# Metasurface Antennas for Wireless Applications: Applications & Challenges, Design of Metamaterial Unit Cell

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## Abstract

In this paper, various applications of metasurface antennas are presented and discussed. The discussion also includes the trends in designing metasurface antennas for different wireless applications. There are several challenges while designing antennas based on the metasurface concept which is also highlighted in the paper. The paper gives an indication of metasurface antennas and how they can be used to enhance certain antenna parameters. Using knowledge gained from various papers, a split ring resonator unit cell is designed and results presented. The unit cell is to behave as metamaterial, the refractive index should be negative. For this either permittivity or permeability should be negative. The unit cell has negative permittivity between 2 & 3.7GHz. and negative permeability between 4 &5.2 GHz. Hence the unit cell behaved as metamaterial in said frequency ranges.

## Keywords

***Metamaterials, Metasurface antennas, bandwidth, gain, permeability, permittivity***

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## 1.Introduction

Meta comes from the Greek Language which means to go beyond. Metamaterials means to go beyond naturally available materials i.e., to derive the material properties not feasible in naturally occurring materials [1]. All the available materials can be categorized into 4 quadrants as shown in Figure 1. The materials in the 3rd quadrant are metamaterials and materials of our interest. They are artificially engineered materials i.e.; they are the materials whose structure is manufactured in a way to get special properties of negative permittivity, negative permeability and thus negative refractive index. These properties are not available in any natural occurring materials [2]. Metamaterials are materials that are designed by arrangement of artificial structural elements. But these structural elements are themselves made out of conventional materials. In Fact, metamaterials are the next level of structural arrangement. These materials are designed in a way to produce advantageous and unusual electromagnetic [3]. Metamaterials achieve their properties from the newly designed structure and not from base material. The shape, geometry, size, orientation, arrangements of elements and compositions of inclusions in structure give the capability to manipulate electromagnetic waves. They can block, bend, enhance or absorb the waves to go beyond the properties of naturally available materials [4].

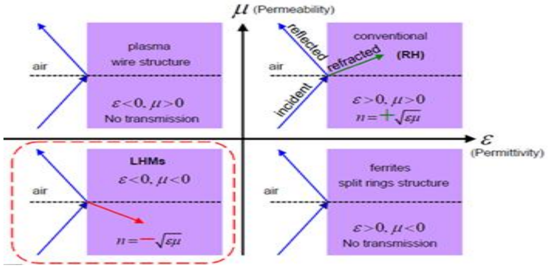


**Figure 1** Classification of materials

### 1.1Applications

Metamaterials, on account of their special properties, have found application in many spheres of science. Some of applications include invisible submarines, frequency selective surfaces, polarization manipulation, the negative refractive-index lenses, Anti-reflection metasurfaces, miniaturized and more efficient antennas [5]. Use of metasurface in antenna design is the latest and important application [6, 7]. Use of Metamaterials allow designing and creation of antennas with unorthodox characteristics not possible with conventional materials. The metasurface can be considered as a two-dimensional analogy of metamaterials. They have layers of metamaterials etched on substrates or can be used with existing configuration of conventional antennas to enhance its performance [8-10]. The properties and functionality of the metasurfaces is dictated by the specific geometrical shape of the unit cells fabricated on the substrate [11]. These materials can provide the novel characteristics of extremely low profile and enhanced performance in gain, bandwidth and radiation pattern [12-14]. The use of metasurfaces has some inherent advantages of easy fabrication, low cost of production, extremely good surface and light weight [15]. These properties have led to metasurface research expanding from microwave to optical frequencies [16].

Metasurfaces can be used in designing 2D microwave and optical lenses like Luneburg and fish-eye lenses. These can be applied to surface waveguides for antenna systems and planar microwave [17]. Applications of metasurfaces in manipulation of plane waves in free space [18] are also of extreme importance. Metasurface have the advantage of having extremely small thickness. This new development is being used in various applications such as in imaging,

cloaker, absorber, quantum communication, wave front engg.
etc. Metasurface have homogeneous radiating elements [19-21]. The size of a unit cell is very small as compared to the wavelength. The refractive phenomena in metamaterials controls other phenomena such as diffraction, scattering. These unit cells are homogeneously scattered on the substrate material to form a complete surface. The array size and periodicity affect the permittivity, permeability. As a result, the refractive index is also affected [22, 23].

