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# Multipolar Meta surface Antennas for Enhanced Radiation Performance

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**Research Article**

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# Abstract

In this paper, the design and investigation of a novel meta-surface antenna with SRRs featuring an asymmetric configuration, developed on a silicon substrate, is discussed. With the introduction of asymmetry in the form of a 2° tilt angle in the arms of the resonators, we can efficiently stimulate and combine the higher order magnetic and toroidal modes along with the fundamental electric dipole mode. Our proposed antenna, studied using the RF module in the COMSOL Multiphysics software, shows accurate control over the resonant frequency, which lies in the range of 0.375 to 0.575 THz with a maximum transmission value of 0.3899 at 0.471 THz. With thorough multipolar analysis, the scattering from the different dipoles, i.e., the electric, magnetic, and toroidal dipoles, is estimated, and we find that the radiation characteristics of the antenna are mainly due to electric dipole stimulation, along with the influence of toroidal dipoles.


# I. INTRODUCTION

Meta-surface antennas have been a topic of considerable interest due to their capability of manipulating electromagnetic waves with high efficiency. The subwavelength meta-units can control amplitude, phase, and polarization. As a result, they can be used in high-gain antennas, beam-steering applications, and even in the design of small antennas. Recently, there has been an increasing tendency in antenna science to view the enhancement of radiation from the point of view of modal interactions and not from equivalent circuits alone. In this context, multipolar analysis can prove quite helpful **[1].** In fact, near-field distributions inherently carry physical information related to the confinement, coupling, and redistribution of electromagnetic energy within the antenna geometry. On the other hand, the performance of an antenna is traditionally characterized using its gain, directivity, radiation efficiency, and radiation pattern in the far field region. Consequently, one of the critical questions in antenna design is to identify a physically consistent connection between near-field modal properties and far-field radiating performance. This article attempts to tackle this issue by examining the role of electric dipole, magnetic dipole, electric quadrupole, magnetic quadrupole, and toroidal dipole moments in shaping the radiation properties of meta surface antennas **[2]**. The primary motivation behind this research is to develop a contribution analysis methodology to establish a correlation between near-field properties and far-field radiation performance **[3]**. In particular, the target application area of the proposed method is meta surface antennas with multi-resonant structures where there exist constructive and destructive interactions among different resonances. By establishing such a relation, one can shed light on the reasons why a certain geometric configuration may result in a high gain, low back radiation, stable broadside radiation, or wideband impedance characteristics. The major contributions of this paper are as follows:

- • A rigorous technique for obtaining and analyzing multipole effects from near-field simulations of currents.
- • The development of a relationship between the modal dominance concept and far-field radiation characteristics like gain, directivity, and pattern behavior.

- • The application of the knowledge about multipolar interaction to improve antenna radiation using meta-surface antennas

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well as whether periodic or quasi-periodic, electric and magnetic resonances and even higher order modes may appear simultaneously. Asymmetric structure, slotting, gap splitting and resonator coupling can cause changes in the current pathways leading to hybrid excitation using more complex polarizations of multiple sources **[4]**. This implies that the near field of such an antenna cannot be regarded as one common mode but rather comprises of unique current distributions for each individual channel of radiation. A current that flows linearly will result in an electric dipole effect, while circulating currents on the surface will give rise to magnetic dipole excitation.

Complex current distribution in magnetic dipoles will result in toroidal dipole excitation. Also, complex charge and current distribution may lead to quadrupole excitations affecting side lobes and cross-polarization **[5]**. The improvement in radiation characteristics of the meta surface antenna is thus

understood to arise from the balance between the multipolar components. If the major components interfere constructively in the desired direction of measurement, the radiation gain is improved. Otherwise, an out-of-phase combination of these modes may lead to suppression of radiation or loss reduction in unwanted directions **[6]**.

