A Project Internship Report on

# Multiphase Unit Cell Design with Multi-Focus Generation for Multi-Target Wireless Power Transfer Application

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This is to certify that this report of Project Internship on "Design of Highly Efficient Wireless Power Transfer System Utilizing Metasurface Integrated Planar Antenna for IOT Application" is a record of work done by Ambika Acharya (Project Intern, B.Tech, $8^{th}$ Semester, St. Thomas' College of Engineering & Technology) during $12^{th}$ March to $12^{th}$ May.

In my opinion, this report in its present form is in partial fulfilment of all the requirements, as specified by Institution of Radio Physics and Electronics and as per regulations of the University of Calcutta. To the best of my knowledge, the results embodied in this report, are original in nature.

Date: 12/05/2025
Place: Kolkata

Dr. Kaushik Mandal

Assistant Professor
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# ACKNOWLEDGEMENT

I would like to express my heartfelt gratitude for the invaluable opportunity to work on the project entitled "Design of Highly Efficient Wireless Power Transfer System Utilizing Metasurface Integrated Planar Antenna for IOT Application" at Raja bazar Science College. Being a part of this advanced and intellectually stimulating research endeavor has been a truly rewarding experience that has significantly enriched my academic and technical understanding. I am sincerely thankful to my mentor, Dr. Kaushik Mandal, for his dedicated mentorship, insightful feedBack, and unwavering support throughout the course of the project. His expertise and patience have played a crucial role in guiding me through the complexities of metasurface design. I would also like to extend my profound thanks to Mr. Nilanjan Dutta, Ms. Shrabani Mukherjee, and Ms. Sourasami Nandi, whose valuable suggestions, expert guidance, and continuous encouragement greatly contributed to the successful progression of this research. Their collective insights and academic rigor helped me understand the underlying principles of electromagnetic wave manipulation and designing engineered metasurfaces.

This project has offered me the opportunity to explore cutting-edge concepts in electromagnetic wave theory and practical design simulations, which will serve as a strong foundation for my future academic and professional pursuits. I am deeply grateful for the collaborative environment and the chance to engage in such meaningful scientific exploration.

I would like to thank the professors, staffs and scholars for their valuable suggestions & kind cooperation.

Ambika Acharya

(Ambika Acharya)

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# ABSTRACT

With the rapid proliferation of Internet of Things (IoT) devices, there is an increasing need for efficient, compact, and wireless power delivery solutions that can operate seamlessly across a wide range of environments. Conventional battery-powered systems face challenges related to maintenance, limited lifespan, and environmental concerns. In response to these limitations, this project focuses on the design of a highly efficient Wireless Power Transfer (WPT) system incorporating a metasurface-integrated planar antenna. The integration of a metasurface—a structured, sub-wavelength engineered surface—enhances the system's electromagnetic wave manipulation capabilities, resulting in focused energy transmission and improved coupling efficiency between the transmitter and receiver units.

The proposed design leverages the compact and low-profile nature of planar antennas, which are ideal for integration in IoT systems due to their lightweight and easily manufacturable structure. By embedding a carefully optimized metasurface layer with the antenna structure, the system exhibits significant improvements in gain, directivity, and transmission range while maintaining minimal power loss. Full-wave electromagnetic simulations are conducted using CST Microwave Studio to validate the design parameters, evaluate the radiation characteristics, and optimize performance metrics such as return loss, S-parameters, and power transfer efficiency.

Simulation results reveal that the metasurface integration not only enhances the near-field focusing capabilities but also contributes to better impedance matching and reduced backscattering, thereby ensuring stable and high-efficiency power delivery. The proposed system demonstrates a promising pathway for next-generation IoT deployments where wireless, maintenance-free, and sustainable power solutions are essential. This work contributes to the advancement of WPT technologies by offering a practical and scalable solution suitable for dense IoT networks, smart sensors, and other wireless embedded systems.

# MOTIVATION

- The increasing number of IoT devices requires efficient, low-maintenance power delivery solutions.
- Conventional battery-powered systems are limited by short lifespan, frequent replacement, and environmental impact.
- Wireless Power Transfer (WPT) can eliminate the need for physical connectors and battery replacement, enabling uninterrupted operation.
- Existing WPT systems face challenges such as low power transfer efficiency, limited range, and bulky designs.
- Metasurfaces offer enhanced control over electromagnetic waves, enabling better focusing and directionality in power transmission.

# OBJECTIVES

- To design a compact, low-profile planar antenna tailored for efficient wireless power transmission in IoT environments.
- To integrate a metasurface layer with the antenna to enhance near-field energy focusing and directional power delivery.
- To optimize the metasurface geometry and material properties for maximum power transfer efficiency and minimal losses.
- To simulate and validate the electromagnetic performance of the system using CST Microwave Studio or equivalent tools.
- To evaluate key performance metrics, including gain, return loss, S-parameters, bandwidth, and radiation efficiency.
- To perform parametric studies to analyse the impact of metasurface design variables on system performance.

# CHAPTER 1

# INTRODUCTION

The continuous evolution of wireless communication and energy systems has necessitated the development of novel approaches for efficient electromagnetic wave manipulation. Among these, metasurfaces, which are two-dimensional equivalents of metamaterials, have emerged as a promising solution due to their ability to control wavefronts with subwavelength spatial resolution. The concept of a metasurface hinges on structuring materials at a scale smaller than the operating wavelength, enabling unprecedented control over the phase, amplitude, and polarization of electromagnetic (EM) waves.

In the context of high-power wireless energy transfer, metasurfaces can play a pivotal role by directing energy precisely to desired locations through beamforming. Unlike traditional antenna arrays, metasurfaces offer ultra-thin, lightweight, and low-loss platforms for achieving such functionality. One of the critical innovations in this field is the development of multibeam metasurfaces, which can generate multiple directed beams from a single surface. These systems are particularly beneficial for applications involving simultaneous wireless power transfer (SWPT) to multiple receivers, thereby enhancing efficiency and coverage.

The focus of this report is to explore a highly efficient multibeam metasurface designed for high power transfer, operating at gigahertz (GHz) frequencies. The design leverages a novel metaatom structure, which enables multiple resonance modes and precise phase manipulation. By simulating and analysing this structure, we aim to demonstrate its potential for practical high-power WPT systems. The figure is shown in figure 1.