## 2.Trends

Nowadays developments in antennas are evolving very fast, especially in terms of wideband, increasing the gain of the antenna, antenna miniaturization etc. One of the emerging techniques is the use of two-dimensional metamaterials known as metasurfaces. They can be used to control and alter the electromagnetic They can be embedded in a low-permittivity substrate to increase the effective permittivity and therefore minimize the antenna size. The advantage of

Metamaterial Absorber

Polarization Conversion using metamaterial

Beam Forming Network using metamaterial

Metamaterial Cloak for EMI

**Figure 2** Trends in Metamaterials

MTS are easy fabrication on general PCB materials, easily embedded on antenna and cost-effective Metamaterials and metasurfaces have demonstrated a number of applications in radar cross section (RCS) reduction and antenna design. Specifically, polarization conversion characteristics of MMs have been applied to design circularly polarized (CP) antennas with linearly polarized (LP).

## 3.Challenges

Generating and receiving millimeter waves is a challenge, but the most challenging factor is the communication medium, atmospheric and free space losses. Coverage decreases up to 16% due to path loss within 200 m. To reduce propagation loss, an antenna with high gain is desired at both the transmitter and receiver side. Using metasurface structures helps us in achieving numerous antenna performance enhancements but still designing such a metasurface for multiband and wide band applications is a tedious task. For applications like enhancing gain, bandwidth and radiation pattern, the overall size of the antenna structure including metasurface can be significant. For mm waveband the design of metasurfaces is complex as every minute change in dimensions results in significant change in performance.

## 4.Literature Review

**Chen ke et al [24]** in their research, tried to improve the antenna gain and bandwidth with phase compensation metasurface. The proposed metasurface unit cells have both inductive and capacitive elements. They took 4mm thick dielectric substrate and used 17µm copper thin film wires on both sides of the substrate as shown in Figure 3. The copper wires act as inductors and the gap acts as capacitors. Two holes of diameter 1mm are drilled in substrate material to reduce the effective permittivity. This proposed unit cell can be assumed to be a Huyzgen source having electric and magnetic dipoles cross with each other. The array of these Huygen source units completes the asurface. When the metasurface was used with conventional patch antenna, each unit changes the patch antenna radiation phase to an in-phase

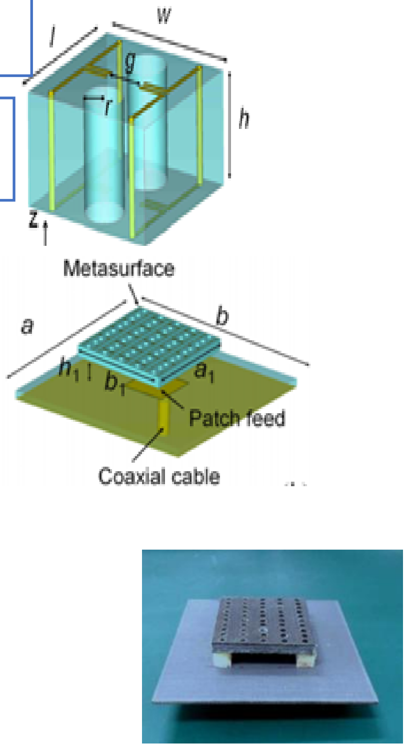


**Figure 3** Unit cell of phase compensation metasurface with resonant structure and schematic of the phase compensation antenna, and Patch antenna with modified metasurface [24]

profile. When the metasurface was energized by radiation from a linear patch antenna, each wavelength inclusion produces a different phase shift. This compensates for the phase difference that was occurring on the surface of the patch antenna. An improvement in antenna gains and double bandwidth was obtained with the use of the proposed metasurface antenna.

A wideband high gain, circularly polarized antenna was proposed by **Son Xuat [25]**. A 2×2 metasurface array was used, thus consisting of 4 metasurface units. Each unit further had a 4×4 matrix of square metasurface patches with truncated corners as shown in Figure 4. Antenna uses two layers substrates Rogers RO4003. Each single element had micro strip line feeding, rotated at 90$^{o}$ with each other to obtain circular polarity. The network printed on the bottom of substrate1, this slot acts as a radiating element of antenna.