# III. MULTIPOLE CONTRIBUTION ANALYSIS

Multipole decomposition provides a mathematical bridge between induced current density and radiated fields. For a time-harmonic current distribution $\mathbf{J}(\mathbf{r})$, the lowest-order radiating moments may be expressed through electric (p), magnetic (m), and toroidal terms (T). The electric dipole moment is written as

$$\mathbf{p} = \frac{1}{-\mathrm{i}\omega} \int \mathbf{J}(\mathbf{r}) \, \mathrm{d}^3\mathrm{r}$$

1

while the magnetic dipole moment is given by

$$\mathbf{m} = \frac{1}{2} \int \mathbf{r} \times \mathbf{J}(\mathbf{r}) \, \mathrm{d}^3\mathrm{r}$$

2

and the toroidal dipole moment is commonly represented as

$$\mathbf{T} = \frac{1}{10\mathrm{c}} \int \left[ (\mathbf{r} \cdot \mathbf{J}(\mathbf{r})) \mathbf{r} - 2\mathrm{r}^2 \mathbf{J}(\mathbf{r}) \right] \mathrm{d}^3\mathrm{r}$$

3

where $\omega$ is the angular frequency and $c$ is the speed of light. In practical full-wave simulations, these moments are evaluated from current distributions obtained on the metallic and dielectric regions of the antenna. The radiated power contributions of different moments can then be compared across frequency to determine the dominant modal regimes **[7]**. In the suggested workflow, the first step involves conducting a full-wave simulation of the meta surface antenna using either a finite element or finite integration electromagnetic simulator. The surface currents, electric field intensity, magnetic field concentration, and charge distribution at the resonance condition as well as nearby off-resonance frequencies are measured. Post-processing of the obtained data enables us to determine whether the resonance that is present is of the dipole, toroidal, or quadrupole type. After that, the moments are normalized to a common scale and shown as a function of the frequency for detecting mode interactions **[8]**. The multipolar analysis provides significant benefits particularly in those situations where the only information on the performance we have comes from the far-field. Thus, two antennas

with identical resonances but varying gain and front-to-back ratio can be analyzed in terms of dipolar radiation, toroidal assistance, and parasitic mode suppression.

# IV. CORRELATION BETWEEN NEAR FIELD AND FAR FIELD

The near-field condition refers to localized energy storage and current flow, while the far-field condition pertains to energy transfer to the surrounding space from the antenna. A connection can be made between the two by following the transformation process of certain near-field characteristics into far-field parameters. The presence of strongly localized currents along a linear direction is favorable for the generation of electric dipole radiation in a broadside

However, the formation of currents that form loops signifies magnetic dipole excitation. Toroidal dipole excitation is of special interest due to its appearance as a consequence of poloidal current loops, which generate a closed magnetic vortex structure. For meta surface antennas, the mode can decrease radiated power losses in certain arrangements but increase directionality in other cases through interaction with electric dipoles. If there are proper phase and amplitude relationships between the electric and toroidal dipoles, then the far-field pattern may show improvements in its peak sharpness, directivity, and sidelobe levels **[9]**. Higher-order moments are also important for shaping antenna radiation patterns. Electric quadrupoles and magnetic quadrupoles are usually generated in cases where the currents have a non-uniform spatial distribution in the radiating aperture. The modes may distort the pattern through excessive sidelobes and cross polarization or assist in beam shaping if intentionally introduced. Therefore, any gain in radiation must be considered as an effect of optimized modal content rather than just resonance amplification.

Such a correlation process can be outlined as:

- • Find resonant frequencies by reflection coefficient or impedance considerations.
- • Plot the distributions of surface currents, the electric fields, and the magnetic fields at these resonances.
- • Employ simulated currents to compute electric, magnetic, toroidal, and quadrupole moments.
- • Analyze the modal power spectra compared to gains, directive gains, radiation efficiencies, and pattern shapes.
- • Figure out what particular modal combination is causing such an increase.

# V. EXPECTED RADIATION ENHANCEMENT MECHANISMS

A number of physical effects responsible for improved radiating characteristics in multipolar meta surface antennas include constructive interference between the major electric and magnetic dipoles. When they radiate coherently in the broadside direction, the magnitude of far field becomes greater, and, as a result, radiation gain is improved. Another effect is elimination of nonradiative or weakly radiating parasitic modes that minimize reactive energy storage. Another effect responsible for improved radiation

performance is an aperture homogenization. When the meta surface design manages to increase the uniformity of the surface currents on the radiating surface, effective aperture usage is increased, resulting in improved directivity of the antenna. Yet another effect responsible for better radiating performance is electromagnetic energy confinement and release assisted by the toroidal component. In this case, the energy is confined near the antenna surface but effectively coupled to radiating channels due to interactions with dipolar moments. Finally, a similar approach can be used to explain the phenomenon of bandwidth improvement. When resonances of closely spaced multipoles overlap appropriately, they contribute to a single operational bandwidth instead of having individual resonances at distinct frequencies. On the other hand, uncontrolled higher order excitations can adversely affect pattern matching and impedance tuning **[10]**.