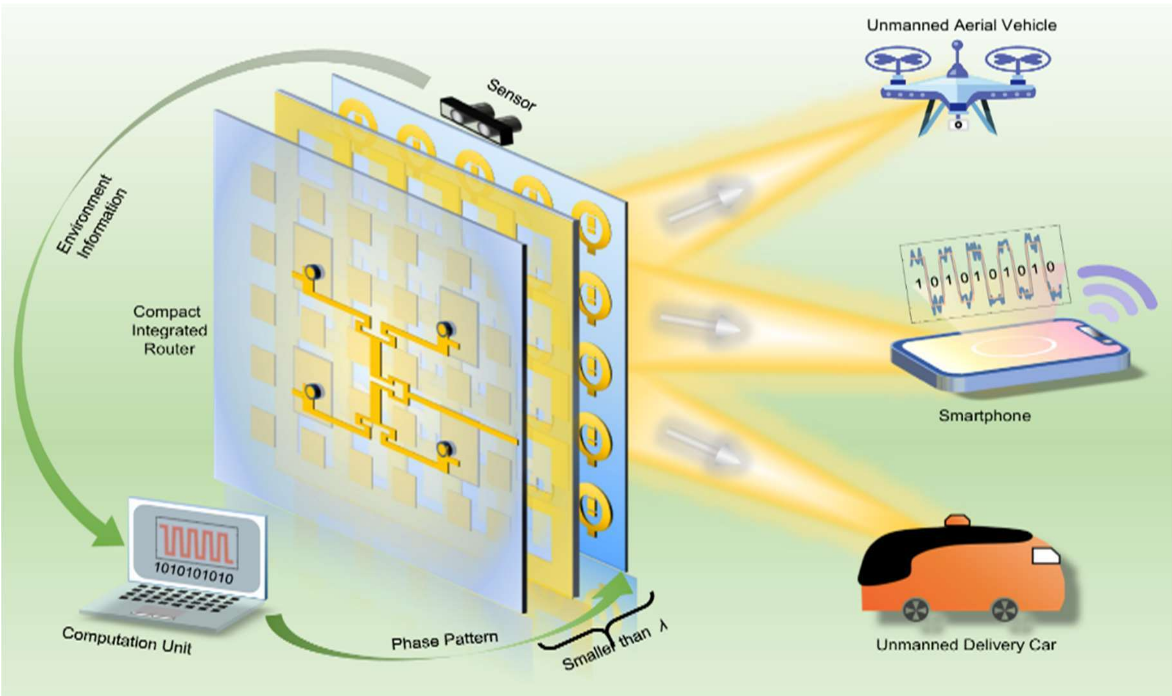



**Figure 1:** The Summary of the Entire Project

### *1.1 Importance of Metasurface-Enabled Wireless Energy and Information Transfer:*

The advancement of wireless energy and communication systems has led to increased interest in technologies that can simultaneously transmit power and data. A recent approach based on anisotropic metasurfaces allows for multitarget simultaneous wireless information and power transfer (SWIPT), offering a field-synthesis method to direct energy and data independently to multiple users [1]. Such methods demonstrate that metasurfaces are not limited to beamforming alone—they are also capable of joint energy and data modulation, which is vital for integrated next-generation systems. Building on this, metasurfaces can be configured to produce quasi-Bessel beams with large half-power beam lengths, which are beneficial for multitarget wireless power transfer (WPT) systems. These beams exhibit extended focus regions and maintain high intensity over longer ranges, enhancing spatial coverage and energy concentration [2]. This enables metasurfaces to deliver power more efficiently to distributed Internet of Things (IoT) nodes.

### *1.2 Beam Generation:*

Further refinement of this idea involves using metasurface holography to generate multiple focal beams with high spatial precision. Wu et al. demonstrated that by encoding specific phase maps across a metasurface, one can simultaneously form multiple beams directed at different targets—a strategy especially beneficial for dynamic and multitarget WPT systems [3]. Additionally, programmable metasurfaces have shown promise for discrete nondiffractive beam generation. Qu et al. developed a system where a single surface could switch between multiple target beams, each retaining strong directionality and minimized diffraction. This approach supports the idea of on-demand, user-specific beam creation in dense communication environments [4].

### *1.3 Areas of Work:*

<u>Biomedical Applications and Impedance Matching</u>
In parallel, metasurfaces have demonstrated significant promise in biomedical fields. Dellabate et al. designed a metasurface for impedance matching in microwave-based medical devices, improving energy transfer into tissue while minimizing reflection losses. This highlights the versatility of metasurfaces for both communication and sensing in complex environments [6].

<u>Multibeam Holographic Metasurface Antennas</u>
The holographic theory of metasurface design has also enabled the creation of antennas that produce independently steerable beams. Kampouridou and Feresidis presented a holographic multibeam antenna that uses impedance modulation and reconfigurable diodes to dynamically redirect radiation at GHz frequencies—a key inspiration for this report's metasurface concept [7].

<u>High-Gain, Multibeam Systems for GHz Power Delivery</u>
The capacity of metasurfaces to generate multiple high-gain directive beams from a single surface has been further confirmed in foundational works like González-Ovejero et al., where multiple beams

were created with low sidelobe levels and high directivity, forming the baseline architecture for multitarget GHz power transfer systems [8].

### Flat Optics and Subwavelength Phase Control

These multibeam capabilities are made possible due to the flat-optics nature of metasurfaces. By engineering subwavelength-scale unit cells—called metaatoms—designers can manipulate electromagnetic wavefronts with extreme precision. Yu and Capasso's work established this concept, demonstrating unprecedented control of phase, amplitude, and polarization using ultra-thin surfaces [9].

### Frequency-Controlled Beam Scanning

Moreover, frequency-tunable metasurfaces allow control over multibeam scanning without mechanical movement. Li et al. presented a frequency-controlled multibeam metasurface system capable of real-time directional steering by varying the input frequency [10].

### Dynamic Reconfigurability and Reflectarrays

Hum and Perruisseau-Carrier emphasized the importance of dynamic control in metasurface-based reflectarrays. Their review outlined several hardware-level methods to achieve real-time tunability of beam direction and amplitude, making metasurfaces highly adaptable to changing environments [11].

### Planar Light Manipulation at Microwave Frequencies

The fundamental concept of flat optics with designer metasurfaces, reiterated by Yu and Capasso, underpins the development of efficient, compact antenna systems. Their work supports the scalability of these designs into GHz and higher frequency regimes with minimal bulk [12].

### Multifunctional Beam Steering and Power Combining

Multibeam metasurface antennas, such as those explored by González-Ovejero et al., combine multiple directional outputs into a single metasurface platform. This configuration is ideal for scalable wireless power transfer with independent target control [13].

### BroadBand Operation and High-Efficiency Beam Control

High-efficiency wavefront control across a broad bandwidth is also achievable with specially designed metasurfaces. Li et al. demonstrated this in the GHz regime, showing how broadBand response and low insertion loss can improve power delivery across varied channels [14].

### Use in 5G and Millimeter-Wave Networks

The adoption of metasurfaces in 5G infrastructure has validated their relevance for future GHz-band wireless systems. As described by Hong et al., metasurfaces enable flexible beam steering, space-division multiplexing, and compact antenna arrays for dense urban networks [15].

## CHAPTER 2

## LITERATURE SURVEY

- ***Summary of the Selected Works***
  - The work in [1] presents a novel multitarget Simultaneous Wireless Information and Power Transfer (SWIPT) scheme using anisotropy-metasurface field synthesis. The researchers designed anisotropic metasurface units capable of independently modulating dual-polarization waves, allowing x-polarization waves to carry wireless power and y-polarization waves to carry information simultaneously to multiple targets. The paper details two metasurface designs: a Single-Feed and Multiple-Focus (SFMF) metasurface and a Dual-Feed and Multiple-Focus (DFMF) metasurface, both achieving over 40% total transfer efficiency while creating multiple focal points in space. Additionally, they developed a dual-polarization and dual-port receiving antenna array to effectively separate the power and information components in SWIPT systems. The approach uses polarization diversity to enable simple separation of power and information signals, providing an efficient solution for multitarget wireless power and information transfer in 5G/6G applications where numerous wireless devices require both power supply and communication capabilities.

