

Research Article

A Reconfigurable Reflectarray Structure Based on Metamaterial Unit Cells for 5G Applications

Reham Mahmood Yaseen ^{1,*} , Ali Khalid Jassim ¹ 

¹ Department of Electrical Engineering, College of Engineering, Mustansiriya University, Baghdad, 10011, Iraq

* Corresponding Author: Reham Mahmood Yaseen, E-mail: reham-mahmood@uomustansiriya.edu.iq

Article Info	Abstract
Article History	This article presents the design and analysis of the reconfigurable reflectarray structure based on metamaterials for Sub-6 GHz 5G applications. The proposed reflectarray structure is printed on a 1 mm-thick FR4 dielectric substrate with a total size of $180 \times 180 \text{ mm}^2$. The reflectarray consists of 144 unit cells, each with dimensions of $15 \times 15 \times 1 \text{ mm}^3$. The unit cell design is a single layer based on multi-concentric square rings. A single layer is used to achieve a negative constitutive parameter ($-\epsilon_r$ or $-\mu_r$); multiple rings of different sizes provide a wide reflection bandwidth to improve the performance of the reflective surface. Dual bands of reflection were observed. The first band of reflection is 2.6 GHz, 1.98-4.6 GHz, and the second band is 1.71 GHz, 7.41-9.1 GHz. Two PIN diodes are used in each unit cell of the reflectarray structure for reconfigurable behavior achievement. Depending on the diode states, the phase distribution across the proposed reflectarray structure changes, and the incident waves are reflected at different angles. This work conducted a comprehensive analysis of S-parameters, constitutive parameters, and refractive index, based on full-wave analysis. The CST Microwave Studio software package was used to design and analyze the proposed design structures. A good agreement was observed between the measurement results and those from the simulation.
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1. Introduction

Metamaterials (MTM) are defined as materials with unique properties not found in nature [1-3]. Such properties are achieved by structuring and engineering structures in certain sets. The constitutive parameters, μ_r and/or ϵ_r , of the MTM structures are dependent on the unit cell shape, arrangement, orientation, and size that must be in the range of fraction wavelengths [4]. In 1967, Victor Veselago introduced a material that gives negative constitutive parameters ($-\epsilon_r$ and $-\mu_r$) called left-handed materials. Veselago proved that the phase velocity of such materials can be anti-parallel to the direction of the Poynting vector and opposed to the propagation of waves in natural materials [5]. Later, John Pendry proposed a material that provides a $-\epsilon_r$ by arranging an array of wires along the propagation of the wave, which is not governed by the classical right-hand rules [6]. In 1999, Pendry succeeded in providing a $-\mu_r$ by introducing a split ring resonator

(SRR) structure mounted in parallel with the propagation of waves [2, 3, 7-9]. Smith et al. achieved $-\epsilon_r$ and $-\mu_r$ by combining the previous structures (wire arrays and the SRR) into one structure [2, 3, 8, 9].

Nowadays, the reflectarray structure receives great interest due to its capabilities in 5G wireless systems. Compared to traditional reflectors, the reflectarray has numerous advantages, including its light weight, low profile, flat surface, small volume, and low fabrication costs [10, 11]. Due to such features, the reflectarray structure is preferred in satellite, radar, and long-distance wireless communication applications [12].

The reconfigurable reflectarray structure is preferred and suitable for 5G network applications due to its ability to dynamically control phase distribution and beam direction, thus overcoming signal blockages and path loss issues. A reconfigurable reflectarray offers a low-profile, cost-effective solution to changing the channel state and user location.

Recent studies have shown that reflectarray structures are developed with unit cells of new geometrical shapes to overcome the disadvantage of restricted phase variation. A reflectarray structure based on unit cell elements can be employed for various purposes [13]. In [14], a reflectarray structure with nine elements of different sizes of frequency selective surfaces (FSS) is introduced to reduce radar cross section (RCS) levels. A reflectarray structure based on a stepped impedance resonator backed by an FSS is proposed for RCS level reduction [15]. Double-cut ring unit cells based on compact reflectarray structure are suggested for performance enhancement, where the required phase delay is compensated by the use of variably sized unit cell elements [16]. Such elements are employed to reflect or scatter the waves incident within a phase delay to observe a desired beam shape [17-21].