# VI. DESIGN METHODOLOGY

The design for the proposed split-ring resonator (SRR) meta-surface antennas has been done according to an optimization approach for better radiation performances. The design starts with choosing the right unit cell configuration that can support multiple modes of currents which is achieved here through the use of two symmetric and asymmetric square SRRs fabricated on a silicon wafer **[11]**. The design geometry is characterized by a 3 μm gap spacing between the SRR elements along with a 6 μm width of the trace. In order to induce higher-order magnetic and toroidal mode resonances, asymmetry is introduced through the tilting of one arm at 2° along with other two arms at 0° and 2°. All numerical analyses have been done through COMSOL Multiphysics RF Module with user-controlled fine meshing settings (maximum element size 80 μm with minimum size of 10 μm) **[12]**. Simulation has been done with parametric sweep analysis from 0.375 THz to 0.575 THz for $S_{11}$ reflection parameter and near-field plots.

Therefore, for surpassing the classical circuit theory, the multi-pole decomposition technique is used for measuring the values of electric, magnetic, and toroidal scattering power, WP, WM, and WT, respectively, to determine the physical processes responsible for the performance of the antenna.

# VII. RESULTS AND DISCUSSION FRAMEWORK

Two sets of square split ring resonators (SRRs) were designed on silicon substrate using FEM (Finite Element Method) in COMSOL Multiphysics where the gap distance between the resonators was 3 μm and the resonator trace width was 6 μm. While one set of SRR was made symmetric, having both arms tilted at 2° from the horizontal position, the other set was made asymmetric, with one arm being at an angle of 2° and the other being 0° **[13]**. The entire area covered by the SRR is 5217.3 μm², the volume is 503.95 μm³, the inner perimeter is 186 μm, and the outer perimeter is 239.97 μm **(**Fig. 1**(a))**. The corresponding fine meshing image is shown in the **(**Fig. 1**(b))**.

The mesh created for the SRRs that exist on the silicon substrate is shown in **(**Fig. 2**(a)&(b))**. The 3D view of the detailed mesh can be seen in **(**Fig. 2**(a)).** The xy-plane view of the mesh on the two SRR

antennas. It is evident from the figures that a high density of meshes has been created in an effort to ensure quality elements, which are necessary for electromagnetic simulation and calculation of resonant frequencies in the RF module **(**Fig. 2**(b))**. User defined fine mesh was used in COMSOL Multiphysics using General physics settings, where maximum element size was kept at 80 μm, minimum element size was taken as 10 μm, maximum element growth rate was set at 1.45, curvature factor as 0.5, and narrow region resolution as 0.6 **[14]**.

The mesh statistics for the SRR structure, generated in COMSOL Multiphysics, are summarized as: The finite-element mesh comprises 62,270 domain elements, 1,237 edge elements, and 106 vertex elements, with a total mesh volume of $1.28 \times 10^{7}$ μm³. The quality of these elements is assessed through a histogram, which shows an average element quality of 0.5282, indicating a well-balanced discretization for the simulation. The minimum element quality recorded is 0.00271, with an element volume ratio of $2.951 \times 10^{-10}$. In element quality histogram, 1 means perfect element shape in the chosen quality metric (best possible, fully regular element). 0 means degenerated element (collapsed or nearly collapsed, extremely poor quality). The complete setup of SRR, more elements show near 1 which reflects better over all mesh in all the elements qualities values between 0 and 1**(**Fig. 3**(a))**. Mesh qualities enhance in the as histogram bars move towards 1 in the domain (Volume) part of the SRR (Split Ring Resonators) **(**Fig. 3**(b))**. The histogram bars are near 1 reflects better mesh element qualities on boundaries (Surface) in the SRR **(**Fig. 3**(c)) [15]**.

For the frequency-domain response of the SRR antenna structures, the FEM was conducted on a parameter sweep of 0.375 to 0.575 THz in steps of 0.004 THz. From the transmission spectrums, it can be noted that there are clear resonant features that correspond to each configuration of the SRR antenna structures **[16]**. For the first SRR structure configuration, the maximum transmission point is 0.3899 with a resonant frequency of 0.471 THz. For the second SRR antenna structure configuration, the transmission value of 0.16274 is observed at 0.467 THz **(**Fig. 4**(a))**.