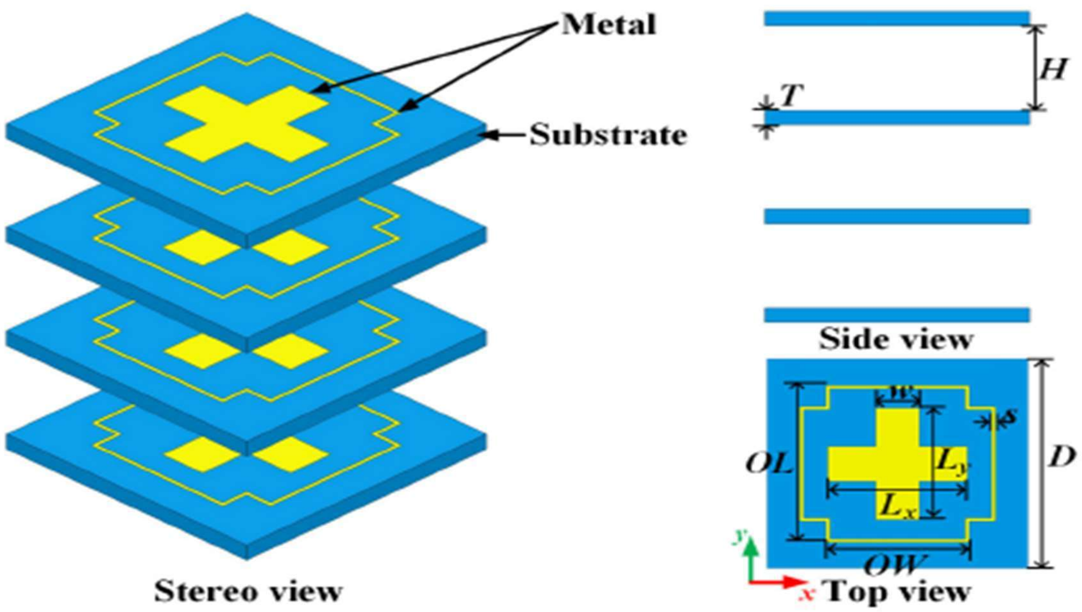



**Figure 1:** Plus-shaped metaatom

  - In [2] the collection of papers presents innovative advancements in wireless power transfer (WPT) and antenna technologies utilizing metasurfaces. Key contributions include a multitarget WPT system employing quasi-Bessel beams for uniform energy distribution, enhancing efficiency for multiple targets; a metasurface capable of generating multifocal beams for simultaneous power and information transfer; and the design of compact antennas with high gain and circular polarization for biomedical applications. Additionally, several papers explore programmable metasurfaces for multibeam shaping, liquid crystal-based reflect array antennas for 6G applications, and the integration of metasurfaces with integrated circuits to improve telecommunications. Overall, these studies highlight the potential of metasurfaces in enhancing wireless energy transmission and communication systems, paving the way for more efficient and versatile applications in modern technology.

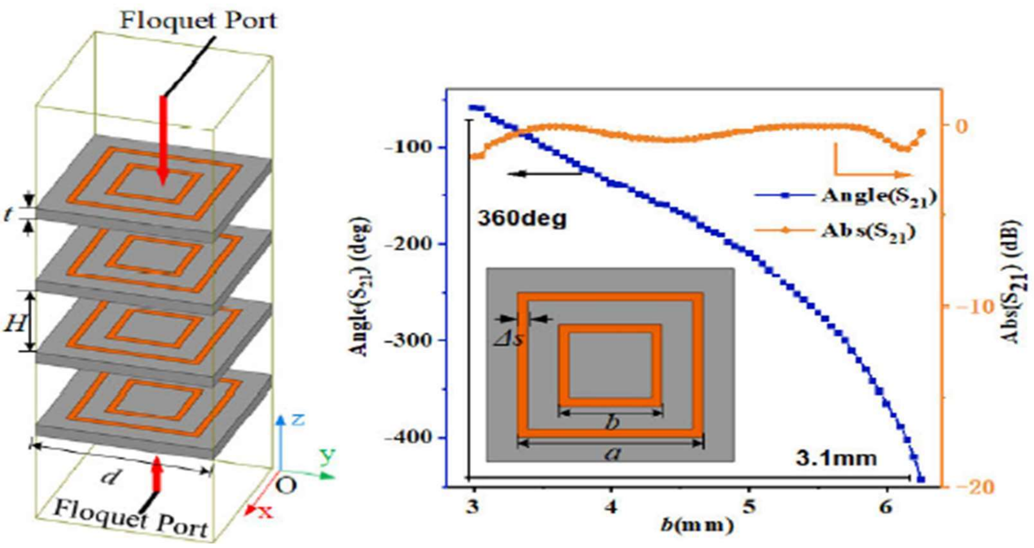



**Figure 2:** Ring-shaped metaatom

- In [3] the paper titled "Multitarget Wireless Power Transfer System Strategy Based on Metasurface-Holography Multifocal Beams" investigates a multitarget wireless power transfer (WPT) system that utilizes metasurface-holography to generate multifocal beams. It introduces a new field calculation formula derived from the Friis formula, which overcomes the limitations of paraxial approximation, enabling effective power transfer in wide-angle, long-distance, and non-planar scenarios. The study details the design of a metasurface that radiates a multifocal beam, allowing for uniform power distribution to multiple targets. Simulation results demonstrate the system's capability to achieve high efficiency and effective energy convergence at various focal points, confirming the proposed method's feasibility for practical applications in powering multiple wireless devices simultaneously.

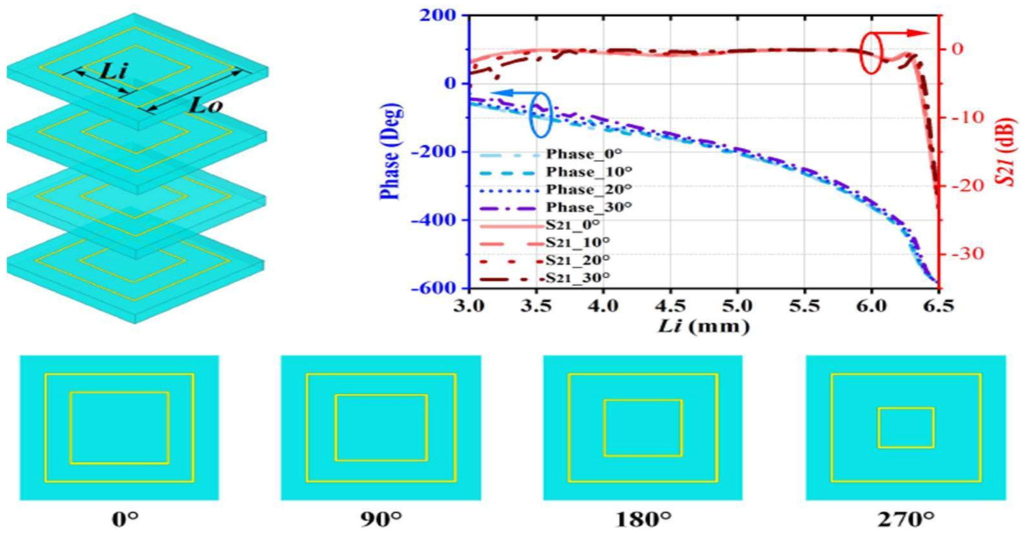



**Figure 3:** layers if square shaped meta-atom

- In the work [4], the paper titled "Generation of Discrete Nondiffractive Beams Based on Programmable Metasurface for Multitarget Communications" presents a novel programmable transmissive metasurface designed to generate discrete nondiffractive beams, which can deliver consistent power to multiple targets. The authors calculate the phase distribution of a Bessel beam with arbitrary deflection and employ binary modulation to transform it into a nondiffractive beam with discrete focusing lines. By utilizing different coding matrices, the metasurface can deflect the generated beam in any direction. The study includes the construction and fabrication of a 31 × 31 supercell array, demonstrating its ability to produce discrete diffraction-free beams in various transmission directions. Experimental results confirm that the communication quality remains consistent even when obstacles block some targets, addressing challenges related to path loss. The proposed design holds promise for applications in secure communication and energy transmission across multiple targets.

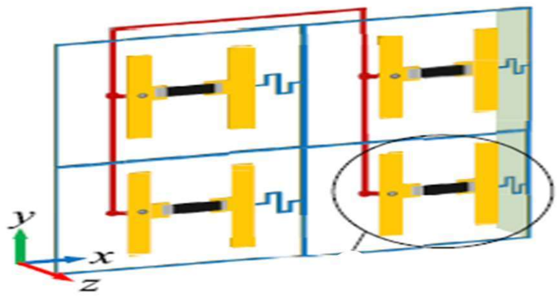



**Figure 4:** H shaped metaatom

- In [5] the paper titled "A F-shaped Gigahertz Chiral Metasurface with a High Circular Dichroism" proposes a novel chiral metasurface designed for detecting circular polarization and biological macromolecules. The metasurface consists of a three-layer structure featuring an F-shaped metal design, a dielectric substrate, and a metal ground plane. It achieves a strong circular dichroism (CD) of 0.82, indicating significant differences in absorption between right-handed circularly polarized (RCP) and left-handed circularly polarized (LCP) waves. The study highlights the potential applications of this metasurface in biosensing and the detection of circular polarization, emphasizing its advantages over natural materials in producing stronger chiral responses. The findings suggest that this chiral Gigahertz metasurface could play a crucial role in advancing detection technologies in various scientific fields.