This article presents a reconfigurable reflectarray structure based on single-negative metamaterials for 5G applications. The single-negative metamaterial is proposed to observe $-\epsilon_r$ or $-\mu_r$ for reflecting purposes. The PIN diodes are integrated into each unit cell for reconfigurable behavior. The commercial software package CST MWS is used to design and analyze the proposed structures [22]. Section II provides the design and analysis of the proposed reconfigurable reflectarray structure based on metamaterials. Section III introduces the fabricated prototype structures and measurement setup. Section IV concludes the paper.

2. Geometrical Design and Analysis

2.1. Unit Cell Array Configuration

Figure 1 presents the design procedure of the reflected unit cell and introduces four design models. The proposed unit cell design is a single layer, to observe one of the constitutive parameters (μ_r or ϵ_r) with a negative value for reflecting purposes. Multi-square rings of different sizes are used and combined to achieve different resonances and a wideband of reflection. The total dimensions of the unit cells are $15 \times$

15 mm² printed on 1 mm-thick FR-4 dielectric material with ϵ_r and $\tan\delta$ of 4.3 and 0.02, respectively. Table 1 shows other relevant geometric details.

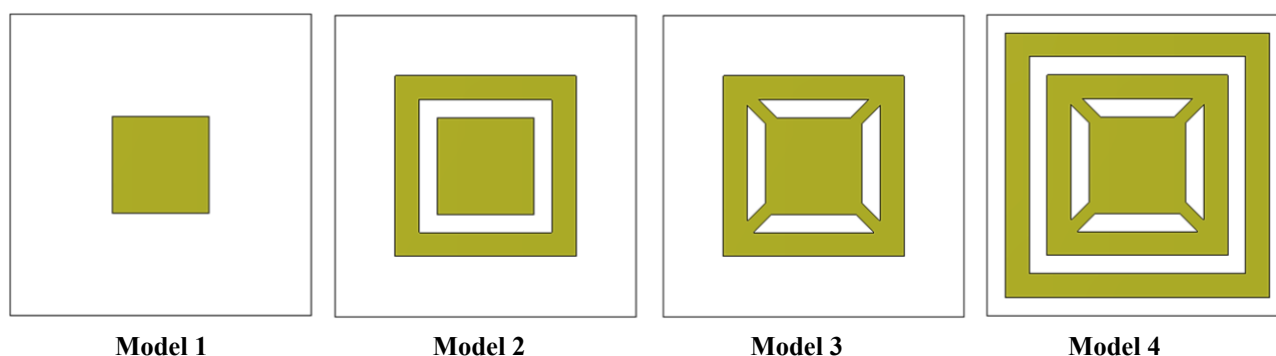


Figure 1. Design procedure of the proposed reflected unit cell

A full-wave analysis technique is applied to test and analyze the unit cell models. The properties in terms of S-parameters, constitutive parameters, and refraction index are presented. The unit cell structure is inserted in the center of the fictitious waveguide, as seen in Figure 2. Two ports are applied with the setting boundary conditions: perfect electrical conductors and perfect magnetic conductors. Figure 3 introduces the S-parameters in a set of magnitudes and phases. For the first model structure, the unit cell shows the lowest reflection coefficient value in the entire band. The structure does not reflect the incident electromagnetic wave. The second and third model unit cells show an increase in the reflection coefficient values, meaning they reflect more of the incident electromagnetic wave. Finally, the proposed unit cell structure achieves the highest reflection coefficient values compared with previous models, where the incident wave is almost totally reflected, especially in the 5G band.