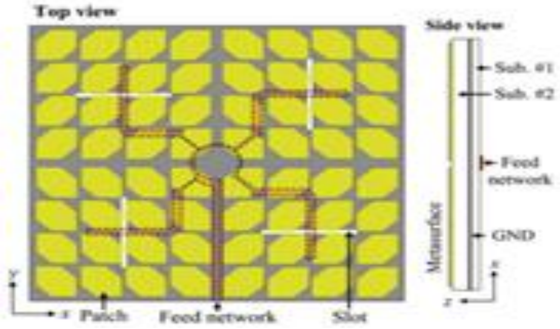


**Figure 4** Geometry of the single element [25]

They compared conventional slot antenna, 4× 4 patch antenna and proposed antenna with truncated corners in the paper as shown in Figure 5. It was realized that bandwidth of LP slot antenna 1 is increased by using simple metasurface antenna 2.

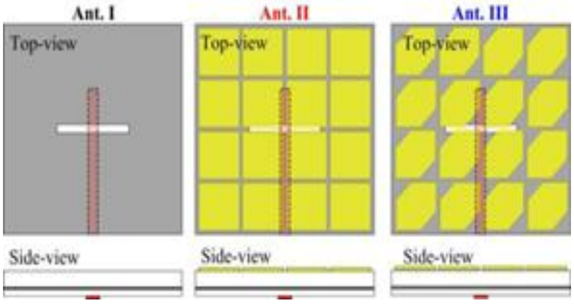


**Figure 5** Antenna 1 Antenna 2 Antenna 3 [25]

But the convention metasurface doesn't alter the polarization of the wave from the slot LP antenna. Hence a simple square unit's metasurface antenna 2 is also a linear polarized antenna. With the use of truncated corner units, the circular polarization was achieved in antenna 3. It was found out that both square and truncated corner square antennas have almost the same bandwidth but the gain of square patch becomes almost nil in between this range but truncated square patch antenna has good gain. 3-dB axial bandwidth is almost half of $S_{11}$ bandwidth as depicted in Figure 6.

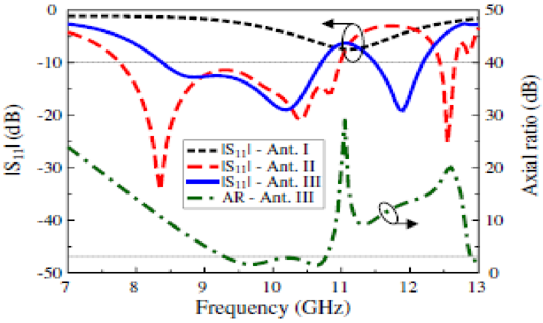


**Figure 6** Return loss and axial ratio [25]

**Wei E. I. Liu et al [26]** proposed antenna miniaturization by using single- and double-layer square patch metasurface. In the proposed antennas, an array of metasurfaces square patches was used. Bottom substrate was grounded to form waveguide feeding dielectric. The refractive index of conventional antennas was used to derive propagation constant. This was used to find the approximate frequencies at which the single and dual layer metasurface antenna will resonate. Firstly, a single layer metasurface square patch was used as shown in Figure 7. They varied the periodicity and gap between the patch to vary the refractive index of the metasurface antenna. Comparison of the bandwidth and gain with patch antenna was done as shown in Figure 8.

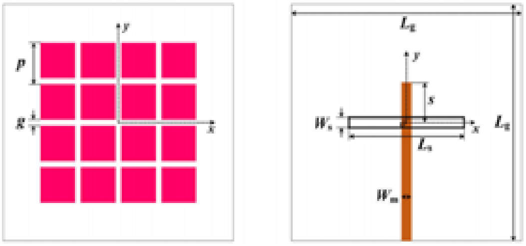


**Figure 7** Layout Single layer MTS antenna [26]

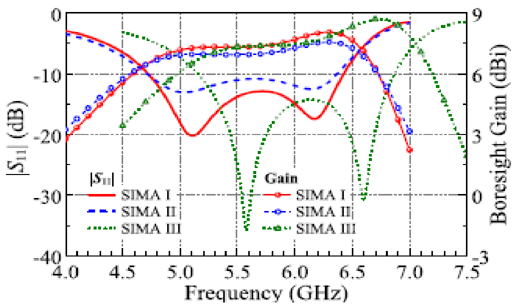


**Figure 8** Return Loss and gain of the single-layer metasurface antenna [26]

They used 6 ×6 patch and 4 × 4 square patch on top and bottom of substrate as shown in Figure 9

