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DESIGN OF METASURFACE FOR ANTENNA GAIN ENHANCEMENT AND BEAM SPLITTING AT 5G APPLICATIONS

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Abstract: This paper presents a Metasurface for the Microstrip patch antenna for fifth generation applications at 3.5GHz to enhance the gain and to split the beam. Highly Directional multi-beam antennas are essential for 5G mobile networks, and they can be realized using array antennas. But array antennas functioning at lower frequencies elevate both the intricacy and scale of the entire network. Therefore, the proposal for a metasurface involves directing surface currents while exhibiting multi-beam and high gain properties. Implementing a metasurface composed of a single square patch antenna involves the utilization of both Square Split Ring Resonator(SSRR) and U-Shaped unit cell configurations. By manipulating this hybrid metasurface configuration, counter currents can be introduced on the unit cell, there by causing the beam to split. The hybrid metasurface and metasurface antenna were fabricated on FR-4 Substrate. The results show that the antenna resonates well at the frequency of 3.5 GHz, the reflection coefficient is less than −10 dB. The arrangement of unit cells on the metasurface of the metasurface is capable of splitting the current, and thus the beam in the radiation pattern is divided into two beams in the E-plane at an angle of ±45°. This antenna is a good candidate for future 5G Pico mobile base stations in urban or suburban areas with high power and interference.

***Keywords* - Metasurface, Microstrip patch antenna, SSRR**

I. INTRODUCTION

The fifth-generation (5G) systems are required to provide multiple beams with high gain and capacity towards the target.5G technology suggests a lower band of 3.5 GHz for 5G mobile applications. Overcoming challenges of low-frequency antennas, a proposed Meta surface with high gain and multi-beam properties utilizes a Square Split Ring Resonator (SSRR) and U-shaped unit cell.

A metamaterial (from the Greek word meta, meaning "beyond" or "after", and the Latin word materia, meaning "matter" or "material") is any material engineered to have a property that is rarely observed in naturally occurring materials. They are made from assemblies of multiple elements fashioned from composite materials such as metals and plastics. These materials are usually arranged in repeating patterns, at scales that are smaller than the wavelengths of the phenomena they influence. Metamaterials derive their properties not from the properties of the base materials, but from their newly designed structures. Their precise shape, geometry, size, orientation and arrangement gives them their smart properties capable of manipulating electromagnetic waves: by blocking, absorbing, enhancing, or bending waves, to achieve benefits that go beyond what is possible with conventional materials. A metamaterial is any material engineered to have a property that is rarely observed in naturally occurring materials. They are made from assemblies of multiple elements fashioned from composite materials such as metals and plastics. These materials are usually arranged in repeating patterns, at scales that are smaller than the wavelengths of the phenomena they influence. Metamaterials derive their properties not from the properties of the base materials, but from their newly designed structures. Their precise shape, geometry, size, orientation and arrangement gives them their smart properties capable of manipulating electromagnetic waves: by blocking, absorbing, enhancing, or bending waves, to achieve benefits that go beyond what is possible with conventional materials.

An electromagnetic metasurface refers to a kind of artificial sheet material with sub-wavelength thickness. Metasurfaces can be either structured or unstructured with subwavelength-scaled patterns in the horizontal dimensions. A liquid-tunable electromagnetic metasurface. In electromagnetic theory, metasurfaces modulate the behaviors of electromagnetic waves through specific boundary conditions rather than constitutive parameters in three-dimensional (3D) space, which is commonly exploited in natural materials and metamaterials. Metasurfaces may also refer to the two-dimensional counterparts of metamaterials. Gain refers to the measure of the antenna's ability to direct or concentrate its radiated power in a specific direction. Gain enhancement for antennas is pursued for several reasons are Increased Improved range, Signal quality, Directionality, System design optimization. Beam splitting involves dividing the main beam into multiple smaller beams, each pointing in a different direction. Beam splitting for antennas can be useful for various reasons are Multi Beam Coverage, Increased capacity, Diversity and redundancy.

II. Design Of Antenna

For the Design of our proposed Antenna, first we will design a Hybrid Metamaterial unit cell and with that unit cells of different configurations, we will design the metasurface antenna model with Gain SSRR for gain enhancement and metasurface antenna model with Beam split SSRR for Beam splitting at 5G applications. The whole simulation can be designed using Ansys HFSS software.

