International Journal of Information System & Innovative Technology 4(2) (2025) 30-35

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Reflection Phase Characterization of Metasurfaces Enabling Reflection and Transmission in Wireless Systems

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Article Info

Article history:

Received November 10, 2025
Revised December 12, 2025
Accepted December 24, 2025

Keywords:

Metasurface
RIS
Reconfigurable Antennas
Metamaterial
Wireless Communication

ABSTRACT

This paper presents the design and analysis of metasurfaces for surface-based wireless communication systems. Metasurfaces are widely used as reflecting or transmitting surfaces in wireless communications. The reflection phase characteristic of a metasurface plays an important role in determining its operating behavior, namely whether it functions as a reflector or a transmitter. In this work, a comprehensive analysis is conducted to obtain two distinct reflection phase characteristics of metasurface unit cells. The unit cells are analyzed at an operating frequency of 3.5 GHz. It is observed that the unit cell exhibits a reflection phase close to 0° when designed using two rectangular rings, while a reflection phase close to 180° is achieved when the unit cell is modeled as a square ring. In both designs, the unit-cell substrate size is fixed at 16.25 × 16.25 mm². The presented reflection phase characterization provides a clear design guideline for selecting metasurface unit-cell geometries to support reflection and transmission functionalities in future surface-based wireless communication systems.

1. INTRODUCTION

Metasurfaces are two-dimensional arrays of subwavelength-scale resonant structures engineered to control and manipulate electromagnetic waves with unprecedented precision [1], [2]. These structures are typically arranged on a planar surface and can produce exceptional electromagnetic properties, such as negative refractive index, anomalous reflection, polarization conversion, and wavefront shaping, by tailoring the geometrical parameters and material properties of individual meta-atoms [3], [4] In antenna designs, metasurfaces offer a paradigm shift by providing a versatile platform for tailoring the electromagnetic properties of antennas and controlling their radiation characteristics with high efficiency and accuracy [5]. Unlike conventional antennas, which rely on bulky and complex configurations to achieve desired functionalities, metasurface-based antennas leverage the compactness, flexibility, and scalability of metasurface structures to realize novel antenna functionalities, including beam steering, polarization manipulation, frequency agility, and low-profile integration[6].

Integrating metasurfaces with antennas offers several advantages such as enhanced performance, compactness and miniaturization, versatility and reconfigurability [7]. In such a scenario, switchable metasurfaces further extend the functionality of metasurface-based antennas by introducing dynamic tunability and reconfigurability into the metasurface structure. By incorporating switchable elements, such as PIN diodes, varactors, or phase-change materials, into the meta-atoms, switchable metasurfaces enable real-time control over the electromagnetic properties of antennas, opening new possibilities for adaptive and agile antenna systems [8].

In this work, the characteristics of metasurface is analysed in terms of reflector and transmitter. In particular, reflection phase results is analysed to study the metasurface characteristic.

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2. DESIGN METHODOLOGY

The unit cell metasurface is design on Rogers RO4003 C with dielectric constant of 3.55, dissipation factor of 0.0027 and a thickness of 1.524 mm. The size of the unit cell is 16.25 × 16.25 mm².

2.1. Square ring resonator unit cell design

Ring resonator is widely used in metasurface design where square ring or circular ring were adopted [9], [10]. In this work, A simple square ring is adopted to study the effect towards the reflection phase. The unit cell design with square ring is shown in Figure 1. The material of the ring resonator is copper with thickness of 0.0035 mm. The width of the ring is 1 mm. The rest of the dimensions are highlighted in Figure 1.