Decomposition of the multipolar scattered power from the SRRs antennas shows a very clear ranking for the modes participating in the formation of the scattered power. The scattered power is mostly associated with the electric dipole (WP) mode with its maximum value of $4.846 \times 10^{-11}$ W at 0.4671 THz. Second is the toroidal dipole (WT) mode, which has a maximum scattered power of $9.647 \times 10^{-13}$ W at 0.4661 THz. However, the scattered power associated with the magnetic dipole (WM) mode is negligibly small with a maximum value of only $9.027 \times 10^{-15}$ W at 0.4669 THz. Thus, it can be said that the scattering features of the proposed SRR antennas are mainly due to the electric dipole excitation, with an auxiliary role played by the toroidal dipole excitation **(**Fig. 4 **(b)) [17]**.

Electric field intensity distribution for the SRR antennas at 0.575 THz, showcasing strong field localization near the split-gap regions, which is approximately in the range $(0.6 - 1.67) \times 10^{7}$ V/m **(**Fig. 5**(a))**. $S_{11}$ denotes the input reflection coefficient (return loss) of the antenna, representing the fraction of incident power that is reflected back from the feed port due to impedance mismatch **(**Fig. 5**(b)) [18]**.

### A. Reflection and Bandwidth

Simulation in the frequency domain (0.375–0.575 THz) reveals individual resonant modes. For the first SRR structure, the highest level of transmission is achieved at 0.3899 at 0.471 THz, whereas for the second structure, there is a shift in the resonance to 0.467 THz with a level of transmission $(\mathrm{S}_{21})$ of 0.16274.

### B. Near-Field Maps

From near-field analysis on resonance frequencies, there is a clear concentration of charges on the splits at the resonant gaps. The field profile shows that there is mainly an electric dipole mode because of the presence of linear field lines within the gap, along with secondary toroidal coupling due to asymmetric structure.

### C. Multipole Spectra

Multipolar decomposition confirms that the scattering response is dominated by the WP, peaking at $4.846 \times 10^{-11}$ W at 0.4671 THz. The WT provides a secondary contribution $9.647 \times 10^{-13}$ W at 0.4661 THz, whereas the WM remains suppressed $9.027 \times 10^{-15}$ W at 0.4669 THz, confirming the electric-dominated nature of the radiator.

### D. Far-Field Performance

These measured radiation characteristics match with the prevailing electric dipole mode to give a broadside directive emission. The consistency between the far-field gain values and the modal power calculation is an indication that the asymmetry-driven coupling has improved the directive performance of the antenna [18].

### E. Comparative Analysis

A comparison of symmetric and asymmetric SRR designs demonstrates that incorporating asymmetry into the structure leads to a successful combination of multipolar modes. The transmission shifting and additional toroid mode excitation occurring in the asymmetric design contribute to the enhancement of radiation control. This proves that the proposed meta-surface asymmetry provides better results for antennas.

## VIII. CONCLUSION

A systematic design approach for SRR-based meta-surface antennas exploiting asymmetry for improved radiation properties was presented. As proved via our parametric FEM study, tuning geometries lead to significant changes in resonant frequency bands and transmission magnitudes, allowing considerable freedom of band choice. By applying the concept of multipolar spectral decomposition, an obvious structure of modes can be observed, in which an electric dipole moment mode plays a major role and

can be greatly strengthened by asymmetry for higher field confinement and radiative properties. The combination of multipole decomposition and the classical concept of reflection coefficient provide a valuable means of designing efficient terahertz antennas. The next step will be to fabricate such meta-surface elements and examine their multipolar interactions in a THz environment.