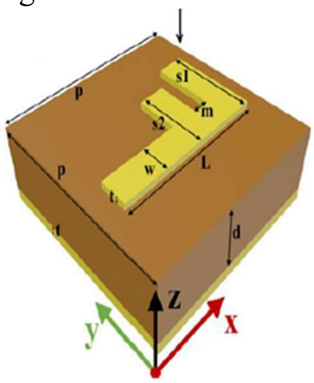



**Figure 5:** F-shaped metaatom

- In [6] The paper titled "An Electromagnetic Metasurface for Impedance Matching in Microwave Biomedical Applications" presents the design of a metasurface aimed at enhancing electric field transmission within the human body for microwave imaging and sensing applications. Utilizing a transmission line model, the authors tailor the metasurface properties to compensate for the impedance mismatch between air and biological tissues, thereby minimizing reflection at the air-tissue interface. Through comprehensive full-wave simulations, the study demonstrates that the proposed metasurface can achieve a significant improvement in the transmitted electric field, with a maximum enhancement of 6.6 dB at a frequency of 1.61 GHz. The compact dimensions of the metasurface (56 mm × 56 mm) make it suitable for various anatomical applications, indicating its potential to improve the safety and effectiveness of microwave biomedical devices.

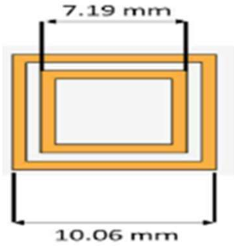



**Figure 6:** Square Shaped metaatom

- In [7] presents a novel design for a multibeam holographic metasurface antenna that can independently steer multiple directive beams at microwave frequencies, particularly around 7.4 GHz. By leveraging holographic theory, the surface impedance of the metasurface is synthesized through the linear superposition of individual beam impedance modulations. Each unit cell in the metasurface incorporates a low-loss varactor diode, allowing dynamic reconfiguration of surface reactance via bias voltage control. Simulations using CST software confirm that the antenna can steer one beam independently while keeping the other fixed, with minimal angular deviation from theoretical targets. The design demonstrates low side lobe levels and satisfactory beam gain, making it a promising candidate for advanced wireless communication systems requiring flexible and efficient multibeam radiation.

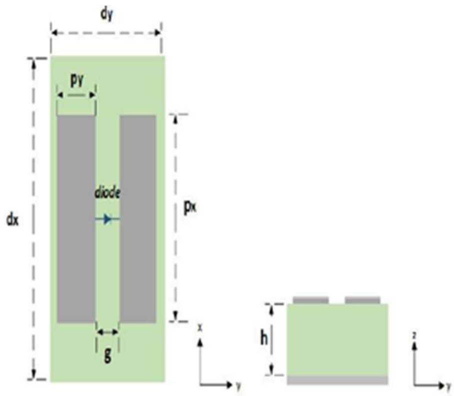



**Figure 7:** Holographic Antennas

# CHAPTER 3

# DESIGN & ANALYSIS

### 3.1 PHASE MAP:

This project focuses on designing a compact, efficient Wireless Power Transfer (WPT) system using a metasurface-integrated planar antenna, specifically for IoT applications. Traditional WPT systems often suffer from limited range and low power transfer efficiency[30],[31]. By integrating a metasurface composed of engineered metaatoms, the antenna's radiation can be precisely controlled to enhance directionality and focusing of electromagnetic waves, leading to higher power delivery at specific receiver points [8],[9]. The metasurface is designed to act as a transmit lens that applies spatially varying phase shifts across its surface to shape and focus the emitted beam toward intended IoT receivers. This is particularly useful in environments with distributed sensors and devices, where power needs to be directed selectively without physical connections.

To achieve this, a phase map is computed and applied to the metasurface layer, where each metaatom introduces a specific phase delay to the wavefront, enabling wave convergence at a designated focal point [9],[10].

### 3.2 Phase Map Generation:

The phase map figure 7 represents the phase shifts required for each unit cell (metaatom) in a 100x100 metasurface to direct waves to 81 distinct, non-overlapping focal points in space [26],[27]. Each point on the map corresponds to a unit cell's position, with the colour (or numerical value) indicating the phase shift in degrees (−180° to +180°) [21],[22]. The map encodes the necessary phase adjustments so that the incident wavefronts interfere constructively at the target foci [24],[25]. By carefully tuning the phase distribution, the metasurface will focus multiple beams at predefined spots, avoiding overlap and ensuring efficient multibeam wireless power transfer [28],[29]. This phase map can be used to guide the physical configuration of the metaatoms in the metasurface for optimal performance [8],[11].

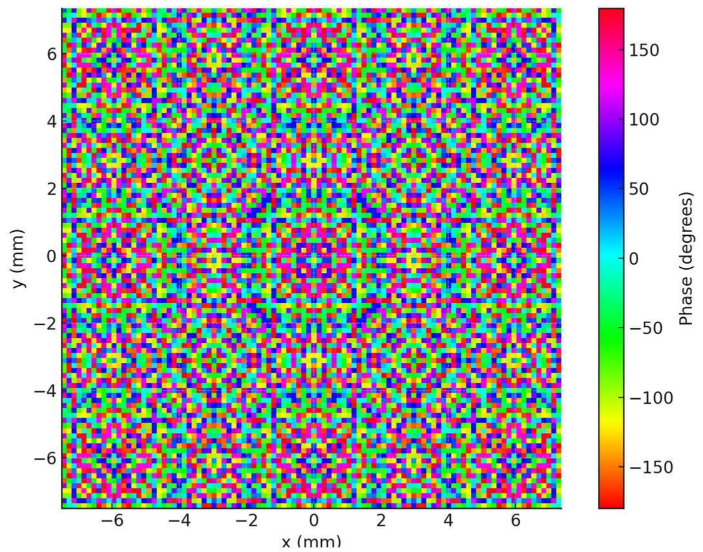



**Figure 7:** Phase-map of 9x9 Multi-Focus Metasurface for WPT

### *3.3: Meta Atom Design:*

#### *3.3.1: Substrate & Material Selection:*

**Substrate:**

- Material: FR4 (Lossy)
- Characteristics: FR4 is a common PCB substrate with moderate dielectric constant (~4.4) and significant loss tangent, not ideal for high-frequency (Gigahertz) but acceptable for simulations at 2.45 GHz.

**Conducting Patches:**

- Material: Copper (annealed – likely meaning standard copper layer used in PCB manufacturing).
- Shape: The design contains a central cross with four rectangular stubs, enclosed by two concentric partial rings and a square boundary.
- Function: This complex structure is likely engineered for specific resonance, phase manipulation, or beam-shaping behaviour.