2.1 Design of Hybrid Metamaterial Unit Cell

The hybrid metamaterial unit cell is designed theoretically based on the SSRR and U-shaped equivalent circuit as shown in Fig 2.1. The resonant frequency of the hybrid unit cell is obtained by $f0=(1)/(2\pi(L[(2l-g/2)C+(\varepsilon0wh)/2g1/2$.

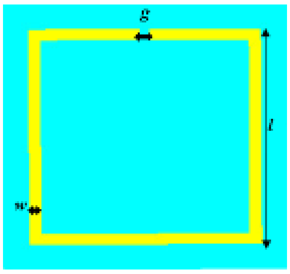


Fig .2.1.1 Design of unit cell with one SSRR

The diagram illustrates the design of a hybrid metamaterial unit cell aimed at forming a metasurface composed of multiple unit cells. Each unit cell is constructed using a square split-ring resonator (SSRR) configuration, featuring a square-shaped metallic ring that is split into two halves with a narrow gap "g" between them, the length of SSRR is denoted by the letter 'w' and the width of SSRR is denoted by the letter 'l'

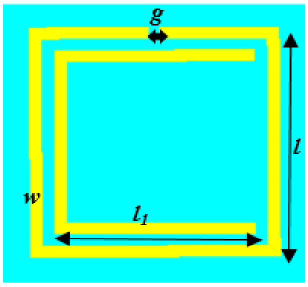


Fig 2.1.2. Design of unit cell with one SSRR and one U-Shaped unit cell

The diagram Fig 2.1.2 depicts a hybrid metamaterial unit cell intended to form a metasurface through the combination of multiple unit cells. Each unit cell within this hybrid design incorporates two distinct elements: a square slit ring resonator (SSRR) and a U-shaped unit cell. By combining the SSRR and the U-shaped unit cell within a single unit cell design, the diagram illustrates a sophisticated approach to metamaterial engineering. The resulting metasurface, formed by assembling multiple unit cells, can be tailored to exhibit desired electromagnetic functionalities such as anomalous reflection, polarization manipulation, or frequency filtering. This hybrid metamaterial unit cell design offers a versatile platform for various applications in areas such as antenna technology, imaging, sensing, and optical devices.

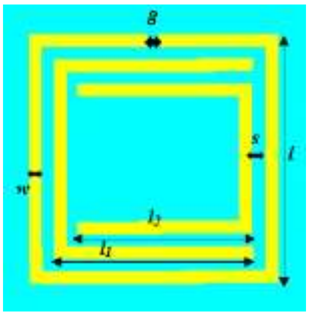


Fig 2.1.3 Design of unit cell with one SSRR and two U-Shaped unit cell

The diagram Fig 2.1.3.unit cell depicted in the diagram of the hybrid metamaterial unit cell comprises three main components: one square slit ring resonator (SSRR) and two U-shaped unit cells. By combining the SSRR with two U-shaped unit cells within a single unit cell design, the diagram illustrates a hybrid approach to metamaterial engineering. This hybrid metamaterial unit cell can be replicated and arranged in a periodic fashion to form a metasurface comprising multiple unit cells. The resulting metasurface can be tailored to exhibit desired electromagnetic functionalities, such as frequency-selective properties, polarization control, or anomalous reflection behavior.

Parameter	Definition	Value(mm)
L	Length of SSRR	6.5
G	Gap cut of SSRR+U-shape	0.5
W	Width of SSRR+U-shape	0.5
S	Gap between SSRR and U-shape	0.3
L1	Length of first U-shape	5.20
l2	Length of second U-shape	4.55

Table 2.1 Physical dimension values of unit cell

From the table 2.1, we have used physical dimension values to design the hybrid Metamaterial unit cell

2.2 Design of 4x4 Metasurface

The proposed hybrid unit cell with SSRR integrated with U shape structure to form a metasurface. The 4x4 metasurface structures are shown in Figure 3. Two different configurations are implemented for the proposed metasurface. The first configuration consists of unit cells arranged with the Fig 2.2. The dimensions of the proposed SSRR U-shape unit cell at 3.5 GHz. same current direction along with the four row elements. The second configuration has a unit cell distributed in opposite direction along with the two adjusted columns. This allows the current to ow oppositely inside the unit cell and split the beam into two different directions. Metasurface compact size is sufficient for practical use to prevent wasting too much simulation time and resources.