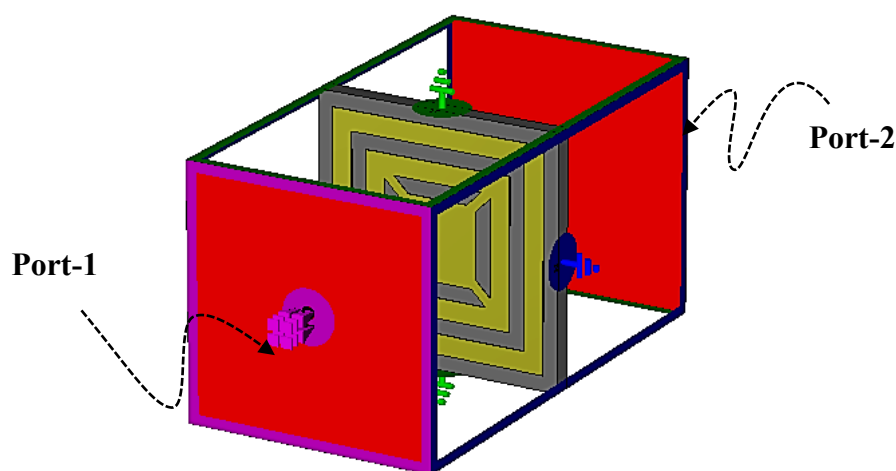


Figure 2. Port excitation with boundary condition setup

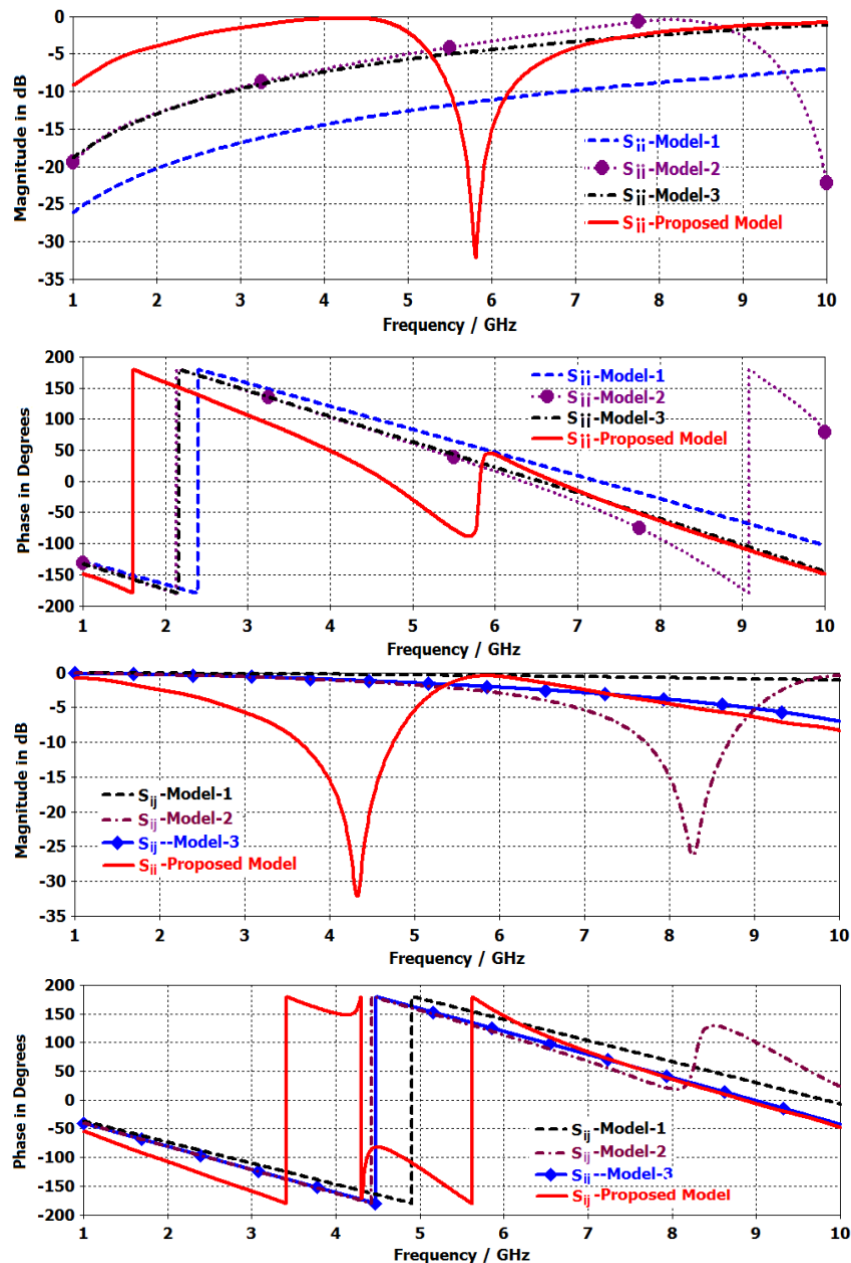


Figure 3. S-parameter (S_{ii} , S_{ij}) results of the unit cell models in magnitude (dB) and phase (degrees)

From the evaluated scattering parameters, the constitutive parameters presented by μ_r and ϵ_r are obtained and are introduced in Figure 4. For the first model, the unit cell exhibits a negative value of ϵ_r , $-1.4 \leq \epsilon_r < 0$, from 4.73 GHz to 5.21 GHz, while a negative μ_r , $-1.53 \leq \mu_r < 0$, is exhibited from 9.52 GHz to 10 GHz. For the second model, the unit cell shows a negative value of ϵ_r , $-5.6 \leq \epsilon_r < 0$, from 3.97 GHz to 5 GHz. Then, a negative μ_r , $-13.25 \leq \mu_r < 0$, is