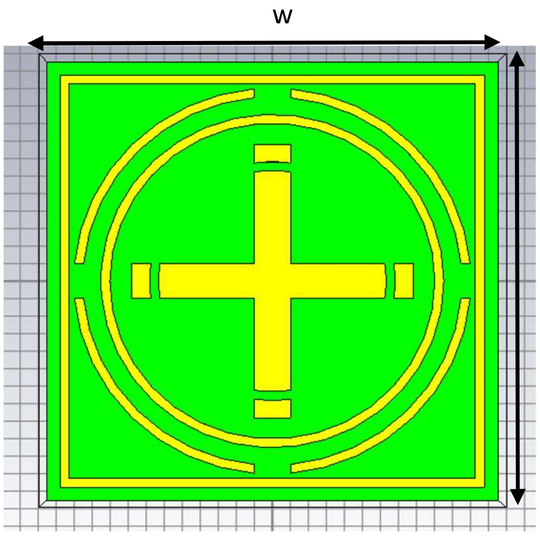
#### *3.3.2: Design Methodology:*

The metaatom was designed and analysed using CST Microwave Studio, employing the following simulation steps:

1. First substrate was designed by using FR4(lossy material)
   Dimensions:(l=w=25mm, h=1.6mm)
2. Then a ring was made using copper
   Dimensions:(Outer r=11mm, Inner r=r-0.5mm, copper t =0.035)
3. Then 2 patch was designed like a plus and they add with each other and subtracted from the ring using copper
   Dimension:(l1=l mm and wl=2mm, copper t=0.035)
4. Then another ring is made using copper
   Dimensions:(Outer r1=r-1.5mm and Inner r1=r1-0.5mm & copper t=0.035)
5. Then one metal patch was taken and subtracted from another metal patch and made a border of 0.5cm using copper
   Dimensions:(Outer lp=wp=2*r+1.5, Inner lp=wp=2*r+1, copper t=0.035)
6. Then 2 metal patch was made and added using copper
   Dimensions:(l3=2*r3+2 mm, w2=2mm, copper t=0.035)
7. Then another ring is made and subtracted from plus using copper
   Dimensions:(Outer r3=r1-1.5mm and Inner r3=r3-0.5mm, copper t=0.035)

**Table 1: Design Parameter**

| **Parameters** | l | w | r | l1 | w1 | w2 | r1 | lp | wp | l3 | r3 | h | t |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dimensions (in mm)** | 23 | 23 | 11 | 23 | 2 | 2 | 9.5 | 23.5 | 23.5 | 18 | 8 | 1.6 | 0.035 |



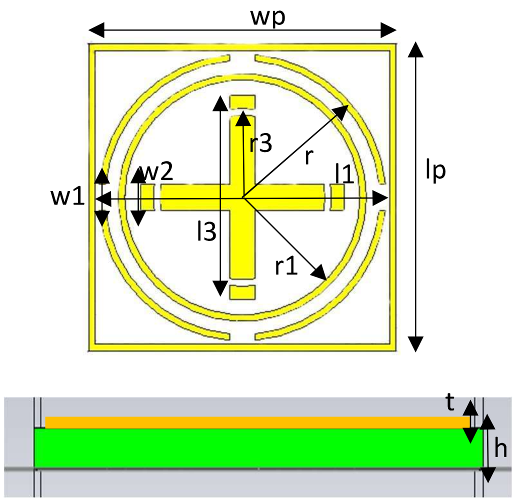




**Figure 8(a):** Front View **Figure 8(b):** Side View

### *3.4 Simulation & Result:*

#### *3.4.1 S-Parameter (S11) Analysis at 2.45 GHz:*

- $S_{11}$ (Return Loss) tells how much power is reflected back. A dip at 2.45 GHz implies good resonance. The diagram shown in fig 9(a).
- If $S_{11} < -10$ dB at 2.45 GHz, it means efficient radiation and matching.

#### *3.4.2 Phase Response at 2.45 GHz:*

- The metasurface phase response across frequency is likely analyzed to check if it gives desired phase shifts for beam steering, focusing, or reflection control. In the fig. 9(b) the diagram is shown.