# Declarations


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# Figures

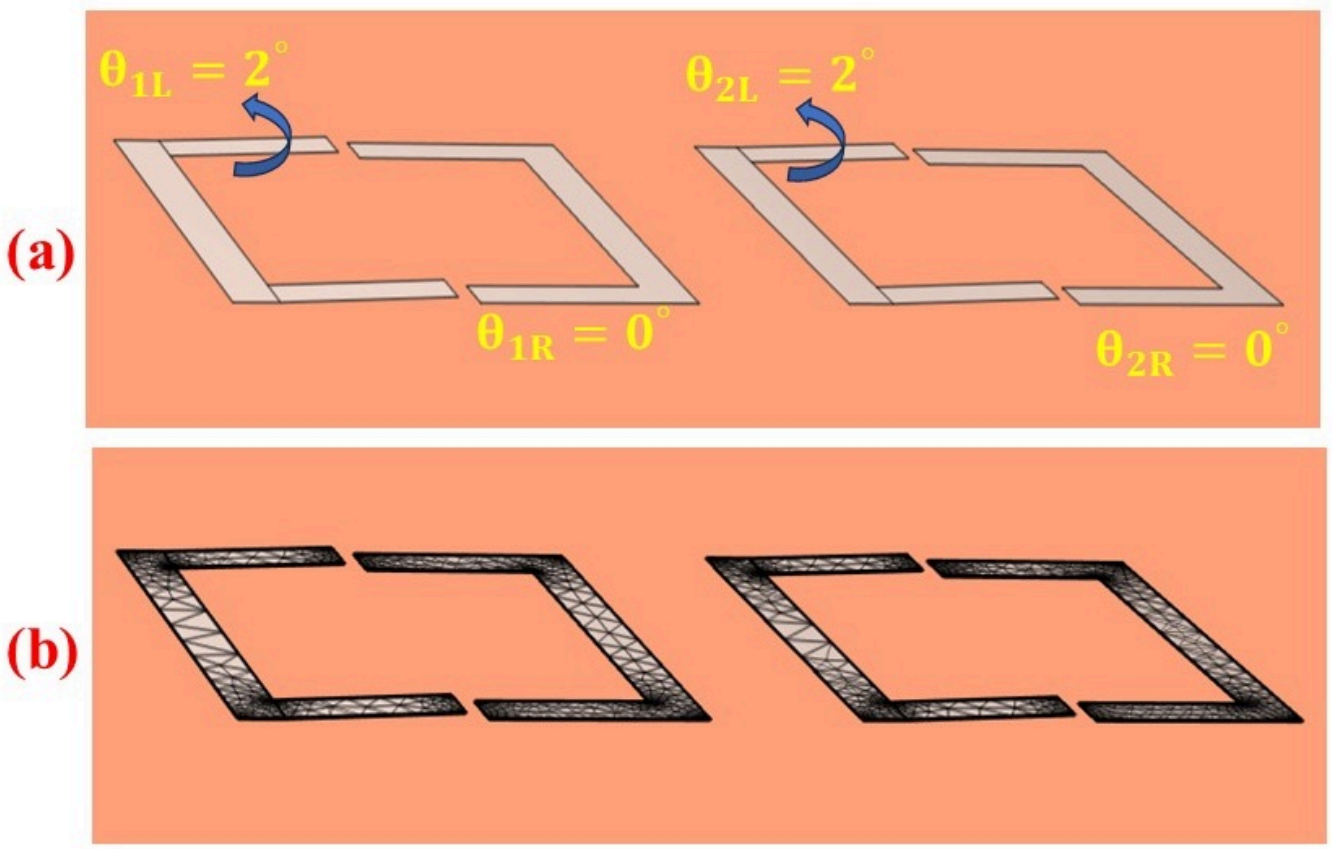



**Figure 1**

(a) Geometry of the SRRs-antenna modeled in COMSOL Multiphysics, showing the arm orientations; (b) corresponding fine finite element mesh of the SRR.