Parameter	Definition	Value(mm)
Lsub	Substrate Length	52.62
Wsub	Substrate width	40.40
Lmeta	Metasurface length	52.62
Wmeta	Metasurface width	40.40
Lgnd	Ground length	52.62
Wgnd	Ground width	40.40
Lmpa	Patch length	26.31
Wmpa	Patch width	20.20
Lfeed	Feed length	15.25
Wfeed	Feed width	3.127
d	Air gap distance	15

Tables 2.2 Physical dimensions of metasurface

From Table 2.2, we have used the physical dimension values to design the metasurface.

2.2.1 Metasurface Used for Gain Enhancement and Beam splitting

We have used two different types of metasurface configurations for gain enhancement and beam splitting.

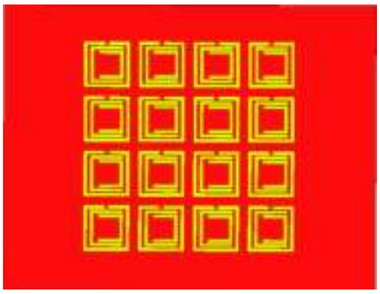


Fig 2.2.1 Metasurface for Gain Enhancement

The first configuration consists of unit cells in the Fig 2.2.1 arranged with the same current direction along with the four row elements. The metasurface arrangement with the same current direction results in not splitting the beam. It increases the current flow and leads to an increase in the gain of the placed antenna.

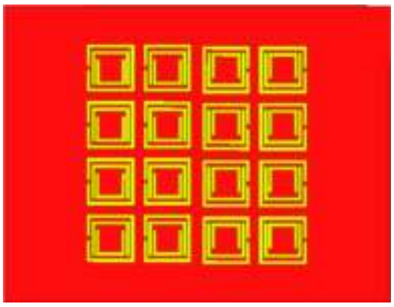


Fig .2.2.2 Metasurface for Beam splitting

The second configuration has a unit cells in the Fig 2.2.2 distributed in opposite direction along with the two adjusted columns. This allows the current to flow oppositely inside the unit cell and split the beam into two different directions. To achieve the split beam property, the unit cells are rearranged to produce opposite current flow as shown in Fig 4.3.2. By observing the current flow for every two cells in one column the beam is produced in a different direction.

2.3 Antenna Design

Calculation of the patch Length and Width (a): The dimensions of the Microstrip patch is given by:

$$W = \frac{c}{2f_o\sqrt{\frac{(\varepsilon_r + 1)}{2}}} \quad (1)$$

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

$$L_{eff} = \frac{c}{2f_o\sqrt{\varepsilon_{eff}}} \quad (3)$$

$$\Delta L = 0.412h\frac{(\varepsilon_{eff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{eff} - 0.258)\left(\frac{W}{h} + 0.8\right)} \quad (4)$$

$$L = L_{eff} - 2\Delta L \quad (5)$$

Where f_r is Frequency of operation, $\varepsilon_r$and h are Dielectric constant and height of substrate.

Fig. 2.3 Basic Antenna

2.4 Design of proposed antennas

In our proposed method we have designed two antenna models i.e, Design of Antenna with Gain SSRR and Design of Antenna with Beam split SSRR with two different configurations.

2.4.1 Design of Antenna with Gain SSRR

By using the metasurface for gain enhancement with different configuration i.e., The first configuration consists of unit cells arranged with the same current direction along with the four row elements. The metasurface arrangement with the same current direction results in not splitting the beam. It increases the current flow and leadsto an increase in the gain of the placed antenna.

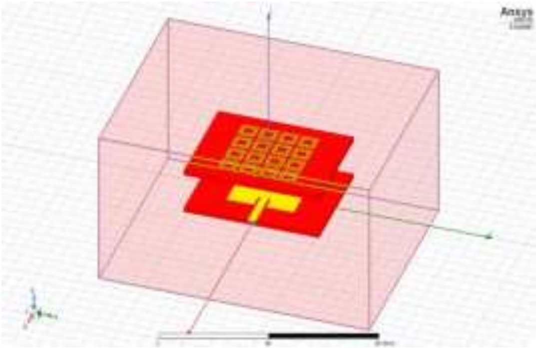


Fig. 2.4.1 Design of Antenna with Gain SSRR

2.4.2 Design of Antenna with Beam split SSRR

By using the metasurface for Beam split with different configuration in the Fig 2.4.2 i.e., To achieve the split beam property, the unit cells are rearranged to produce opposite current flow. By observing the current flow for every two cells in one column the beam is produced in a different direction.