observed from 7.28 GHz to 8.71 GHz. The third model has a negative value of ϵ_r , $-5.16 \leq \epsilon_r < 0$, from 4.02 GHz to 5.06 GHz, while a negative μ_r , $-5.85 \leq \mu_r < 0$, is observed from 8 GHz to 10 GHz. Finally, the last unit cell model proposed structure has a negative value of ϵ_r , $-28.52 \leq \epsilon_r < 0$, from 2.51 GHz to 4.56 GHz, while a negative μ_r , $-6.61 \leq \mu_r < 0$, is observed from 7.9 GHz to 10 GHz.

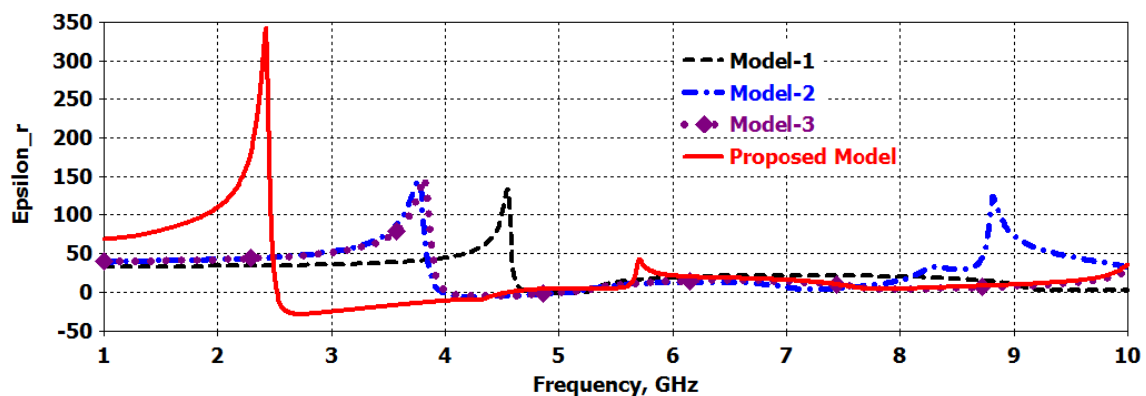
From the results presented, the proposed unit cell Model 4 exhibits the highest negative values of both μ_r and ϵ_r , with a wider frequency band compared to other models. This wide band of negative μ_r and ϵ_r is achieved through the use and combination of rings with different shapes and sizes.