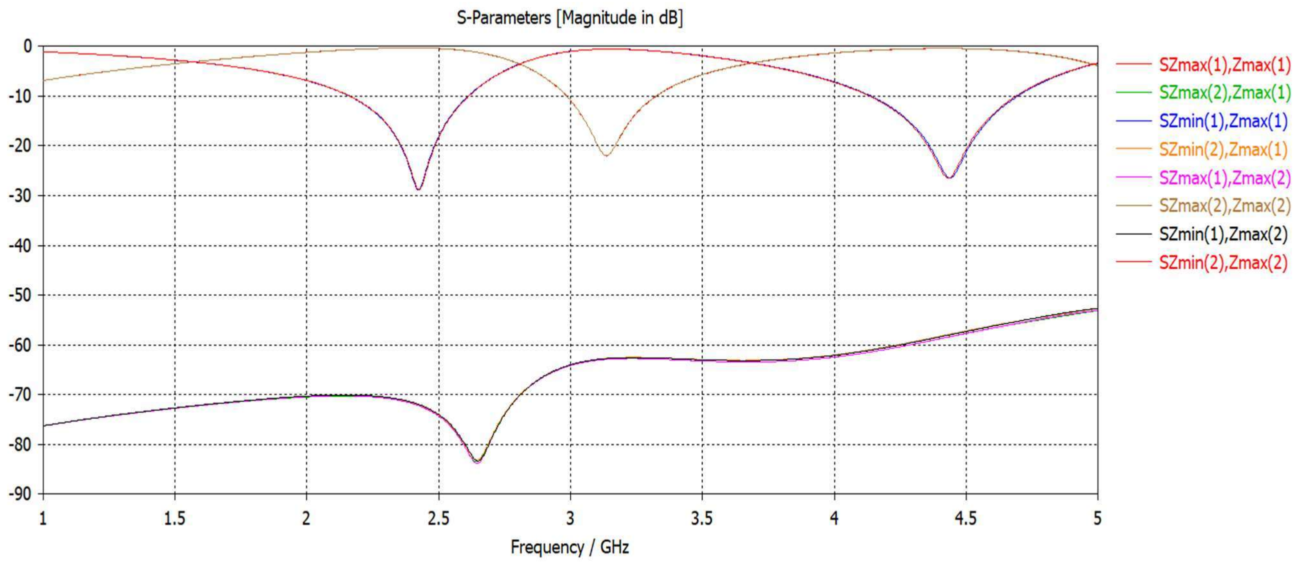



**Figure 9(a):** S parameter response 2.45GHz

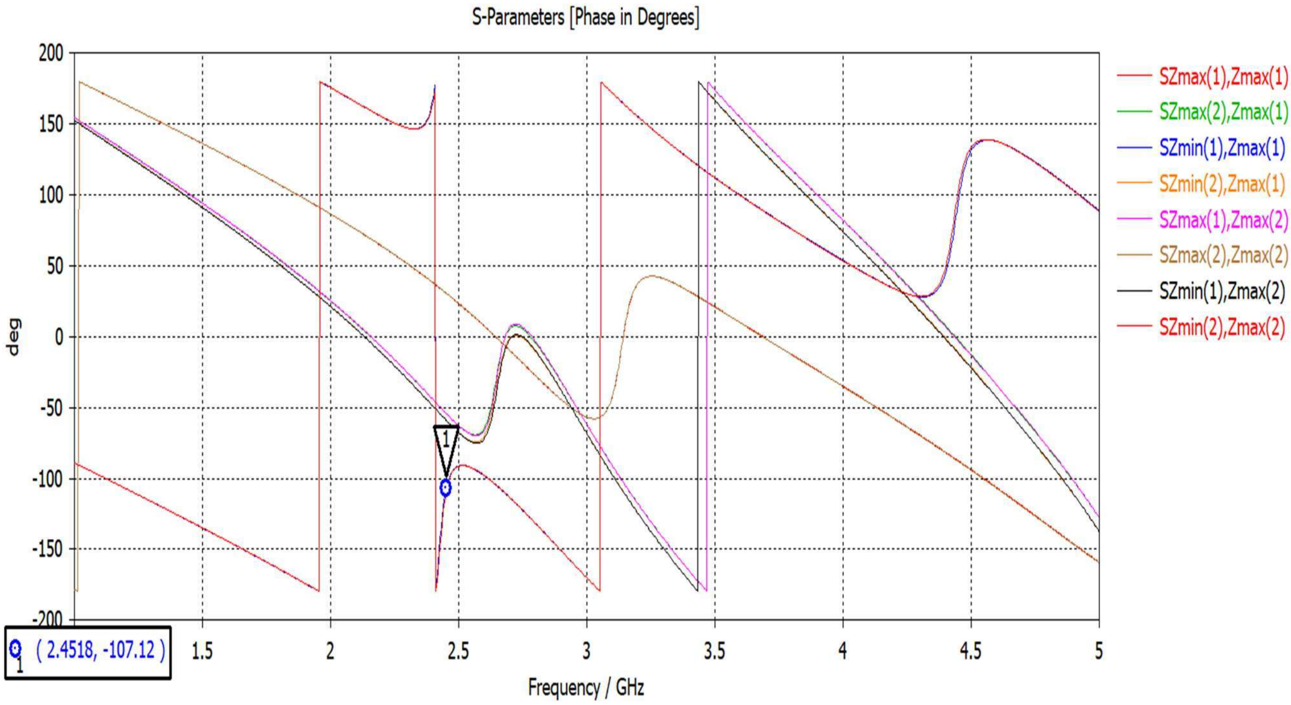



**Figure 9(b):** Phase response at 2.45GHz

### *3.4.3 Far-field Radiation Pattern:*

- The pattern could show **directional** or **broadside** radiation, depending on phase behaviour. The pattern could show directional or broadside radiation, depending on phase behaviour and symmetry.

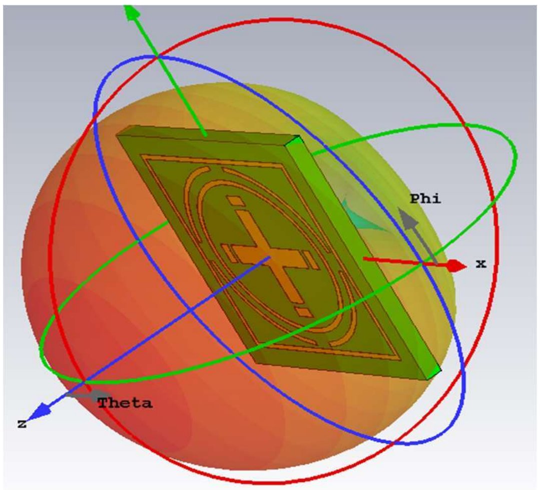



**Figure 10:** Far-field Radiation

- **Power Transfer Efficiency**: It is greater than78% efficiency per beam, even under high input power.

### *3.4.4 Changes of Phase Response :*

By varying the parameter of r we are going to to get different phase response and that's necessary for creating the Meta surface. And we get response on the basis of varying r parameter according to phase map in the fig (7) & on the basis of that we are going to calculate the s-parameter. If the s-parameter below -2dB then we need to neglect those values. By doing the parametric we get the results where the values of r greater than 7 mm exceeds the boundary.

As a result of it we get the phase map on the distance of 3 degree and that's how we are going to generate the phase-map. The phase map represents the phase shifts required for each unit cell (metaatom) in a 100x100 metasurface to direct waves to 81 distinct, non-overlapping focal points in space. Each point on the map corresponds to a unit cell's position, with the color (or numerical value) indicating the phase shift in degrees (−180° to +180°). The map encodes the necessary phase adjustments so that the incident wavefronts interfere constructively at the target foci. The figure 11: it shows the phase response of it.

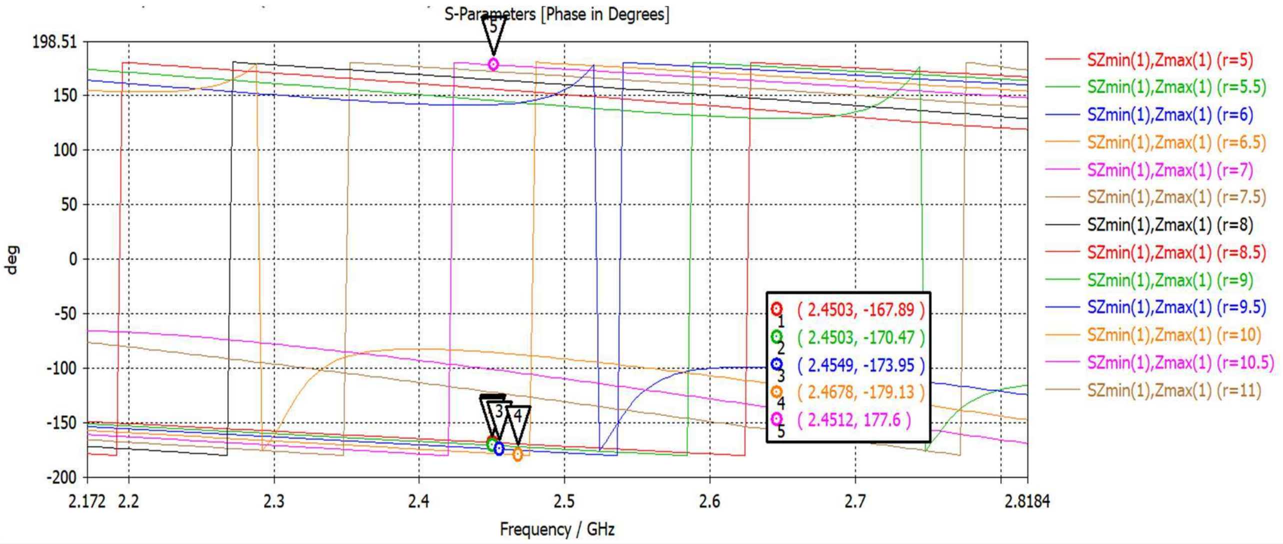



**Figure 11:** Phase-response of the metaatom

### *3.4.5 E-Field Distribution & Surface Current Vectors:*

The figure 12(a) presents the electric field (E-field) distribution of the metaatom structure, showcasing a well-defined, symmetric resonance pattern essential for Gigahertz metasurface functionality. The strongest E-field intensities are observed along the edges of the inner and outer circular split-ring resonators (SRRs) and at the extremities of the central cross arms. These concentrated "hotspots" indicate areas of significant capacitive interaction due to geometric discontinuities such as gaps and sharp corners, which are key to field localization. The symmetric distribution along both axes suggests excitation of even-order resonant modes, which promotes uniform phase control. Additionally, the cross-shaped arms and circular ring design enable hybrid electric and magnetic dipolar resonances, leading to enhanced near-field interaction and wavefront modulation. The inner region of the structure exhibits relatively weaker field intensity, confirming that most of the electromagnetic activity is confined to the structural boundaries, making it highly suitable for tunable phase modulation in multi-beam metasurface applications.

The figure 12(b) illustrates the surface current density distribution on the metaatom, revealing the electromagnetic response in greater detail. Dense and colorful current vectors (ranging from blue to red in magnitude) indicate strong resonant currents, particularly along the circular rings and the cross arms. The formation of closed-loop currents around the ring structure signifies magnetic dipole behavior, which is crucial for manipulating the magnetic component of incident Gigahertz waves. Meanwhile, the strong linear currents along the arms of the cross reflect electric dipole activity, contributing to the electric response of the unit cell. These distinct current pathways allow for simultaneous excitation of magnetic and electric resonances, enabling precise phase shifting. This dual-resonant behavior, supported by tight confinement of currents and fields, demonstrates that the metaatom design is effective for high-efficiency, broadBand phase manipulation required in wireless power transfer metasurfaces.