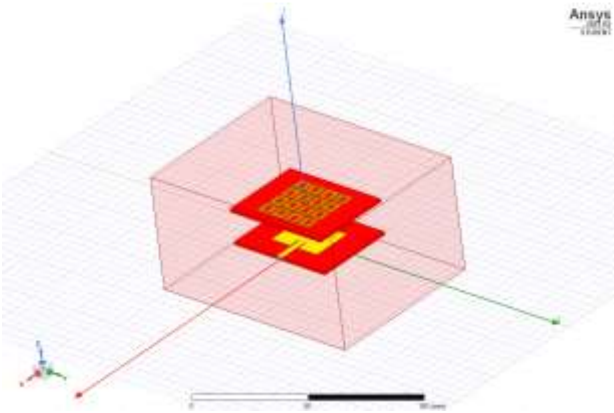


Fig. 2.4.2 Design of Antenna with Beam split SSRR

III. ANYSYS HFSS SOFTWARE

High Frequency Structured Simulated Software (HFSS): The acronym is High frequency structural simulator. It is an Antenna Design Software. ANSYS HFSS 13.0 is a powerful software used for designing and simulating antenna. The display of designing Metasurface Antenna model in HFSS software as shown in below Fig 3.1

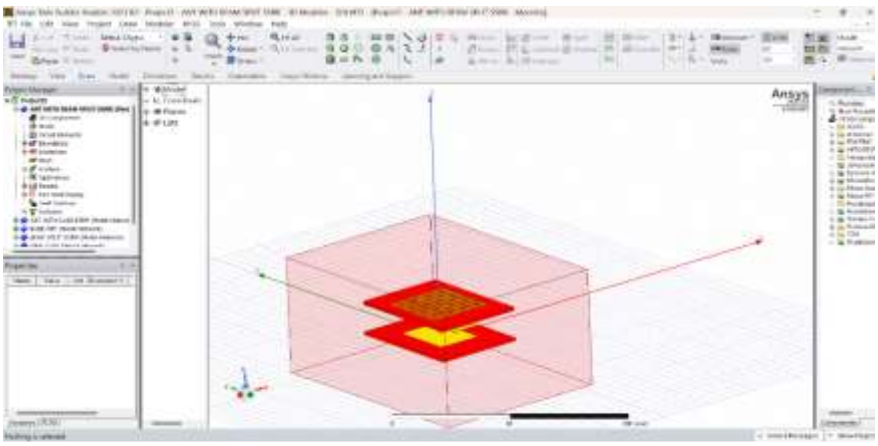
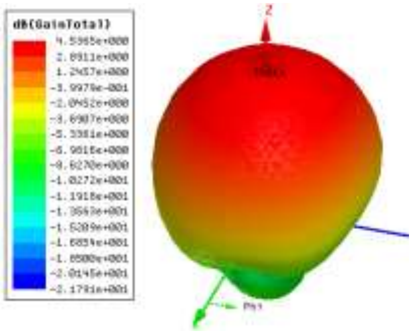


Fig. 3.1 Metasurface Antenna model in HFSS software

IV. RESULTS AND DISCUSSION

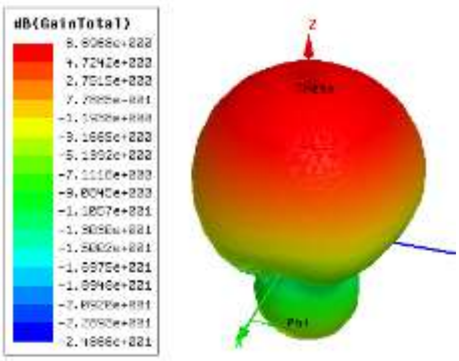
4.1 ANTENNA GAIN

The term Antenna Gain describes how much power is transmitted in the direction of peak radiation to that of anisotropic source. Gain of an antenna is a key performance figure which combines the antenna's directivity and electrical efficiency.



