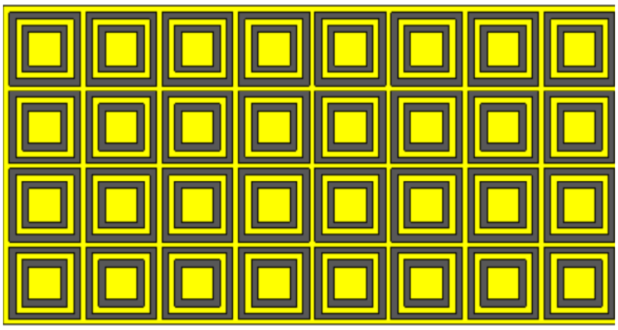
The substrate material is selected with a length 192 μ_m and a width 384 μ_m. Complementary Split Ring Resonator (CSRR) graphene patches are then placed on top of the substrate. Each patch has a length and width of 44 μ_m. A portion of each patch is subtracted to form the CSRR slots, with each slot having a length of 6 units. The distance between adjacent CSRR patches is 3.5 μ_m. In this design, a total of 4 rows and 8 columns of CSRR patches are arranged on the substrate. The evolution stages of graphene based metasurface and its corresponding gain is shown in Fig.3.



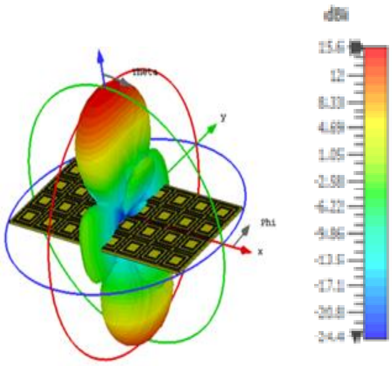
(a): Square Patch Graphene Metasurface



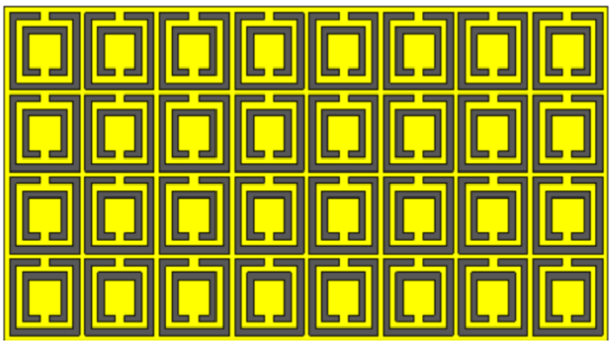
(b): 3D-Radiation pattern



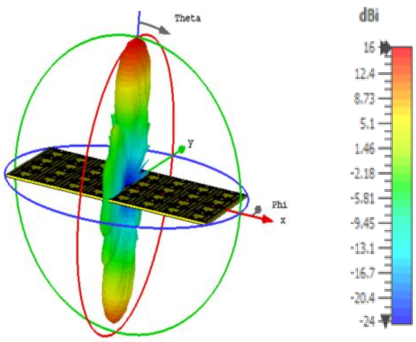
(c)Angular Ring Graphene based metasurfaces



(d): 3D Radiation Pattern



(e): CSRR Graphene based Meta Surfaces



(f): 3D Radiation Pattern

Fig. 3. Evolution stages of Graphene based metasurface

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Overall, it is observed that the gain value of CSRR metasurface has increased significantly compared to the square patch. This improvement in gain indicates better directivity and enhanced radiation efficiency of the antenna structure. Additionally, the radiation pattern shows a noticeable tilt, which suggests a shift in the main lobe direction. This tilting effect can be attributed to the arrangement and interaction of the CSRR graphene patches, as well as the coupling between the elements. Such behaviour is beneficial for applications requiring beam steering or directional control of the radiated

2.4 Positioning of Patch Antenna with Meta-surface

The image shows a front view of a schematic representing a layered structure, likely part of an antenna or metasurface design. A vertical air gap of 25 µm separates the top conductive layer from the bottom structure. This gap is intended to enhance electromagnetic coupling and improve the tuning characteristics of the device. The overall configuration suggests a stacked structure, which can contribute to improved gain, increased bandwidth, and beam tilting through constructive interference.