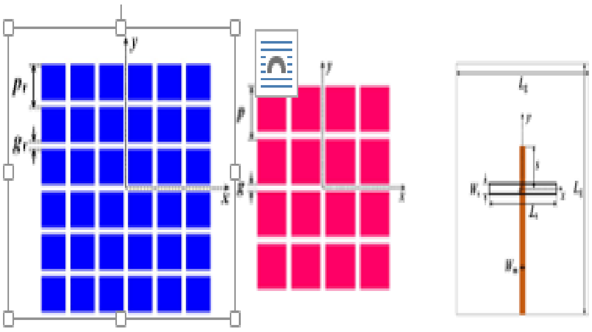


**Figure 9** Double-layer metasurface antenna [26]

The researchers varied periodicity. This dual layer antenna

had same thickness was increased by use of single and dual

layer metasurfaces, there was increased capacitive coupling.

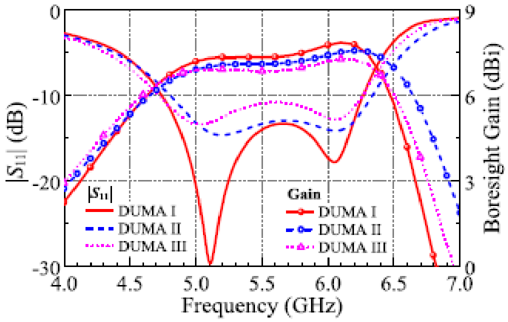


**Figure 10** Return Loss and gain of the double-layer metasurface antenna [26]

It was found out that proposed single layer metasurface antenna is suitable for low frequency range and dual layer antenna is suitable for high frequency range as shown in Figure 10.

**Neha Rajak [27]** in the research paper proposed to increase the bandwidth and gain of traditional patch antennas. A metasurface patch antenna was used as top layer and patch antenna as bottom layer in dual layer antenna. An array of split ring resonators was used as a radiating element. These split ring resonators were two metallic rings, concentric with each other. There was gap in the structure of each ring and the gaps of each ring are kept at 180° apart. The ring material acts as inductors and the gap between rings acts as capacitors and hence LC circuit is obtained as shown in Figure 11. These split rings metasurface patterns had both negative permeability and negative permittivity and behaved as a double negative material. Hence the refractive index which depends upon permeability and permittivity was also negative.

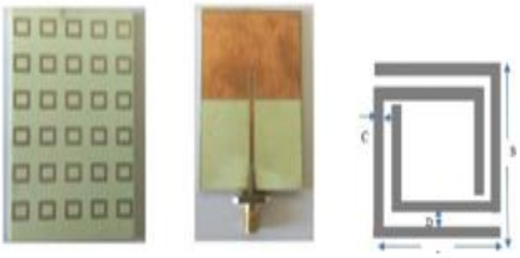
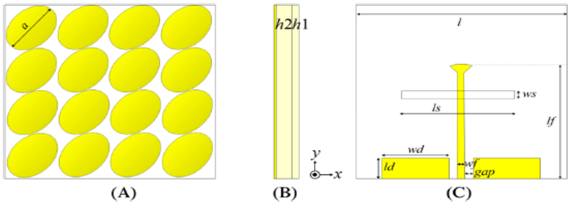


**Figure 11** A, Metasurface. B, Patch antenna. C, Unit of metasurface [27]

The wave coming from the patch antenna interacted with the metasurface pattern at the top layer and hence the equivalent permittivity and permeability of the whole structure changes. This resulted in enhancement of performance of the patch antenna. The resonance of the proposed antenna was obtained 5.7 GHz and the bandwidth enhanced from 150 to 260 MHz with gain of 5.8dBi was achieved. Increase in return loss bandwidth was also obtained, which was 39%.

**Liu Yuan [28],** in paper presented a circular polarization antenna using metasurface unit cells. The researcher proposed elliptical unit cells with their major axis rotated by 45° as shown in Figure 12. The particular unit cell shape was used to convert linear polarization waves into circular polarization. The proposed antenna utilized three layers of $FR_4$ epoxy substrate. The top most layer has a printed metasurface unit pattern, the middle layer has a ground plane and the bottom layer is CW- feeding structure. With coplanar waveguide feeding, linear polarized waves were simulated.