The refractive index (n) of all models is obtained by employing Equation (1) [19]. Figure 5 introduces the simulated results. An imaginary (n) component is observed in the bands of negative μ_r/ϵ_r . The imaginary (n) component determines that no wave will be passed through the unit cell at these bands.

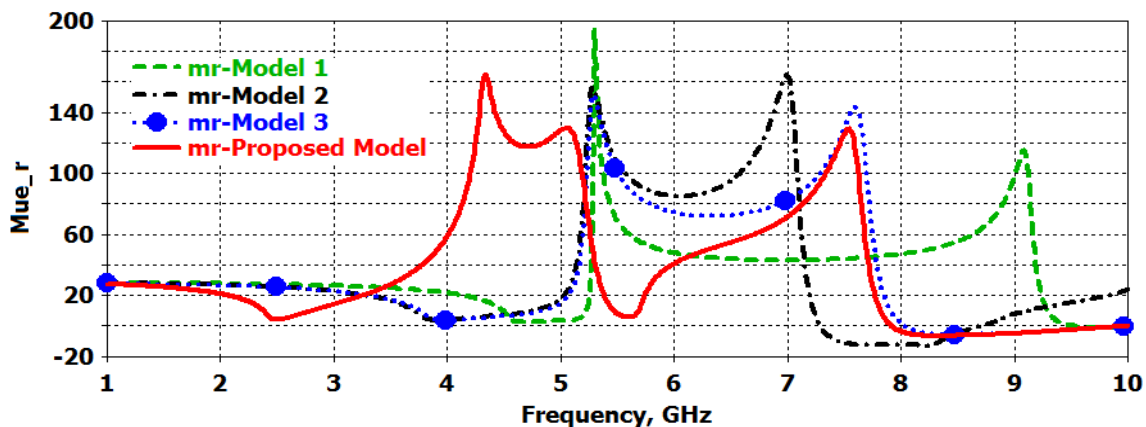
$$n = \sqrt{\epsilon_r \mu_r} \dots \quad (1)$$

The results obtained show that the first model has the lowest band of reflection, which equals 0.765 GHz, starting from 4.34 GHz to 5.1 GHz. Then, the second and third models have double bands of reflection. The second model shows that the first band of reflection equals 1 GHz, 3.57-4.59 GHz, while the second band is 2.29 GHz, 6.58-8.88 GHz. For the third model, the first band of reflection equals 1.5 GHz, 3.15-4.65 GHz, while the second band is 2.53 GHz, 6.75-9.28 GHz.

Finally, the proposed unit cell design is characterized by dual wide bands of reflection and higher imaginary (n) component values compared with other designs. The first band of reflection equals 2.6 GHz, 1.98-4.6 GHz, while the second band is 1.71 GHz, 7.41-9.1 GHz.



(a)



(b)

Figure 4. Constitutive parameters of unit cell models; (a) real ϵ_r , and (b) real μ_r