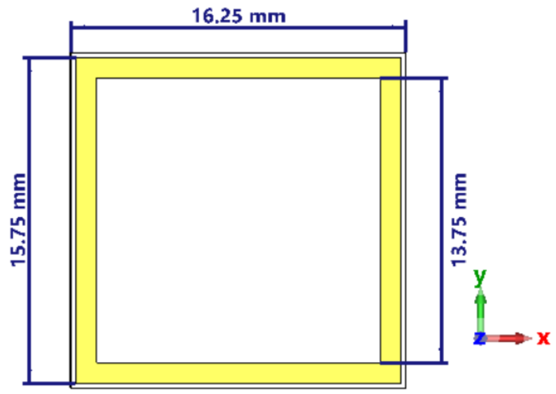

Figure 1. Square ring resonator metasurface

2.2 Rectangular ring resonator design

The rectangular ring resonator is designed on a substrate of size 16.25 × 16.25 mm². Therefore, two ring resonators can be accommodated on the unit-cell surface, as shown in Fig. 2. The width of each ring is maintained at 1 mm, and the ring resonators are separated by a gap of 1.5 mm. No ground plane is present on the bottom side of the unit cell. The unit cells are simulated using CST Studio Suite 2024 for three-dimensional electromagnetic analysis.

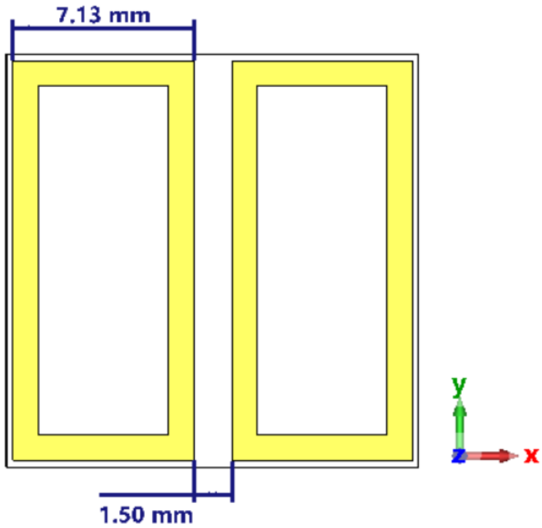

Figure 2. Rectangular ring resonator metasurface

3. RESULTS AND DISCUSSION

This section presents the result obtained for both type of unit cells. The magnitude and reflection phase results are presented.

3.1 Results of Square Ring Resonator

Figure 3 shows the results obtained for square ring resonator-based unit cell. The magnitude results shows that the unit cell resonates near 2.5 GHz. Figure 3(b) shows the reflection phase result. At the desired frequency of 3.5 GHz, the unit cell is having reflection phase 180°. At this condition, the unit cell will act as transmitter for 3.5 GHz frequency. For better understanding, it should be noted that the unit cell acts as reflector when the reflection phase is 0. In this case, the unit cell can act as reflector near 2.5 GHz.

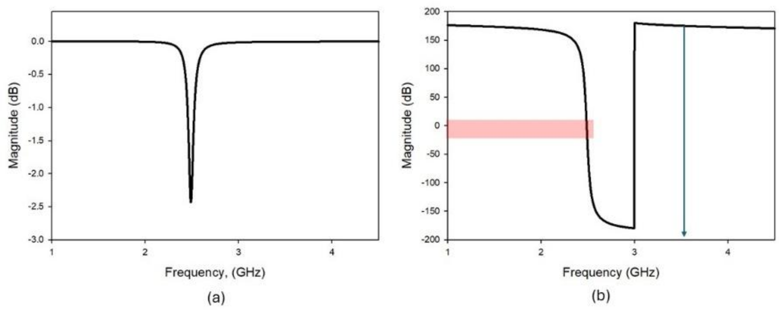

Figure 3. Rectangular ring resonator metasurface

3.2 Results of Rectangular Ring Resonator

Figure 4 depicts the unit cell result of the rectangular ring resonators. The magnitude results shows that unit cell resonates near 3.5 GHz. At this frequency, the unit cell is proven to act as reflector as the reflection phase is near 0°, as shown in Figure 4(b).