(A) (B) (C)

**Figure 12** Different views of antenna [28]

If the antenna was used without a top metasurface layer, it will radiate a linear polarized wave because of the slit ground plane and CW feeding structure. Let the electrical field of the antenna is E. It can be resolved into two orthogonal components E1 and E2. When we put the metasurface antenna at the top, these two components E1 and E2 will interact with the metasurface antenna. By optimizing the major axis dimension of ellipse, the angle of rotation and the periodicity of unit cells, the resultant impedance could be varied. It will result in changed induced currents and E1 and E2 will change. For circular polarization, |E1|should be equal to |E2|.

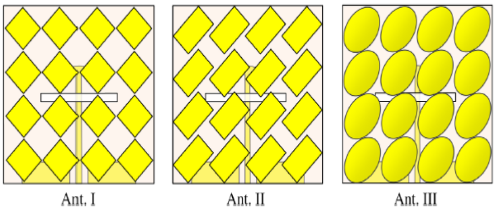


**Figure 13** Different modes in process design [28]

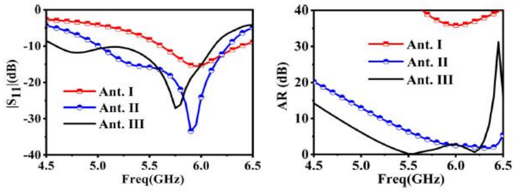


**Figure 14** Return Loss and axial ratio curves for three models [28]

By varying unit cell dimension and form, we can obtain |E1|=|E2| and (E1-E2) = 90°. This would result in circular polarization. The proposed elliptical unit cell metasurface antenna has good characteristic of excellent 3-dB AR bandwidth of 17.4% (5.25-6.25 GHz) as shown in Figure 14.

**Zheng Q et al [29]** achieved circular polarization from linear polarized incident rays. The effort was to use metasurface patches. They truncated the corner of square metasurface patches as shown in Figure 15. To achieve the miniaturization, coplanar waveguide fed structure was used. At the top layer, unit cells of truncated metasurface were printed. The slotted ground plane is at the middle layer and feeding structure at the bottom layer. They all were separated by substrate. The researcher optimized the antenna structure with help of ANSYS HFSS software. They varied the period p, edge a, length b, and width size w of unit cells to achieve a wide bandwidth antenna. As a result of truncated corners, the capacitance along different paths can be varied and hence, the circular polarization could be achieved.

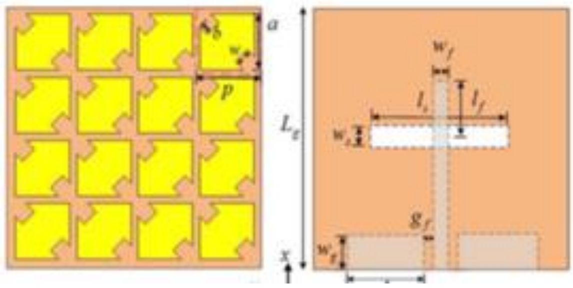


**Figure 15** Geometry of circular polarized antenna [29]

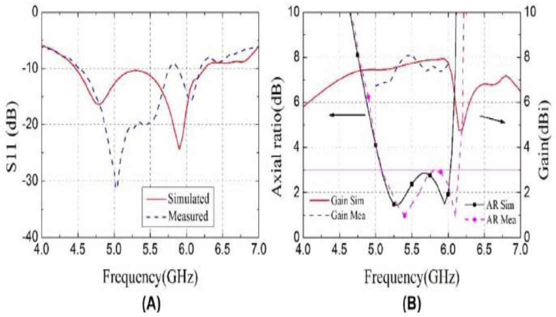


**Figure 16** Measured and simulated (A) S-parameter. (B) AR and gain [29]

They presented the simulated and measured results of S11, axial ratio (AR) and radiation gain as shown in Figure 16. In the studies they concluded that x direction polarized incident waves will be reflected with 90 ° rotation. Thus, it will be converted to its orthogonal direction. Thus, the radar cross section along x-direction will be greatly reduced and miniaturization was achieved.