Fig.4. Front View of Patch Antenna with Meta-surface

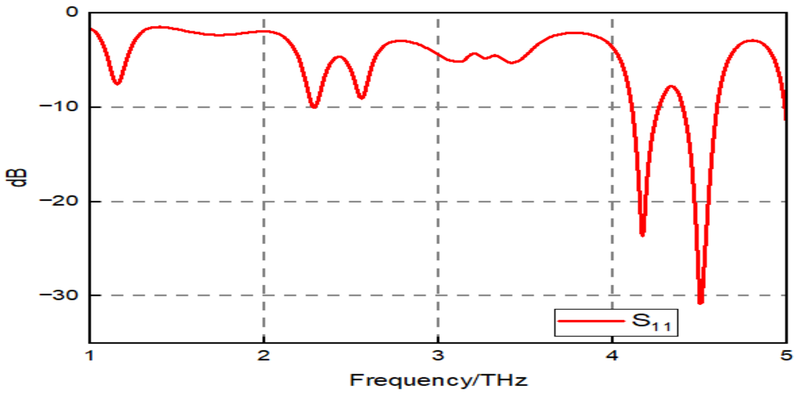
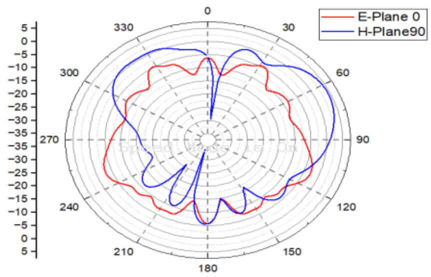
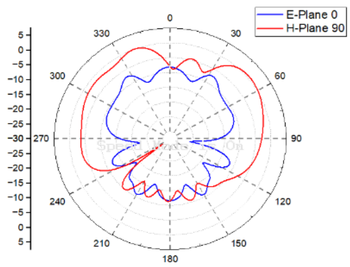


Fig.5. Return Loss Vs Frequency



Resonant Frequency at 4.17 THz



Resonant Frequency at 4.53 THz

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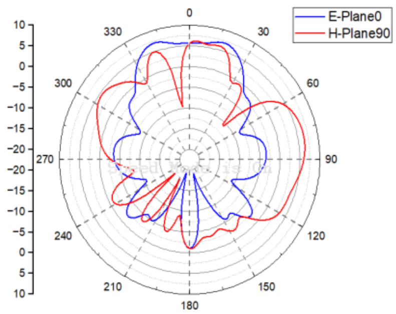
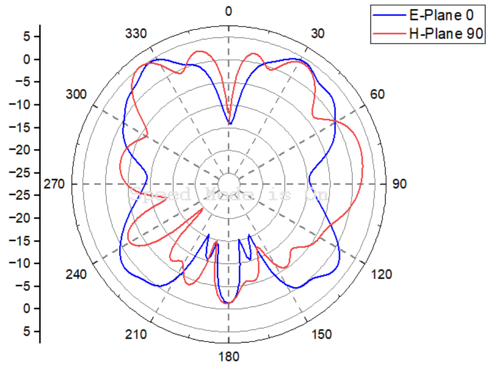


Resonant Frequency at 5.35 THz



Resonant Frequency at 5.73 THz

Fig .6. Radiation Patterns for E-plane & H-plane

2.5 Analysis of Graphene based Meta-surface

A graphene-based metasurface is a two-dimensional engineered structure that leverages the exceptional electromagnetic properties of graphene to precisely control the behaviour of electromagnetic waves. Owing to graphene's tunable conductivity, high carrier mobility, and compatibility with flexible substrates, these metasurfaces enable dynamic manipulation of wave propagation, reflection, absorption, and polarization. They are especially promising for terahertz and infrared frequency applications, supporting advanced functionalities such as beam steering, frequency tuning, and polarization control all within compact and lightweight configurations.

Chemical Potential on Graphene

$$\mu_C = \sqrt[hvf]{\frac{\pi e v g}{e}} \quad \ldots\ldots\ldots (1)$$

Where

μ_c = Chemical Potential
V_f = Fermi level
h = Height of the substrate
V_g = Voltage Bias

Table III: Different Chemical Potential Values Based on Different Environmental Condition

μc	**Voltage Bias V_g (Volts)**	**Environmental Condition**	**Reason**
0	0	Vaccum	No scattering
0.15	0.4	Sunny	Small compensation for signal integrity
0.25	0.6	Moderate Humidity	Consistent performance
0.35	0.6	Windy	Stronger
0.45	1.0	Dusty	Balanced voltage bias
0.55	0.9	Clean air	Higher mobility allows
0.68	0.5	Stable temperature	lower voltage bias
0.74	4.5	Low Humidity	clean air
0.85	0.3	Dust-free environment	High mobility of charge carriers
0.92	0.2	High humidity	Very low voltage bias
1	0.3	Dry environment	Maximum carrier mobility