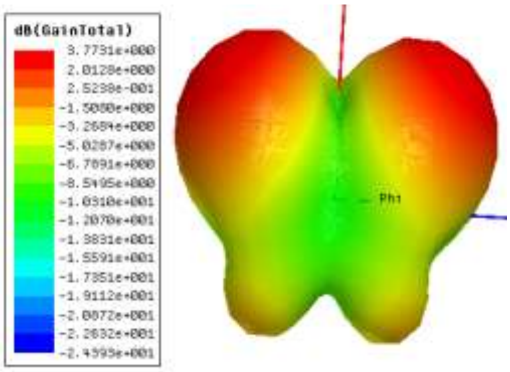
4.1.1. Gain of the Basic Antenna

Gain of the Microstrip patch antenna, which we have taken as basic Antenna can be observed from the Fig 4.1.1 is 4.53dB. In a 3D diagram of antenna gain, colors like yellow, green, red, and dark red typically represent the intensity or magnitude of the gain at different points in space. The gain of an antenna refers to its ability to direct or concentrate radiation in certain directions. So, these colors indicate the relative amount of power radiated or the strength of the radiation pattern in different directions from the antenna.



4.1.2. Gain of proposed Antenna with Gain SSRR

Gain of our proposed Antenna with Gain SSRR can be observed from the Fig 4.1.2.is 6.69dB, in which gain is enhanced by 2.2 dB. In a 3D diagram of antenna gain, colors like yellow, green, red, and dark red typically represent the intensity or magnitude of the gain at different points in space. The gain of an antenna refers to its ability to direct or concentrate radiation in certain directions. So, these colors indicate the relative amount of power radiated or the strength of the radiation pattern in different directions from the antenna.

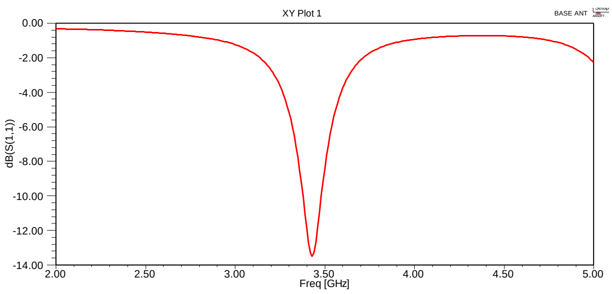


4.1.3. Gain of proposed Antenna with Beam Split SSRR

Gain of our proposed Antenna with Beam Split SSRR can be observed from the Fig 4.1.3. is 7.01 dB, in which gain is enhanced by 2.6dB. In a 3D diagram of antenna gain, colors like yellow, green, red, and dark red typically represent the intensity or magnitude of the gain at different points in space. The gain of an antenna refers to its ability to direct or concentrate radiation in certain directions. So, these colors indicate the relative amount of power radiated or the strength of the radiation pattern in different directions from the antenna.

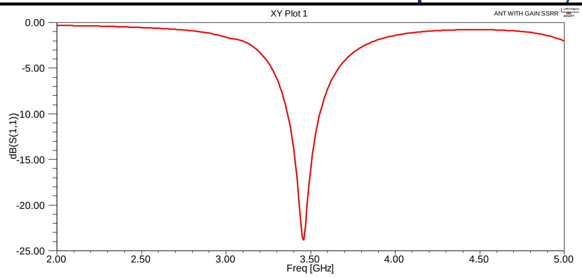
4.2 RETURN LOSS

Return loss is a measure of how well an antenna system is matched to the impedance of the transmission line and the connected equipment, usually expressed in decibels (dB). It quantifies the amount of power that is reflected back towards the source due to impedance mismatches. In the context of antennas and return loss, a value less than -10 dB indicates a significant level of reflected power compared to the incident power. This suggests poor impedance matching between the antenna and the transmission line, leading to inefficient power transfer. Antenna systems with return loss values below -10 dB typically require attention to improve their performance, such as adjusting the matching network or optimizing the antenna design. equation in terms of reflection coefficient is: Here, in Return loss graph x-axis represents Frequency in GHz and y-axis represents Return loss in dB.