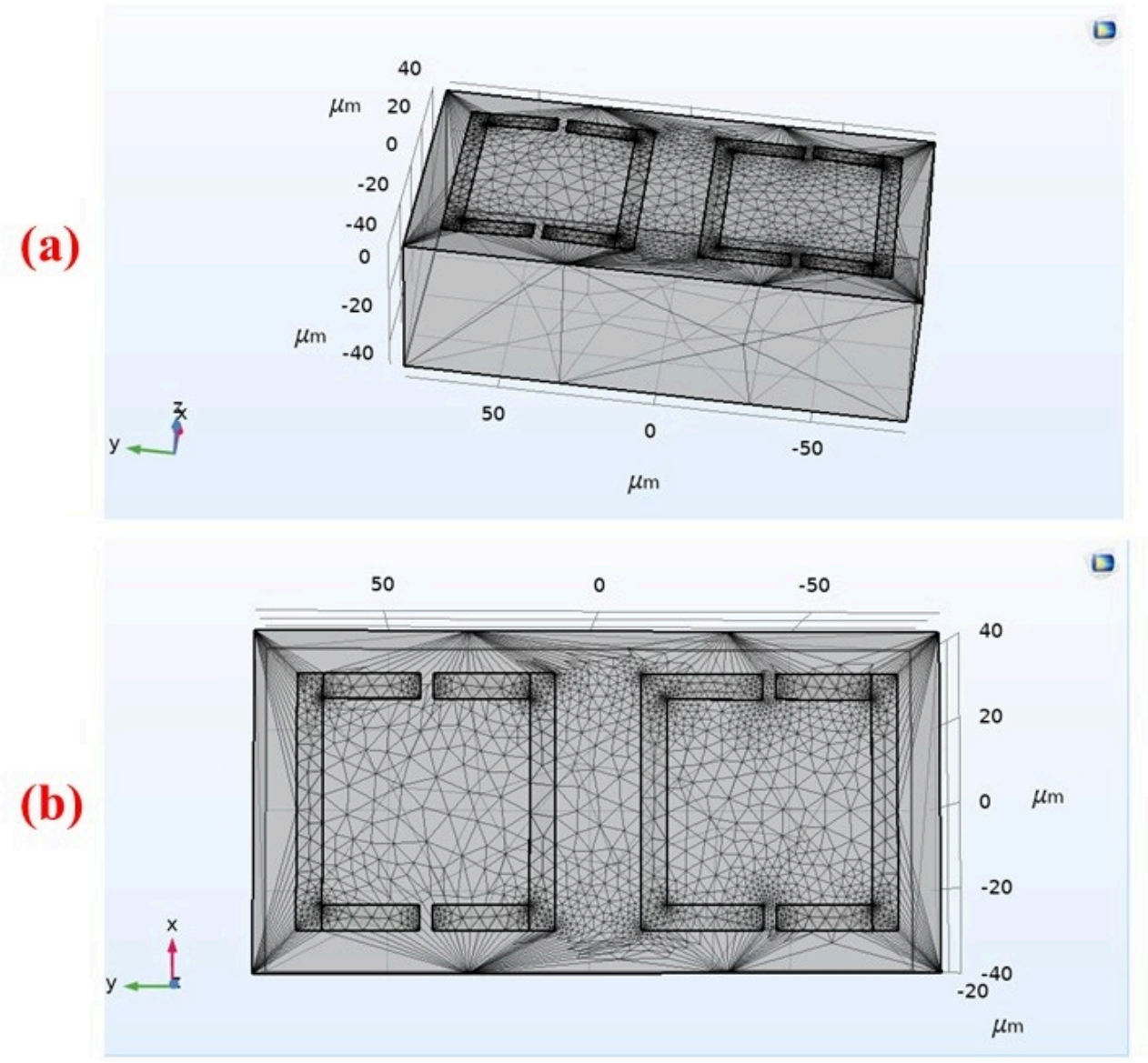



**Figure 2**

(a) Fine 3D mesh of the SRR antennas on the silicon substrate; (b) in-plane view of the fine mesh of the SRR antennas