**Xue Chen et al [30]** proposed miniaturized circular ring patch antennas. It was constructed by employing two layers of metasurface. The top layer has four circular shaped slots connected with each other. The lower metasurface has six rectangular shaped rings as shown in Figure 17. The etched circular shaped pattern of top metasurface improves impedance matching. The proposed antenna used two substrates. The arc shaped slots were etched on the top of substrate-1. Traditional circular patch antenna and rectangular pattern were etched on top and bottom of substrate-2. The antenna can operate in multiple bands. When the circular patch antenna was excited, the current will be induced in an interlaced circular shaped metasurface pattern on substrate-1. Also, current will be produced in a rectangular metallic pattern on substrate-2, which will induce some current in interlaced circular shaped metasurface. For a given frequency of excitation, the current in both metasurface antennas flow in one path. When the excitation frequency changes, the path in the metasurface antenna changes.

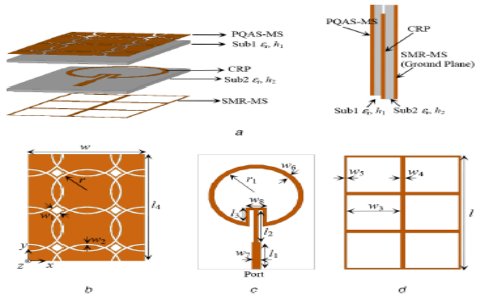


**Figure 17** Configuration of the proposed antenna [30]

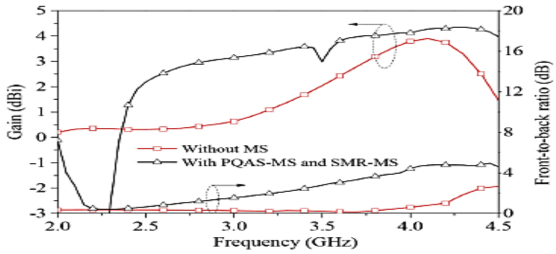


**Figure 18** Simulated gains, front-to-back ratios and electric field distribution of the antennas without and with MS [30]

Simulation was done to find the gain and $S_{11}$ ratio with respect to circular patch antenna as shown in Figure18. It was found out that with the development of dual layer metasurface antenna, the gain had improved up 3dB in a given band. The highest gain achieved is 4.35dBi at 4.3 GHz. Since in the antenna the dual layer of metasurface acts as radiator and ground plane, so $S_{11}$ is not much affected. The radiation pattern was omnidirectional.

**Zhi Ning Chen et al [31]** exited a slotted patch antenna using a Z shaped slot to achieve circular polarization. The researcher carried forward the work done earlier by using mushroom cells to enhance antenna performance. These cells had been used earlier to develop antennas, but their use as radiator was not examined to depth. In 2006, Itoh et al had developed a narrow band antenna based upon mushroom cells. In 2010, the same researcher used 2 × 2 mushroom arrays as radiators for dual band performance. But in their case, the two resonances were separated by frequency spectrum. The challenge remained to get the two frequencies to communicate.

Later in 2014, Chen et al, used characteristic mode analysis to 4 × 4 mushroom cell antennas made of metamaterials. They were able to obtain two separate bands connected with each other. There was no need to introduce a third resonance. Hence broadband response of the proposed antenna was achieved. But these mushroom antennas were linearly polarized. Their main work included developing such a feeding mechanism which produces circular polarization. The structure of the LP mushroom antenna is shown in Figure 19.

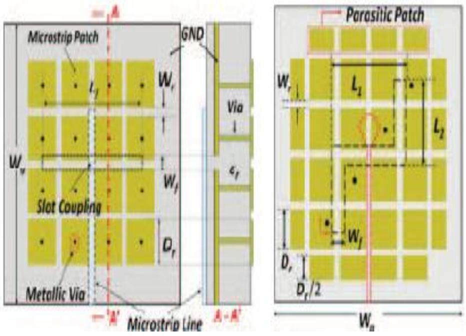


**Figure 19** Geometry of the LPMA and the proposed CP antenna [31]

But this configuration was able to produce linear polarization. The researchers pointed out that two linear

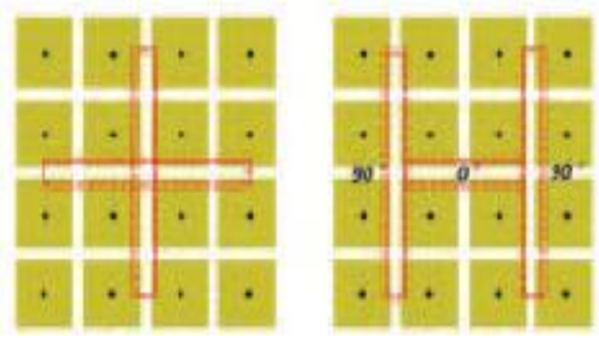


**Figure 20** Cross-shaped slot and H-shaped antennas [31]

polarizations with 90° phase difference between them will be able to convert linear polarization into circular polarization. As shown in Figure 20., the researcher under two cross shaped slots is excited and obtains equal amplitudes. But failure to produce the required 90° phase shift. The researcher used H shaped slots. In this case, it was found that the feeding slots had 90° phase difference, but these H- slots could not provide equal amplitude.