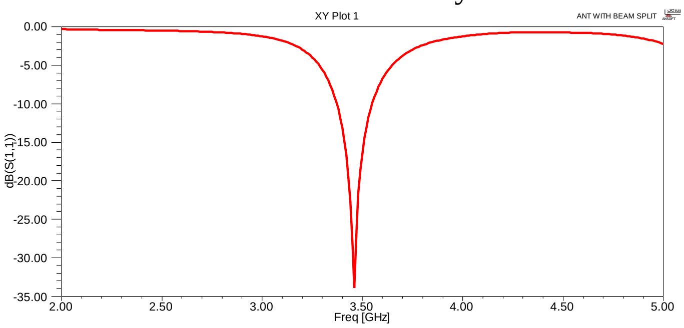
4.2.1. Basic Antenna

The Return loss of the basic antenna is noted as -8dB from the fig 4.2.1, which is greater than -10dB. A return loss of the antenna greater than -10 dB indicates that a significant portion of the signal sent to the antenna is being reflected back to the source rather than being radiated out. This suggests poor impedance matching between the antenna and the transmission line or system it is connected to. In practical terms, a return loss greater than -10 dB indicates inefficiency in the antenna system, as it means that a substantial amount of signal power is not being effectively utilized for radiation but is instead being reflected back towards the signal source. This can result in reduced performance, increased power loss, and potential degradation of the overall system performance. Therefore, achieving a return loss greater than -10 dB is typically considered suboptimal and indicates a need for improvement in the antenna design or its connection to the transmission line.



4.2.2. Return loss of Antenna with Gain SSRR

The Return loss of Antenna with Gain SSRR is noted as -15dB from the fig 4.2.2, which is less than -10dB. A return loss of less than -10 dB indicates that most of the signal sent to the antenna is being efficiently radiated out and very little is being reflected back to the source. In other words, it suggests that the antenna is effectively matched to the transmission line or system it is connected to. This is typically considered a good result in terms of antenna performance, as it implies that there's minimal loss of signal due to reflections. A return loss value greater than -10 dB would indicate more significant signal reflections and potentially poor matching between the antenna and the transmission line or system.

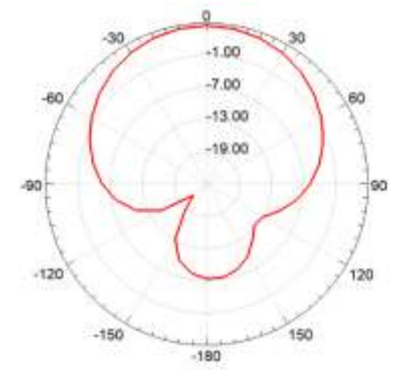


4.2.3. Return loss of Antenna with Beam split SSRR

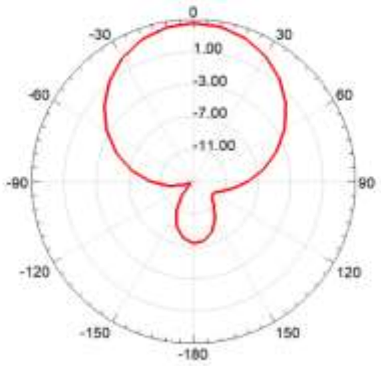
The Return loss of Antenna with Beam split SSRR is noted as -15dB from the fig 4.2.3, which is less than -10dB. A return loss of the antenna less than -10 dB indicates good impedance matching between the antenna and the transmission line or system it is connected to. This means that most of the signal sent to the antenna is efficiently radiated out, with minimal reflection back to the source. In practical terms, it suggests effective utilization of signal power for radiation and typically signifies optimal antenna performance.

4.3 RADIATION PATTERN

The radiation pattern of an antenna illustrates how electromagnetic energy is distributed in space. Antennas with beam splitting capabilities display multiple lobes or beams in their radiation pattern, indicating the directions in which energy is radiated. These patterns demonstrate the antenna's ability to focus or split the transmitted signal into distinct beams, allowing for targeted communication or reception in multiple directions simultaneously.

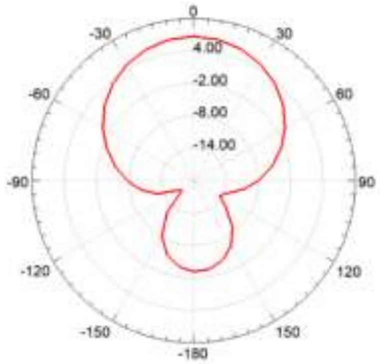


E-Plane



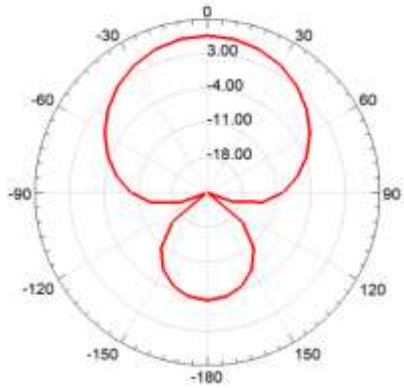
4.3.1 Basic Antenna

The Radiation pattern of the basic microstrip patch Antenna as observed as above Fig 4.3.1 In the radiation pattern of a Microstrip patch antenna, the delineation of beam splitting is notably absent. This absence is characterized by a cohesive, undivided projection of radiation, where the emitted energy remains



concentrated and unified in its propagation direction.