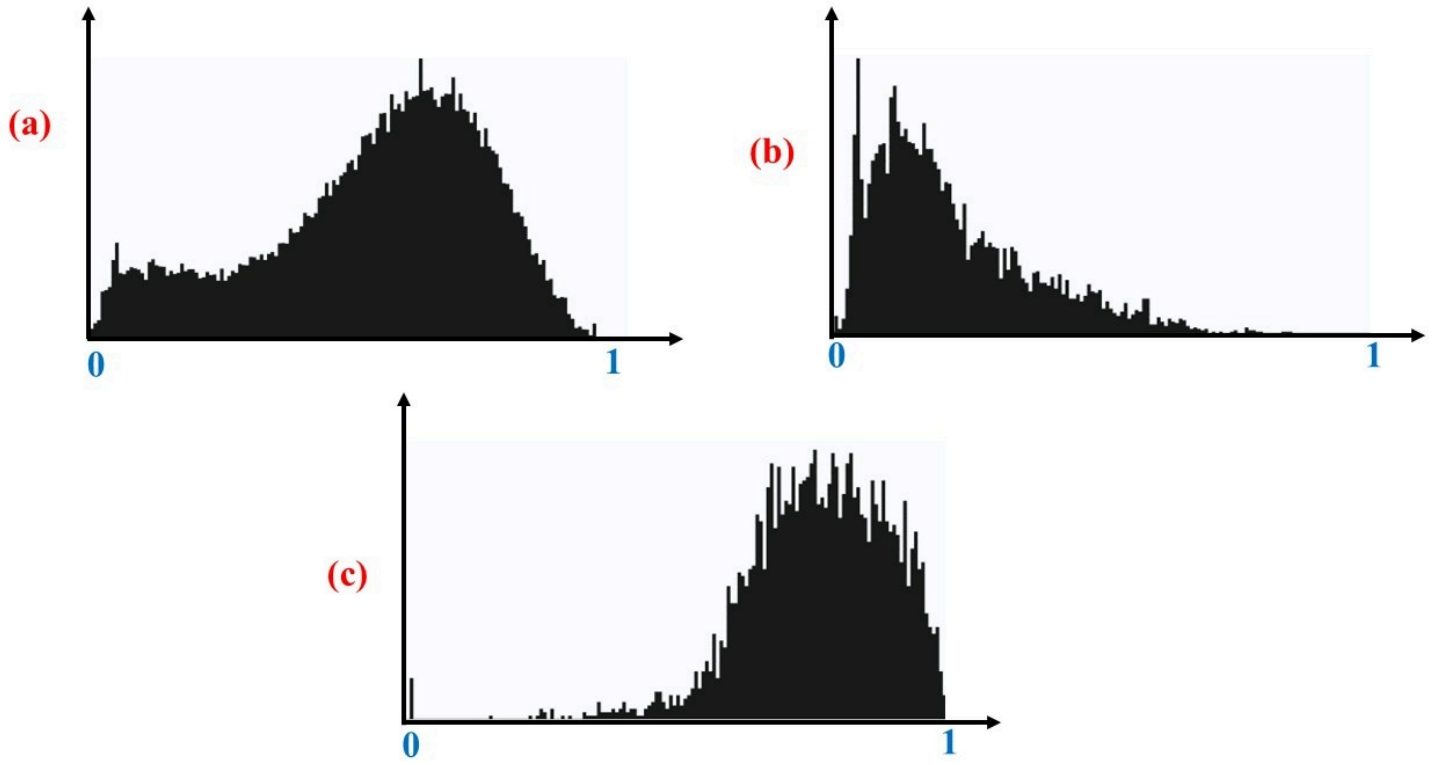



**Figure 3**

Distribution of mesh quality measure in SRRs antennas; (a) entire setup; (b) Domains (Volume); (c) Boundaries (Surface)

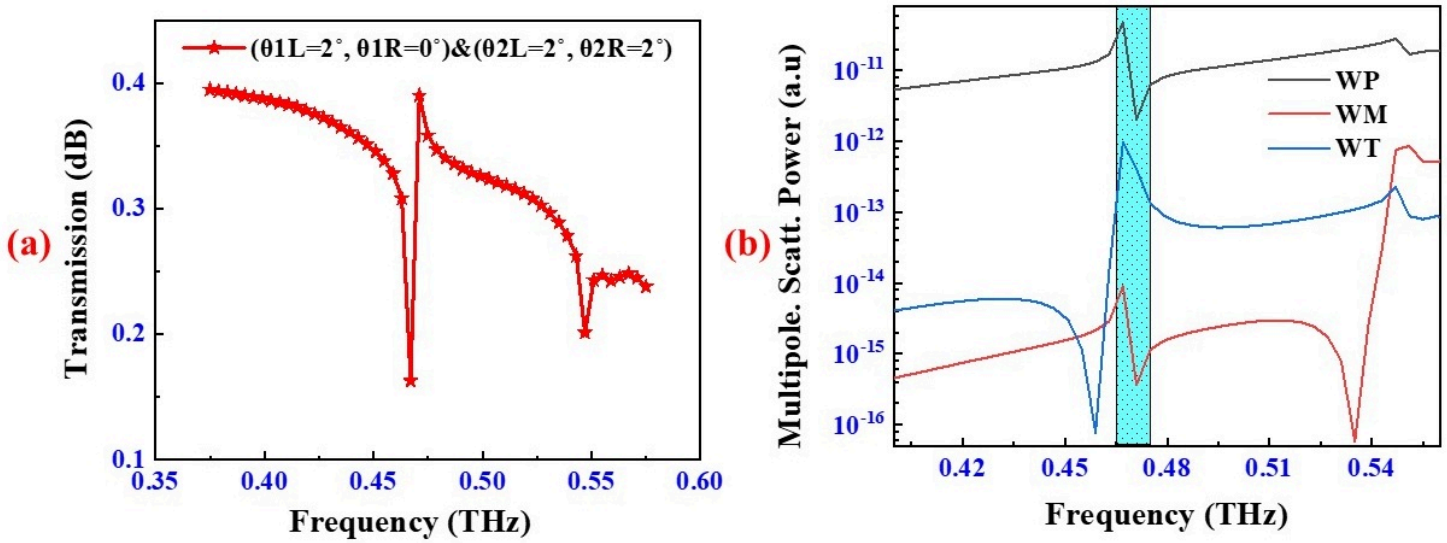



**Figure 4**

(a) Frequencies versus Transmission (b) Frequencies versus Multipoles Scattering Powers in SRRs antenna