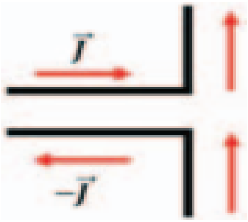


**Figure 21** Dipole antenna [31]

As out of phase electric current flowing in a pair of parallel transmission lines can be changed to in phase current by bending the two terminals of lines in opposite directions as shown in Figure 21. The researcher considered current flowing along the slot line. By bending M3 and M4 by 90°, as shown in Figure 22. They were able to excite circular polarization.

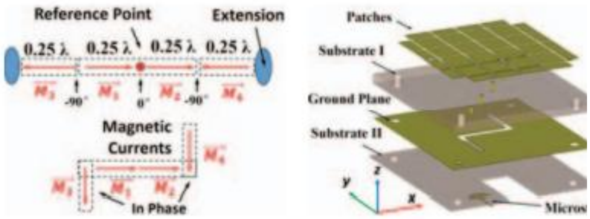


**Figure 22** Operating mechanism of feeding structure and the antenna geometry [31]

**Table 1** Observations and Summary

| **Name of Authors** | **Antenna Type/ Frequency Band** | **Observations** |
|---|---|---|
| Chen, Ke et al. [24] | Patch / Rogers<br>5.7 GHz | Metasurface with both capacitive and inductive elements.Converting spherical wavefront to planar To improve the Gain.<br>Narrow band coverage in 5.7GHz range |
| Son Xuat Ta et al. [25] | Slot antenna/ Rogers RO4003<br>8 -12 GHz | Use of sequentially rotated feed network to feed slot antenna. Metasurface has truncated corner square patches. Circular polarization is achieved.<br>3dB Axial ratio bandwidth is almost half of $S_{11}$ bandwidth. |
| Wei E. I. Liu et al. [26] | Patch / Rogers 4350B<br>5.7 GHz | Miniaturization is achieved using single and double layers of MTS. MTS consists of 4x4 square shaped unit cells. Gain is moderate in the range of 6.4 to 8 dBi even with double MTS layers |
| Neha Rajak et al. [27] | Patch / Rogers 4350B<br>5.7 GHz | Single MTS layer above the patch antenna is used.<br>MTS improved the patch antenna bandwidth.<br>Moderated Gain values of 5.8 dBi is achieved. Narrow bandwidth achieved |
| Liu Yuan et al. [28] | Patch / FR4<br>5.25-6.25GHz | Used elliptical unit cells with their major axis rotated by 45° to achieve circular polarisation.Utilized three layers FR4- epoxy substrate. Has good characteristic of excellent 3-dB AR bandwidth of17.4% (5.25-6.25 GHz). |
| Zheng Q et al. [29] | Slot antenna/ Rogers 4350B<br>4.4-6GHz | MTS consisting of truncated the corner of square metasurface patchesis used for polarization conversion. CPW fed slot antenna is used. Overall size is compact. Optimized the antenna structure with help of ANSYS HFSS softwareGain values are in the range of 7-8 dBi which is moderate. |
| Xue Chen et al. [30] | Circular Ring/ FR4<br>2.57 – 4.12 GHz | Two MTS layers one above and one bottom of the antenna are used. Wide bandwidth is achieved using two MTS.Antenna miniaturization is achieved.<br>Moderate Gain value of 4.17 dBi is achieved. |
| Zhi Ning Chen et al [31] | Mushroom(slotted patch) antenna<br>4.2 to 6.8 GHz | 4 × 4 mushroom cell antennas made of metamaterials. Excitation of a slotted patch antenna using a Z shaped slot to achieve circular polarization. |