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The table illustrates how the chemical potential (μc) and voltage bias (Vg) vary under different environmental conditions, influencing the performance of a graphene-based metasurface. Graphene's electronic properties are highly tunable through electrostatic biasing, and environmental factors such as humidity, temperature, and air quality affect the carrier mobility and scattering mechanisms**.**

III. RESULTS

The analysis shows that increasing the size of a metasurface by adding more rows and columns leads to more frequency bands and higher gain. Larger metasurfaces enable broader bandwidths and improved radiation performance due to enhanced electromagnetic interactions and a larger effective aperture. This confirms that geometrical scaling plays a crucial role in optimizing metasurface performance for applications like multi-band antennas and beam steering. For instance, Metasurface 1, which consists of 3 rows and 5 columns, exhibits a gain of 4.8 dB. When the size is increased to 4 rows and 8 columns in Metasurface 2, the gain improves to 5.5 dB. Similarly, Metasurface 3 with 5 rows and 12 columns shows a gain of 6.2 dB, and Metasurface 4 with 7 rows and 15 columns achieves the highest observed gain of 6.8 dB. This progressive increase in gain demonstrates that a larger number of elements contributes to a more focused and directional radiation pattern, thereby enhancing the overall antenna performance.

3.1 Results and Analysis of Patch Antenna with Meta-surface

(a)15 Elements

The presented structure is a graphene-based metasurface composed of 15 Complementary Split Ring Resonator (CSRR) elements arranged in a 3 × 5 grid three rows and five columns uniformly distributed across the substrate. The substrate, shown in yellow, has a width of Wsub = 248W and a length of Lsub =160. Each CSRR element consists of a square-shaped slot pattern. These periodic slots play a significant role in enabling the metasurface to control the phase, amplitude, and polarization of the waves. When implemented using tunable materials like graphene, the metasurface offers reconfigurable capabilities by adjusting the chemical potential through voltage bias. This allows for dynamic electromagnetic control, supporting functions such as beam steering, frequency filtering, gain enhancement, and wavefront shaping. At a resonant frequency of 4.51 THz, significant beam steering is observed in the E-plane, indicating a strong interaction between the electric field and the tunable material surface, such as graphene in a metasurface or antenna structure. In contrast, the H-plane exhibits maximum beam steering at a different frequency, specifically at 5.73 THz. This difference highlights the directional dependence of the beam steering behaviour. Overall, the most prominent beam steering effects in both planes occur within the 4 THz to 6 THz frequency range, demonstrating the effectiveness of chemical potential tuning for dynamic beam manipulation in this band.

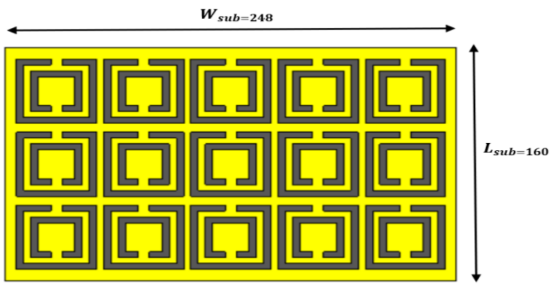

Fig.7. 15 Elements of CSSR Metasurface

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

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Table IV: Chemical Potential of Graphene on Beam Steering at Resonant Frequencies E- plane and H-Plane

μ_c	f_1=4.15	f_2=4.51	f_3=5.07	f_4=5.36	f_5=5.73	f_6=6.38	f_7=6.71
0	75	85	7	18	34	72	13
0.15	75	86	7	18	33	8	12
0.25	76	88	7	18	33	8	12
0.35	76	89	7	17	32	8	12
0.45	76	96	7	17	32	8	12
0.55	76	92	7	17	31	8	12
0.68	29	93	8	14	35	7	11
0.74	30	84	8	11	35	7	11
0.85	31	110	7	10	35	8	10
0.92	29	114	7	10	33	8	10
1	28	119	7	10	33	9	9

μ_c	f_1=4.15	f_2=4.51	f_3=5.07	f_4=5.36	f_5=5.73	f_6=6.38	f_7=6.71
0	67	51	57	72	42	33	53
0.15	68	52	58	73	42	33	53
0.25	68	52	58	73	42	33	53
0.35	68	52	58	74	31	33	53
0.45	68	52	58	74	31	33	54
0.55	69	53	58	75	30	33	54
0.68	69	53	58	75	30	33	54
0.74	69	54	58	72	29	33	54
0.85	70	54	58	72	28	33	54
0.92	70	54	58	72	27	33	55
1	70	55	59	72	26	33	55