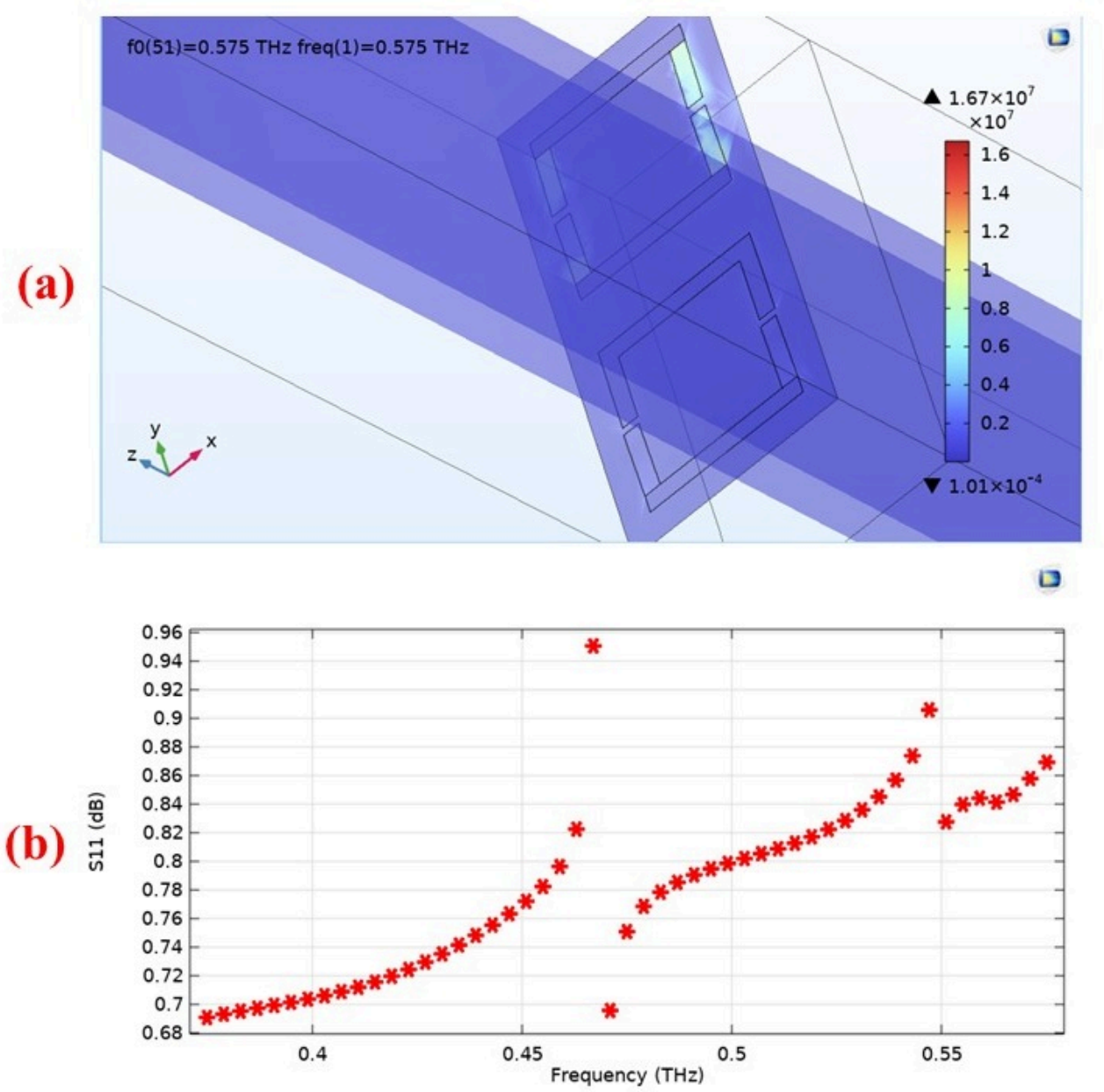



**Figure 5**

(a) Electric field distribution of the square SRRs antennas simulated; (b) Simulated $S_{11}$ reflection coefficient plot of the SRR antenna structure across the frequency range of 0.375–0.575 THz in COMSOL Multiphysics