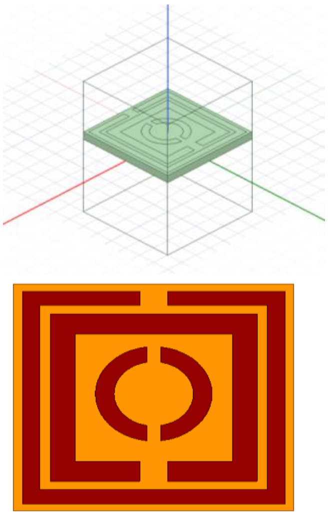


**Figure 23** Proposed novel TSRR unit cell

Proposed split ring resonator has three rings. Outer two rings are from a conventional square split ring structure, while a third double circular split ring is the innermost structure. There is a gap between the structure of each ring. The ring material acts as inductor and the gap acts as capacitor, thus obtaining the LC circuit. We have taken the substrate as $FR_4$. The dimensions of the unit cell are shown in Figure 24. All the dimensions in mm.

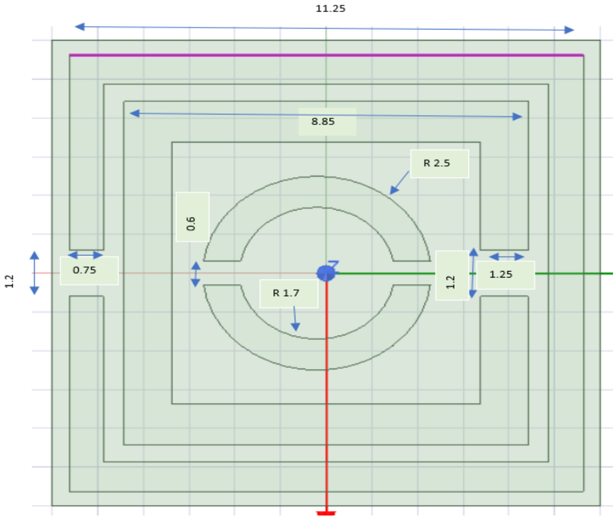


**Figure 24** Dimensions of unit cell

## 5. Result and Analysis

A novel unit cell is designed and analyzed in this section. For a unit cell act as a metamaterial, either permittivity (Ɛ) or permeability (μ) should be negative so that the refractive index is negative. This requires extraction of S- parameters. For this, repetition of unit elements in the lattice vector is required. We need to impose boundary conditions to get the periodicity of a unit cell. To simulate the periodic repetition of a unit cell, a combination of perfect electric (E) and perfect magnetic (H) boundary conditions are implemented. We have used wave port excitation to excite the structure.we have set the solution frequency between 2GHz to 6GHz.

The Figure 25 presents the metamaterial properties in terms of permittivity (Ɛ), permeability (μ), and refractive index (n). When any one of Ɛ and μ is negative or both are negative then the structure is referred as metamaterial. In the said case, permittivity is negative between 2GHz to 3.7 GHz and permeability is negative between 4GHz to 5.2 GHz.

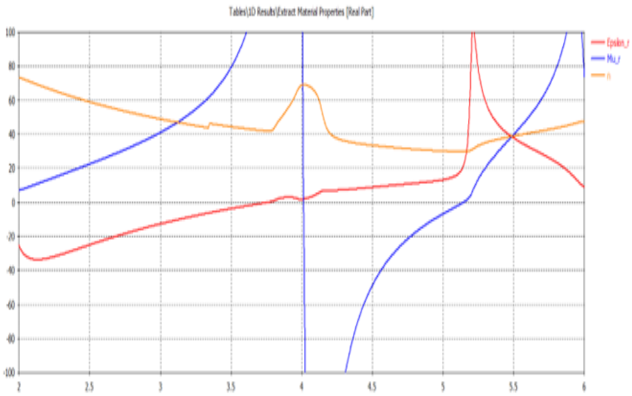


**Figure 25** Metamaterial properties of the proposed unit cell

Hence,the resonator will behave as metamaterial within this range.

## 6. Conclusion

In this paper, we have presented and discussed a few trends and challenges related to metasurface based antennas. It has been found out that the array of radiating unit cells forming metasurface alters the waves coming out of patch antenna. As the metasurface is above the patch antenna, the equivalent relative permittivity and permeability of the structure changes and therefore there is change in the performance of the patch antenna such as its gain and bandwidth.This can have major enhancements in wireless and wifi applications. We have pointed out that for multiband and wide band applications the metasuface design becomes complex. We also tried to present and discussed recent research work on metasurface antennas. A modified tri-split ring resonator is presented and its metamaterial behavior is discussed.

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