(b) 32 Elements

The proposed structure is a graphene-based metasurface consisting of 32 Complementary Split Ring Resonator (CSRR) elements arranged in a 4 × 8 grid four rows and eight columns uniformly distributed across the substrate. The substrate, typically represented in yellow, is dimensioned to accommodate the full array with symmetrical placement and consistent spacing between elements is 3.5. Each CSRR unit features a square-shaped slot. These periodic structures enable precise control over wave characteristics such as phase shift and Pattern Reconfigurability. The larger 32-element array enhances the metasurfaces ability to generate sharper and more directional radiation patterns. When fabricated using graphene, the metasurface becomes dynamically reconfigurable by adjusting the chemical potential through voltage bias. This tunability allows for advanced functionalities including beam steering, frequency reconfiguration, gain improvement, and wavefront shaping. For a 32-element graphene-based metasurface, significant beam steering is observed in the E-plane at a resonant frequency of 4.17 THz, indicating a strong interaction between the electric field and the tunable material surface. In contrast, the H-plane shows maximum beam steering at a slightly higher frequency, specifically at 4.51 THz. This variation underscores the directional dependence of the beam steering behaviour, which is

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influenced by the anisotropic response of the structure and the differing roles of electric and magnetic field components. Overall, the most pronounced beam steering in both planes occurs within the 4 THz to 6 THz frequency range, confirming the effectiveness of chemical potential tuning for dynamic and reconfigurable beam control in terahertz applications.

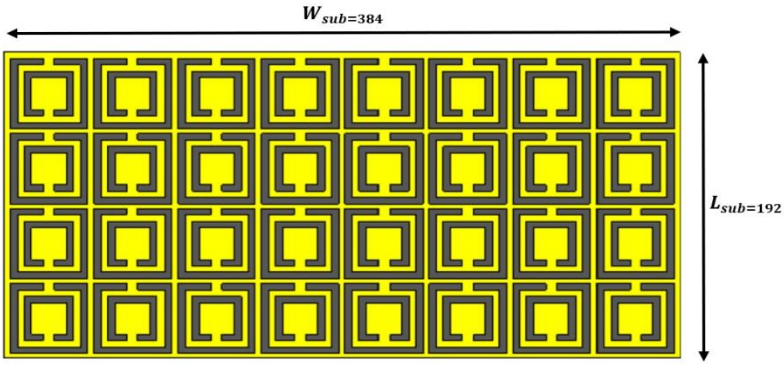

Fig.8. 32 Elements of CSSR Metasurface

Table V: Chemical Potential of Graphene on Beam Steering at Resonant Frequencies plane and H-Plane

μ_c	f_1=4.17	f_2=4.51	f_3=5.35	f_4=5.73
0	111	33	17	33
0.15	112	33	17	33
0.25	112	0	17	34
0.35	113	0	17	34
0.45	83	35	17	35
0.55	26	36	17	35
0.68	20	37	17	35
0.74	15	38	17	35
0.85	10	39	17	35
0.92	8	40	17	35
1	5	40	17	35

μ_c	f_1=4.17	f_2=4.51	f_3=5.35	f_4=5.73
0	64	51	79	37
0.15	64	51	79	37
0.25	64	51	79	37
0.35	64	52	79	37
0.45	63	52	79	37
0.55	62	55	80	37
0.68	61	57	80	37
0.74	60	58	80	37
0.85	59	59	80	37
0.92	59	60	80	37
1	57	61	80	37

(c) 60 Elements

The proposed structure is a graphene-based metasurface composed of 60 Complementary Split Ring Resonator (CSRR) elements arranged in a 5 × 12 grid with a uniform spacing of 3.5 units between elements. Each CSRR unit incorporates a square-shaped slot, enabling precise control over electromagnetic properties such as phase, amplitude, and polarization. The larger 60-element configuration significantly enhances the metasurface ability to generate sharper and more directional radiation patterns due to increased aperture size and element density. When fabricated using graphene, the metasurface becomes dynamically reconfigurable through chemical potential tuning via voltage bias, allowing advanced functionalities such as beam steering and frequency tuning. For this array, notable beam steering occurs in the E-plane at 4.15 THz, whereas the H-plane exhibits maximum beam steering at 5.37 THz, emphasizing the anisotropic response of the structure. The most effective beam manipulation is achieved within the 4 THz to 6 THz range, confirming the suitability of this design for high-performance terahertz systems.