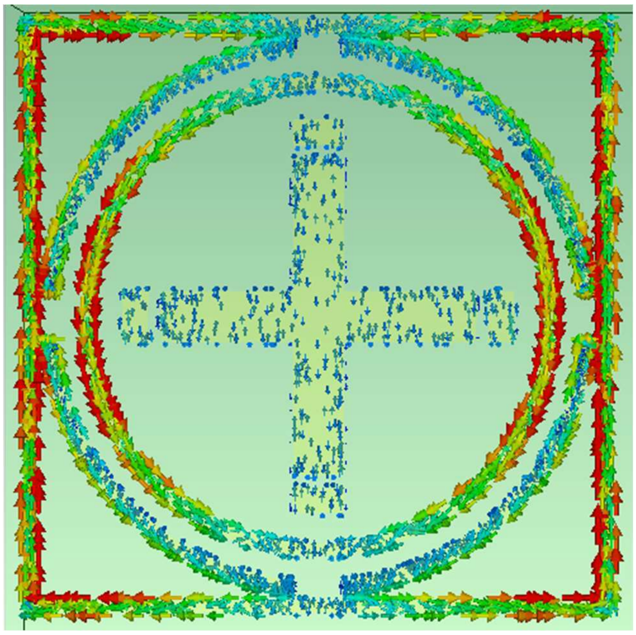


**Figure 12(a):** E-Field

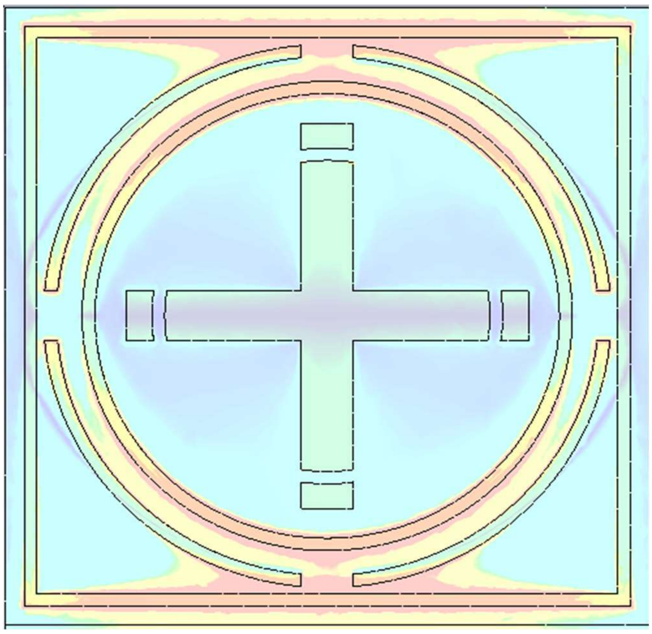


**Figure 12(b):** Surface-Current

# CHAPTER 4
# CONCLUSION & FUTURE WORK

### *4.1 Conclusion:*

This report presents the design, simulation, and potential application of a highly efficient multibeam metasurface intended for high-power Gigahertz wave transfer. The unique metaatom design enables the metasurface to split energy into multiple directional beams with high precision and efficiency. With promising simulation results and a scalable design, this technology holds significant potential for wireless power systems, high-frequency communication, and energy-harvesting platforms.

The design is suitable for various applications including: Wireless Charging Systems, Biomedical Implants, Gigahertz Communication, Space-based Energy Harvesting and so on. The figure12 shows the diverse application of this metasurface.

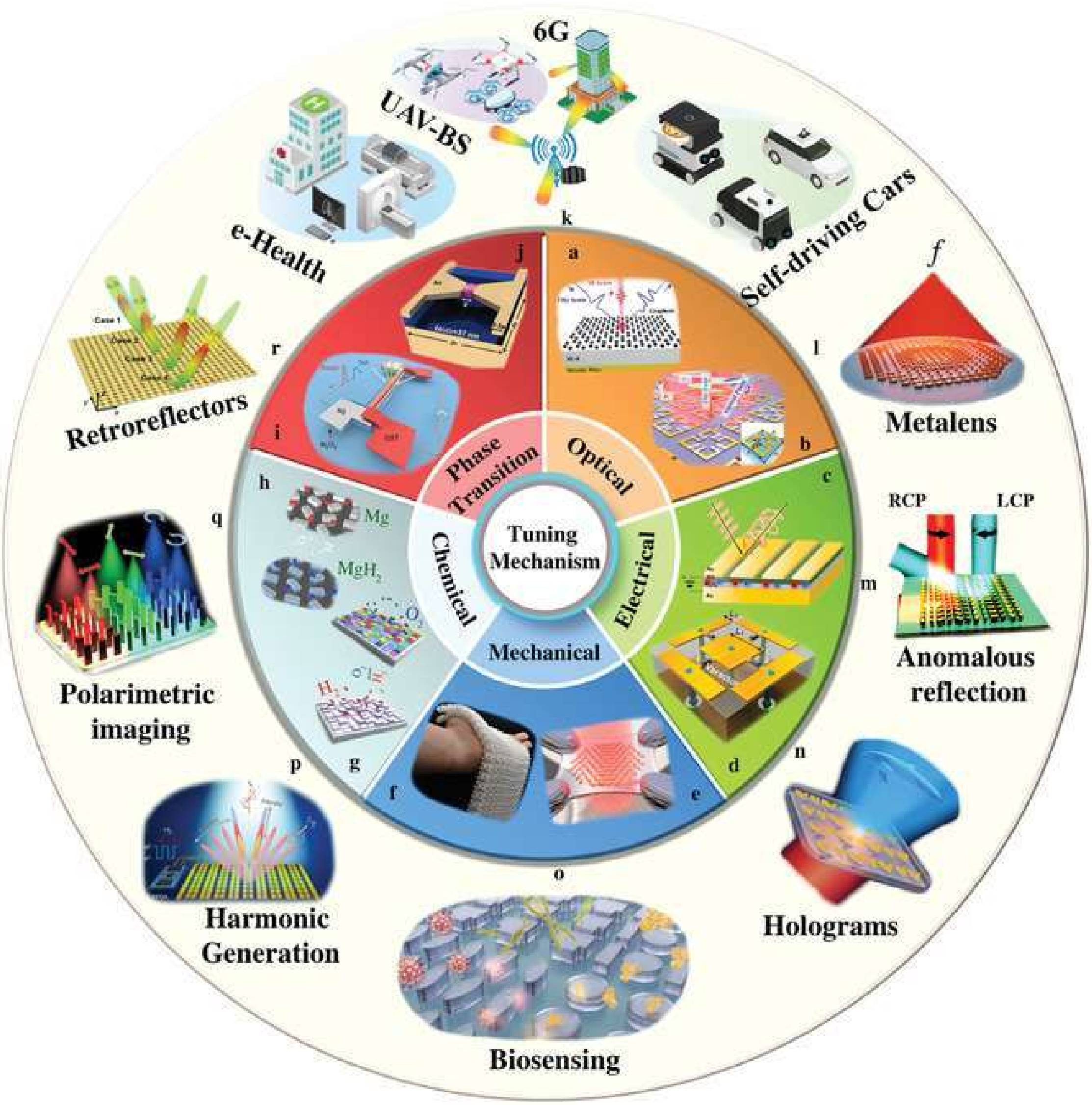



**Figure 12:** Diverse application of metasurface

*4.2: Future Work:*

To enhance performance and bring the system closer to real-world deployment, the following developments are proposed:

- *Reconfigurable Metaatoms:*
  Incorporating tuneable components like varactors, graphene, or phase-change materials can allow real-time beam switching and direction tuning and on the basis of that we are going to create a metasurface for this specific project.
- *Broadband Optimization:*
  Redesigning the metaatoms with multi-resonant geometries or using meta-gratings can extend the operating bandwidth, allowing adaptability to different frequencies.
- *AI-Assisted Beam Control:*
  Implementing machine learning algorithms to dynamically control the phase and amplitude response of each unit cell for adaptive beamforming in changing environments.
- *Fabrication and Measurement:*
  Developing photolithography-based prototypes and testing in anechoic chambers to validate simulation results under real operating conditions.