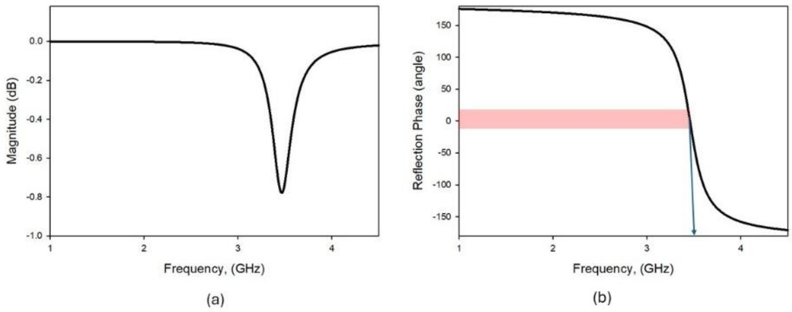

Figure 4. Rectangular ring resonator metasurface

3.3 Surface current distribution comparison

The surface current distribution is observed for both ring resonators. It shows that, the surface current is highly distributed for each of the resonant frequencies. Figure 5 shows the result for square resonator. The maximum current distribution value is 775 A/m. For 3.5 GHz frequency, the surface current distribution is 40.62 A/m.

Figure 6 shows the surface current distribution for rectangular resonator array. The surface current value at 3.5 GHz frequency is 249 A/m.

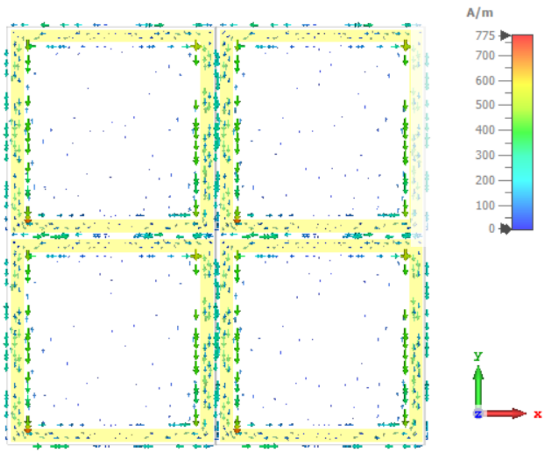

Figure 5. Square resonator array current distribution at 2.5 GHz

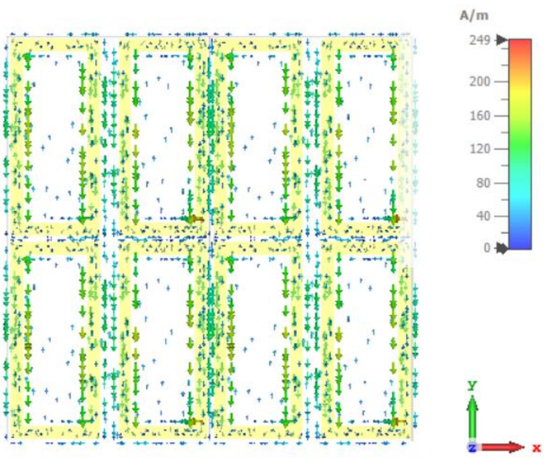

Figure 6. Rectangular resonator array current distribution at 3.5 GHz

4. CONCLUSION

This paper presents a comprehensive study of metasurfaces with respect to their reflecting and transmitting properties. Understanding these properties is essential prior to designing metasurface arrays for wireless communication applications such as reconfigurable intelligent surfaces (RIS), transmitarrays, reflectarrays, and absorbers. Based on the conducted analysis, at an operating frequency of 3.5 GHz, the square ring resonator behaves as a transmitter, as its reflection phase is close to 180°. In contrast, the rectangular ring resonator functions as a reflector, since its reflection phase is close to 0°.

5. ACKNOWLEDGMENT

This work was funded by Ministry of Higher Education through the Fundamental Research Grant Scheme (FRGS) under grant number FRGS/1/2021/TK0/UNIMAP/02/36.

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