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

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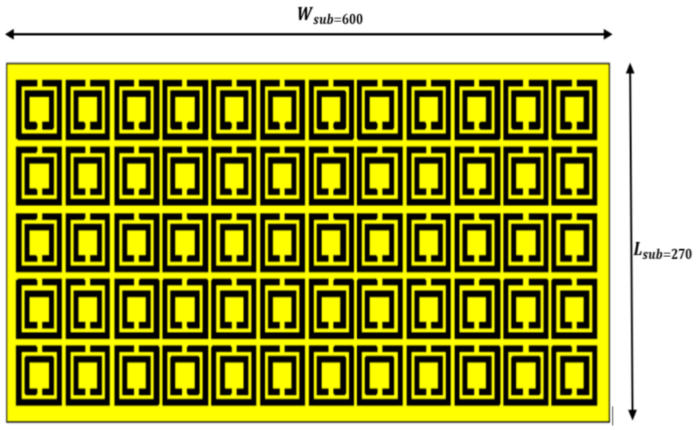

Fig.9. 60 Elements of CSSR Metasurface

Table VI: Chemical Potential of Graphene on Beam Steering at Resonant Frequencies E- plane and H-Plane

μ_c	f_1=4.15	f_2=4.51	f_3=5.37	f_4=6.41
0	74	4	20	180
0.15	134	0	18	80
0.25	135	0	59	18
0.35	136	0	18	18
0.45	137	0	18	180
0.55	139	0	18	180
0.68	140	1	18	180
0.74	141	1	18	180
0.85	142	2	18	180
0.92	143	2	18	180
1	144	2	18	180

μ_c	f_1=4.15	f_2=4.51	f_3=5.37	f_4=6.41
0	69	54	17	52
0.15	69	55	18	52
0.25	67	55	19	52
0.35	68	55	16	52
0.45	68	56	20	53
0.55	70	56	16	53
0.68	68	57	22	53
0.74	72	57	25	53
0.85	68	58	16	54
0.92	68	58	18	54
1	68	59	16	54

(d) 105 Elements

The proposed graphene-based metasurface consists of 105 CSRR elements arranged in a 7 × 15 grid with 3.5-unit spacing. Each square-slotted CSRR enables precise control over phase, amplitude, and polarization. The large array enhances directional radiation due to increased aperture and element density. With graphene-based tunability via chemical potential adjustment, the metasurface supports beam steering, frequency reconfiguration, and wavefront shaping. Notable steering occurs in the E-plane at 4.15 THz and in the H-plane at 5.37 THz, with optimal performance in the 4–6 THz range, making it ideal for advanced terahertz communication and sensing systems.

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IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.066 ⁙ Peer-reviewed & Refereed journal ⁙ Vol. 12, Issue 5, May 2025

DOI: 10.17148/IARJSET.2025.12507

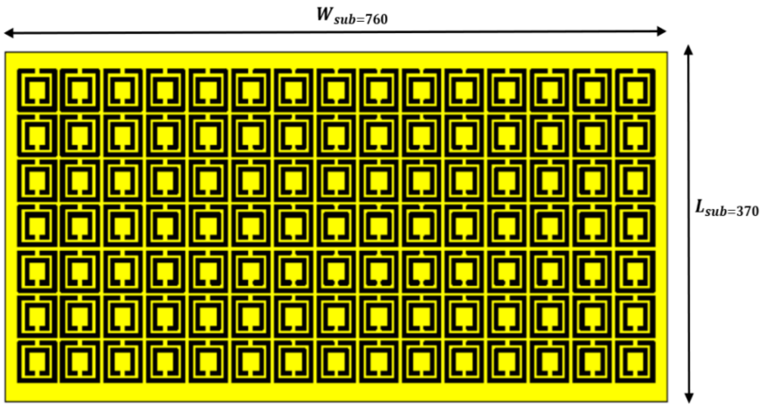

Fig.10. 105 Elements of CSSR Metasurface

Table VII: Chemical Potential of Graphene on Beam Steering at Resonant Frequencies E- plane and H-Plane