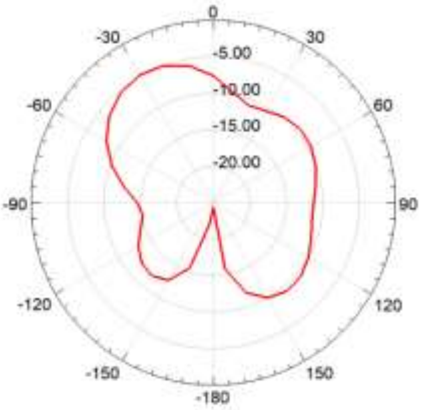
E-Plane



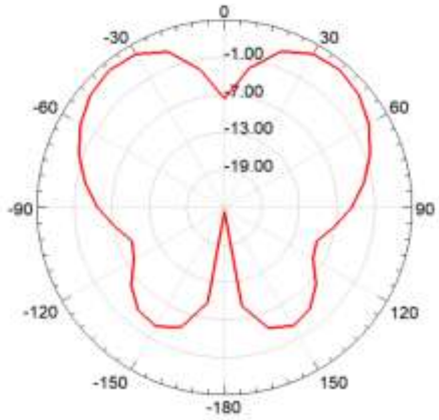
H-Plane

4.3.2. Metasurface for Gain Enhancement

The Radiation pattern of the Antenna with Gain SSRR as observed as above Fig 4.3.2. In the radiation pattern of the antenna with Metasurface Gain Enhancement, specifically utilizing the Square Split Ring Resonator configuration, a distinct absence of beam splitting is evident. This observation is characterized by a unified and undivided projection of radiation, wherein the emitted energy remains concentrated and singular in its propagation direction.



E-Plane



H-Plane

4.3.3. Metasurface for Beam Splitting
E plane and H plane of proposed antenna

The Radiation pattern of the Antenna with Beam Split SSRR as observed as above Fig 4.3.3. In the radiation pattern of the antenna with Metasurface Beam Splitting, specifically employing the Square Split Ring Resonator configuration, presents a distinctive feature: beam splitting. This phenomenon is distinctly noticeable as the emitted radiation pattern exhibits a clear division or bifurcation of the main beam into multiple distinct lobes, particularly evident at approximately plus or minus 45 degrees from the antenna's main propagation axis.

4.4 COMPARISON OF PROPOSED ANTENNA MODELS WITH MICROSTRIP PATCH ANTENNA

Parameter of Antennas	**Microstrip Patch Antenna**	**Our proposed Antennas**	
		Microstrip Patch Antenna with Gain SSRR	**Microstrip Patch Antenna with Beam Split SSRR**
Gain(dB)	4.5dB	**6.72dB**	**7.01dB**
Return Loss (3.5GHz)	-8.42dB	-17.63dB	-14.93dB

From the table we can observe that the gain of our proposed Metasurface antenna with gain SSRR is enhanced by 2.2dB and gain of micro strip patch antenna with beam split SSRR is enhanced by 2.6 dB, when compared with Microstrip patch antenna which is taken as basic antenna

V. CONCLUSION

The hybrid metasurface, combining SSRR and U-shaped unit cells, has been effectively designed and fabricated to manipulate the antenna beam. Upon integration with a microstrip patch antenna operating at 3.5 GHz, the metasurface demonstrates excellent performance, meeting standard specifications with a reflection coefficient below -10 dB at the desired frequency. Additionally, a notable gain enhancement of 2.2 dB is achieved in the antenna's broadside direction within the required impedance bandwidth. Notably, the metasurface enables the observation of a split beam in the E-plane, with each beam exhibiting a gain of 3.77 dB. This split beam feature includes two distinct tilt angles at -45◦ and 45◦, respectively. Such advancements in beam manipulation highlight
the metasurface's potential for beam steering applications crucial in 5G mobile technology operating at 3.5 GHz.

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