## Reference

1. H. Liu et al., "Multitarget Simultaneous Wireless Information and Power Transfer (SWIPT) Scheme Based on Anisotropy-Metasurface Field Synthesis," in IEEE Transactions on Antennas and Propagation, vol. 72, no. 11, pp. 8466-8475, Nov. 2024, doi: 10.1109/TAP.2024.3456380.
2. H. Xue et al., "Multitarget Wireless Power Transfer System Using Metasurface for Quasi-Bessel Beams With Large Half Power Beam Length," in IEEE Transactions on Microwave Theory and Techniques, vol. 70, no. 10, pp. 4449-4462, Oct. 2022, doi: 10.1109/TMTT.2022.3197619.
3. X. Wu et al., "Multitarget Wireless Power Transfer System Strategy Based on Metasurface-Holography Multifocal Beams," in IEEE Transactions on Microwave Theory and Techniques, vol. 71, no. 8, pp. 3479-3489, Aug. 2023, doi: 10.1109/TMTT.2023.3260401.
4. M. Qu, T. Lan, J. Su, P. Zuo and J. Song, "Generation of Discrete Nondiffractive Beams Based on Programmable Metasurface for Multitarget Communications," in IEEE Transactions on Microwave Theory and Techniques, vol. 72, no. 12, pp. 6799-6808, Dec. 2024, doi: 10.1109/TMTT.2024.3405191.
5. X. Tao, L. -m. Qi, J. Yang, Z. -y. Liu and C. -w. Lan, "A F-shaped Gigahertz Chiral metasurface with a high circular dichroism," 2020 Cross Strait Radio Science & Wireless Technology Conference (CSRSWTC), Fuzhou, China, 2020, pp. 1-3, doi: 10.1109/CSRSWTC50769.2020.9372590
6. A. Dellabate, D. Brizi, T. Shaw, M. Perez, R. Augustine and A. Monorchio, "An Electromagnetic Metasurface for Impedance Matching in Microwave Biomedical Applications," 2024 18th European Conference on Antennas and Propagation (EuCAP), Glasgow, United Kingdom, 2024, pp. 1-4, doi: 10.23919/EuCAP60739.2024.10501601.
7. D. Kampouridou and A. Feresidis, "Multibeam Holographic Metasurface Antenna Design," 2022 International Workshop on Antenna Technology (iWAT), Dublin, Ireland, 2022, pp. 4-5, doi: 10.1109/iWAT54881.2022.9811035.

8. D. González-Ovejero, G. Minatti, G. Chattopadhyay, and S. Maci, “Multibeam by metasurface antennas,” IEEE Transactions on Antennas and Propagation, vol. 65, no. 6, pp. 2923–2930, Jun. 2017.
9. N. Yu and F. Capasso, “Flat optics with designer metasurfaces,” Nature Materials, vol. 13, no. 2, pp. 139–150, Feb. 2014.
10. Y. Li, X. Wan, B. G. Cai, Q. Cheng, and T. J. Cui, “Frequency-controls of electromagnetic multi-beam scanning by metasurfaces,” Scientific Reports, vol. 4, 2014.
11. S. V. Hum and J. Perruisseau-Carrier, “Reconfigurable Reflectarrays and Array Lenses for Dynamic Antenna Beam Control: A Review,” IEEE Transactions on Antennas and Propagation, vol. 62, no. 1, pp. 183–198, Jan. 2014.
12. N. Yu and F. Capasso, “Flat optics with designer metasurfaces,” Nature Materials, vol. 13, no. 2, pp. 139–150, Feb. 2014.
13. D. González-Ovejero, G. Minatti, G. Chattopadhyay, and S. Maci, “Multibeam by metasurface antennas,” IEEE Transactions on Antennas and Propagation, vol. 65, no. 6, pp. 2923–2930, Jun. 2017.
14. Y. Li et al., “A BroadBand Gigahertz Metasurface for High-Efficiency Wavefront Control,” IEEE Photonics Journal, vol. 10, no. 4, pp. 1–9, Aug. 2018.
15. W. Hong et al., “Multibeam Antenna Technologies for 5G Wireless Communications,” IEEE Transactions on Antennas and Propagation, vol. 65, no. 12, pp. 6231–6249, Dec. 2017.
16. Z. Li, S. Lin, X. Liu, and Q. Chen, “A Metasurface-Based Wireless Power Transfer System with High Efficiency and High Sensitivity,” IEEE Transactions on Microwave Theory and Techniques, vol. 68, no. 10, pp. 4414–4423, Oct. 2020.
17. R. W. Ziolkowski and N. Engheta, “Metamaterial special issue,” IEEE Transactions on Antennas and Propagation, vol. 51, no. 10, pp. 2546–2547, Oct. 2003.
18. T. A. Khan, J. C. Wang, and M. M. Tentzeris, “3D printed flexible wireless systems: A review of applications, technologies, and future directions,” IEEE Access, vol. 7, pp. 33226–33238, Mar. 2019.
19. S. Abadal, C. Liaskos, A. Tsioliaridou, A. Pitsillides, and A. Cabellos-Aparicio, “Computing and communications for the software-defined metamaterial paradigm: A context analysis,” IEEE Access, vol. 5, pp. 6225–6235, Apr. 2017.
20. K. Zhang, H. Yu, X. Ding, and Q. Wu, “Experimental validation of active holographic metasurface for electrically beam steering,” Optics Express, vol. 26, no. 5, pp. 5803–5810, 2018.
21. F. Ding, A. Pors, and S. I. Bozhevolnyi, “Gradient metasurfaces: A review of fundamentals and applications,” Reports on Progress in Physics, vol. 81, no. 2, 2018.
22. M. A. Vincenti, D. de Ceglia, A. Ciattoni, and M. Scalora, “Nonlinear control of absorption in epsilon-near-zero metamaterials using phase change materials,” Physical Review A, vol. 84, no. 6, 2011.
23. X. Wan, B. G. Cai, Q. Cheng, and T. J. Cui, “Multibeam antennas based on metasurface lens,” IEEE Transactions on Antennas and Propagation, vol. 65, no. 6, pp. 2891–2898, Jun. 2017.
24. B. Zhu, H. Liu, S. Li, and T. J. Cui, “Flexible frequency-selective metasurfaces with multi-band and broadBand functionalities,” Journal of Applied Physics, vol. 118, 2015.
25. J. Yao et al., “BroadBand metasurface for efficient optical absorption,” Nano Letters, vol. 14, no. 11, pp. 6526–6532, 2014.
26. J. Xu, M. Wang, S. V. Hum, and M. Mojahedi, “Neural networks for inverse design of reconfigurable metasurfaces,” IEEE Antennas and Wireless Propagation Letters, vol. 20, no. 6, pp. 1010–1014, 2021.

27. J. Liu et al., "Intelligent metasurfaces with programmable functions enabled by machine learning," Photonics Research, vol. 7, no. 8, pp. 823–833, 2019.
28. J. K. Lee, Y. H. Ahn, and J. Kim, "Reinforcement-learning-based intelligent reconfigurable metasurface for wireless communication," IEEE Access, vol. 9, pp. 75041–75052, 2021.
29. A. V. Kildishev, A. Boltasseva, and V. M. Shalaev, "Planar photonics with metasurfaces," Science, vol. 339, no. 6125, 2013.
30. Q. Ma, R. F. Guo, and D. H. Werner, "Experimental characterization of a Gigahertz metasurface with asymmetric transmission," IEEE Transactions on Gigahertz Science and Technology, vol. 4, no. 5, pp. 598–605, Sep. 2014.
31. F. Monticone and A. Alù, "Metamaterial, plasmonic and nanophotonic devices," Reports on Progress in Physics, vol. 80, no. 3, 2017.