μ_c	f_1=4.15	f_2=4.51	f_3=5.36	f_4=5.65	f_5=6.42
0	111	0	20	36	180
0.15	139	0	20	36	180
0.25	140	0	20	35	180
0.35	0	0	20	35	180
0.45	0	0	20	35	180
0.55	144	0	19	36	180
0.68	145	11	19	36	180
0.74	146	1	19	36	180
0.85	147	1	19	36	180
0.92	148	2	19	36	180
1	149	2	19	36	180

μ_c	f_1=4.15	f_2=4.51	f_3=5.36	f_4=5.65	f_5=6.42
0	73	59	79	39	56
0.15	73	59	79	39	57
0.25	73	59	79	39	58
0.35	73	59	79	39	58
0.45	73	7	79	40	60
0.55	73	60	79	40	61
0.68	76	62	80	40	73
0.74	76	62	81	41	75
0.85	77	63	81	41	78
0.92	77	64	81	42	80
1	78	64	81	42	81

IV. AI-Driven Metasurface Assisted Graphene Based Reconfigurable Antenna for TeraHertz Communication

An AI-driven metasurface is a smart, reconfigurable electromagnetic surface that uses artificial intelligence (AI) algorithms to dynamically control how it interacts with electromagnetic waves. A metasurface itself is a two-dimensional array of engineered unit cells meta-atoms that can manipulate wave properties such as amplitude, phase, polarization, or direction in a controlled way. These properties are typically adjusted by tuning elements such as graphene, varactors, or MEMS switches within each unit cell. When AI is integrated, the system becomes adaptive and self-optimizing. The Random Forest Algorithm is a popular machine learning Algorithm method is used for both classification and Regression. Analyzes real-time data from the environment (like Normal Incidence, based on user direction, or signal strength) and determines the optimal metasurface configuration to achieve desired outcome. A Random Forest Regression model is used to learn the complex mapping between chemical potentials and beam angles so that, when given a desired user direction, the meta-surface can automatically adjust itself to steer the EM beam smartly, efficiently, and in real time evaluated using MSE and R^2 metrics. MSE measures the average of the squares of the errors that is, the average squared difference between the predicted values and the actual values.

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IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.066 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 12, Issue 5, May 2025

DOI: 10.17148/IARJSET.2025.12507

(e) 128 Elements

To predict the performance of the proposed graphene-based metasurface, a Random Forest algorithm is used by first defining a target output such as beam steering angle or resonant frequency and preparing a dataset with key design features like These features typically include the number of CSRR elements (128 in this case), the array configuration (8 × 16), the spacing between elements (3.5 units) array size, spacing, CSRR geometry, chemical potential, frequency, and polarization. The dataset is then split for training and testing, and a Random Forest regression model is trained to learn the complex relationships between inputs and outputs. This approach enables fast and accurate prediction of metasurface behaviour, reducing reliance on full-wave simulations and supporting efficient design optimization within the 4–6 THz range.

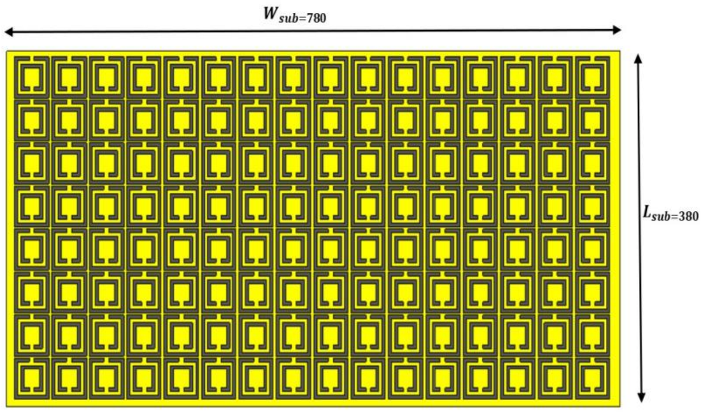

Fig.11. 128 Elements of CSSR Metasurface

Table VIII: Chemical Potential of Graphene on Beam Steering at Resonant Frequencies E- plane and H-Plane

μc	f_1=4.15	f_2=4.51	f_3=5.36	f_4=5.65	f_5=6.42
0	110	1	20	36	178
0.15	122	3	20	36	178
0.25	129	5	21	36	179
0.35	135	6	22	36	179
0.45	139	8	22	37	179
0.55	141	10	22	37	176
0.68	146	12	23	37	176
0.74	145	12	19	37	175
0.85	150	12	24	38	175
0.92	152	14	24	38	175
1	153	16	24	39	175

μc	f_1=4.15	f_2=4.51	f_3=5.36	f_4=5.65	f_5=6.42
0	105	2	18	34	172
0.15	118	4	19	35	173
0.25	126	6	20	35	174
0.35	132	7	21	35	174
0.45	137	9	22	36	175
0.55	140	11	23	36	172
0.68	144	13	24	37	171
0.74	143	13	28	37	171
0.85	148	14	30	38	171
0.92	150	16	33	38	171
1	151	18	36	39	171

(f) 200 Elements

The performance of AI prediction of the graphene-based metasurface with 200 CSRR elements can be effectively achieved using a Random Forest algorithm. The process begins by selecting a specific output to predict, such as the beam steering angle or resonant frequency. A comprehensive dataset is then constructed, incorporating essential design parameters including the total number of elements (200), the grid arrangement (10 × 20), inter-element spacing (3.5 units), detailed CSRR geometry, the chemical potential of the graphene layer, the operating frequency, and the polarization of

IARJSET
ISSN (O) 2393-8021, ISSN (P) 2394-1588
International Advanced Research Journal in Science, Engineering and Technology
Impact Factor 8.066 ⁑ Peer-reviewed & Refereed journal ⁑ Vol. 12, Issue 5, May 2025
DOI: 10.17148/IARJSET.2025.12507

the incoming wave. After preparing the dataset, it is split into training and testing subsets to develop and validate the model. The Random Forest regression algorithm is trained on this data to learn the intricate dependencies between the design features and the desired output. This machine learning technique enables accurate and rapid predictions, significantly reducing reliance on computationally expensive full-wave simulations, and facilitates efficient metasurface design within the targeted 4–6 THz terahertz band.

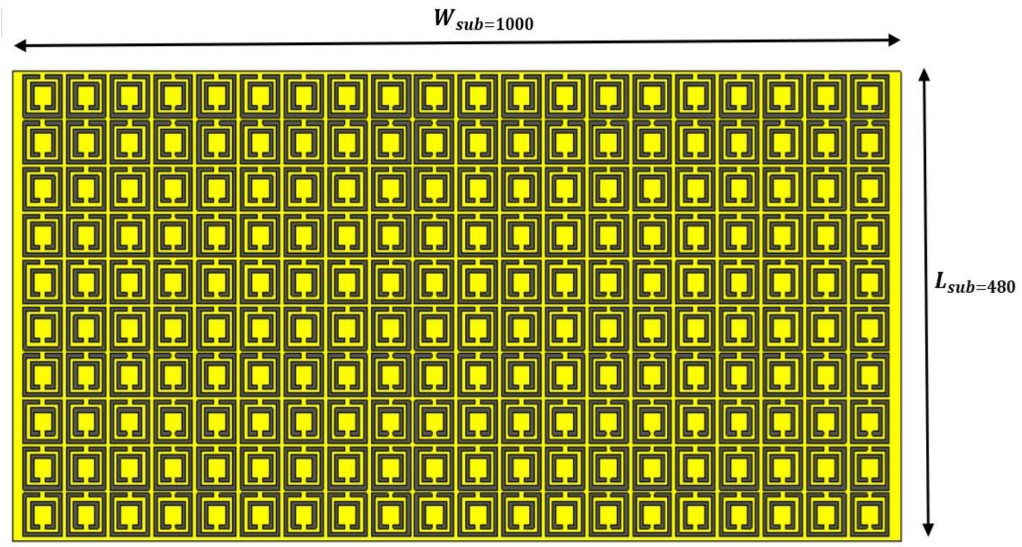

Fig.12. 200 Elements of CSSR Metasurface

Table IX: Chemical Potential of Graphene on Beam Steering at Resonant Frequencies E- plane and H-Plane

μc	f_1=4.15	f_2=4.51	f_3=5.07	f_4=5.36	f_5=5.73
0	112	0	18	35	152
0.15	112	2	18	35	152
0.25	114	2	18	35	153
0.35	120	2	19	37	153
0.45	123	5	19	37	153
0.55	126	6	19	38	154
0.68	130	6	22	38	154
0.74	134	6	22	38	154
0.85	137	8	22	39	156
0.92	141	8	23	39	157
1	142	8	23	39	157

μc	f_1=4.15	f_2=4.51	f_3=5.07	f_4=5.36	f_5=5.73
0	108	1	16	33	148
0.15	110	3	17	33	149
0.25	112	3	17	34	150
0.35	117	4	18	35	150
0.45	120	6	18	36	151
0.55	124	7	19	37	151
0.68	127	7	21	37	152
0.74	130	8	21	38	152
0.85	134	9	22	38	154
0.92	137	10	23	39	155
1	139	10	23	39	155

(g) 256 Elements

Predicting the performance of a graphene-based metasurface with 256 CSRR elements can be accomplished using a Random Forest algorithm, a powerful machine learning technique. The process starts by selecting a specific output to forecast such as the beam steering angle or the resonant frequency based on the metasurface's design objectives. A detailed dataset is created, incorporating crucial parameters such as the number of CSRR elements (256), their configuration in a 16 × 16 grid, consistent spacing of 3.5 units, the physical structure of each CSRR, the graphene's tunable chemical potential, the operational frequency, and the polarization characteristics of the incident wave. This

DOI: 10.17148/IARJSET.2025.12507

dataset is then split into training and testing portions, allowing the model to learn from a portion of the data and validate its predictions on the rest. The Random Forest regression model is trained to uncover and model the nonlinear relationships between these input variables and the desired electromagnetic responses.

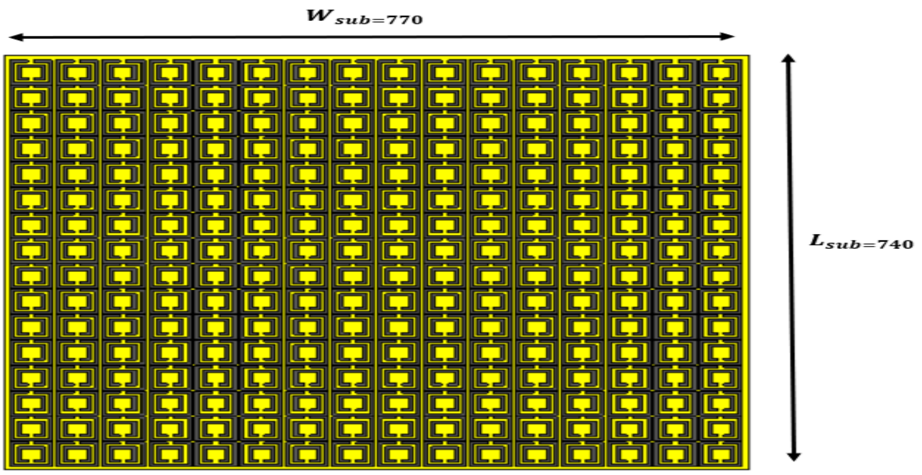

Fig.13. 256 Elements of CSSR Metasurface

Table X: Chemical Potential of Graphene on Beam Steering at Resonant Frequencies E- plane and H-Plane

μ_c	f_1=4.15	f_2=4.51	f_3=5.36	f_4=5.65
0	110	5	34	178
0.15	111	8	34	178
0.25	117	11	34	179
0.35	131	14	35	172
0.45	140	18	35	173
0.55	150	22	35	173
0.68	162	26	38	174
0.74	174	31	38	174
0.85	187	36	39	174
0.92	201	41	40	175
1	208	43	40	175

μ_c	f_1=4.15	f_2=4.51	f_3=5.36	f_4=5.65
0	106	2	31	172
0.15	109	6	32	172
0.25	115	9	33	173
0.35	128	12	34	173
0.45	136	16	35	174
0.55	145	19	36	174
0.68	155	23	36	175
0.74	167	28	37	175
0.85	179	32	38	176
0.92	193	36	38	176
1	200	39	39	177

V. CONCLUSION

In this work, an AI-driven metasurface-assisted graphene-based reconfigurable antenna for terahertz (THz) communications has been explored and demonstrated by leveraging the unique tunable properties of graphene, combined with the dynamic control offered by metasurface, High efficiency, and beam steering capabilities. The simulation work is carried out by investigation 15, 32, 60 and 105 elements at various chemical potentials 0, 0.15, 0.25, 0.35, 0.45, 0.55, 0.68, 0.74, 0.85, 0.92, 1 It is observed that for 32 elements optimal beam steering is achieved in E plane at 4.17 THz frequency and H-plane is at 4.51 THz frequency. The integration of artificial intelligence optimizes performance in real time. Random Forest Machine learning algorithm is used to predict the beam angles in E and H planes of 128, 200 and 256 elements metasurface for the same chemical potential and frequencies. This approach not only overcomes many of the limitations associated with conventional THz antennas energy-efficient, and highly flexible THz communication networks.

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.066 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 12, Issue 5, May 2025

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