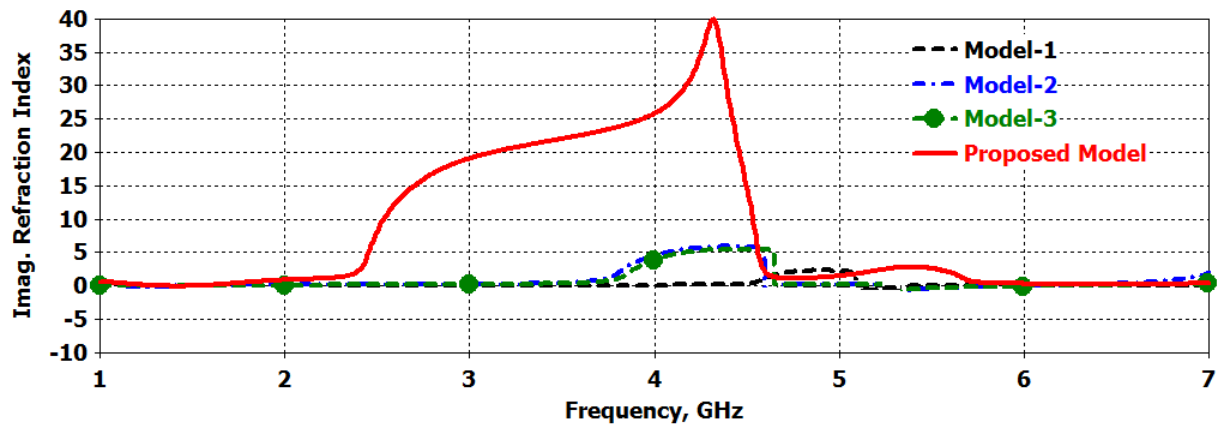


Figure 5. Refraction index (n) of the unit cell models

Figure 6 proposes and presents an array of reflectarray structures based on unit cells. The reflectarray structure has a total of 144 unit cells (12×12), with a size of $180 \times 180 \text{ mm}^2$ printed on 1 mm-thick FR-4 dielectric material with ϵ_r and $\tan\delta$ of 4.3 and 0.02, respectively. Figure 6 introduces a concentric square rings unit cell with the derived equivalent circuit.

The reflectarray structure is placed in the direction of the electromagnetic wave propagation to achieve a resonance state. This prevents the propagation of electromagnetic waves through the proposed reflectarray structure, leading to the largest radiation power reflected. Moreover, two PIN diodes are inserted into each unit cell for reconfigurable behavior. The stripline is used as a PIN diode with ON and OFF states. Figure 7 introduces the S-parameters in a set of magnitudes and phases of the proposed unit cell.

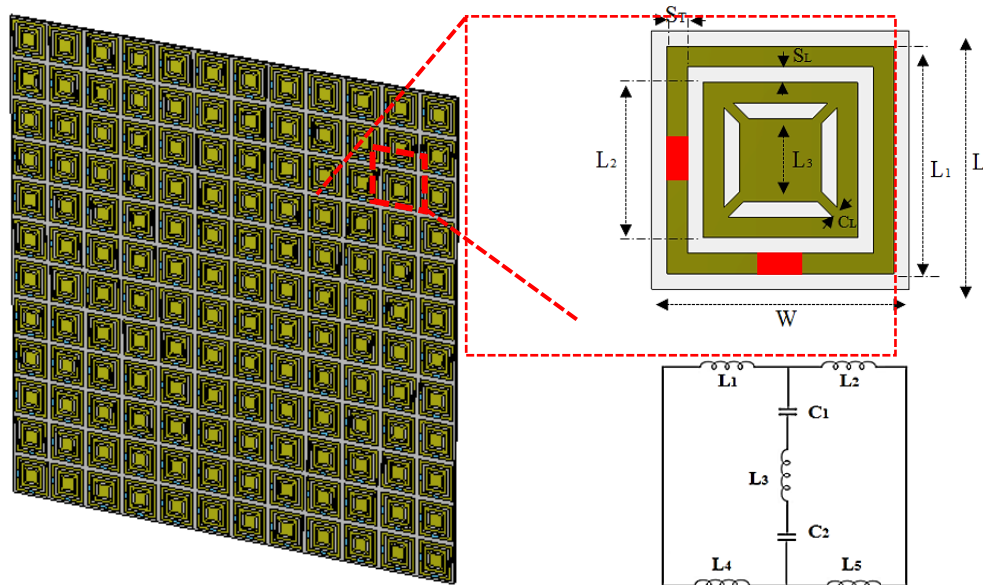


Figure 6. Reconfigurable unit cell metamaterial-based reflectarray structure with the equivalent circuit

Table 1. Proposed structure geometrical details in mm.

Parameter	Value (mm)	Parameter	Value (mm)
L	15	L_3	4.8
W	15	S_T	1.19
L_1	13.2	S_L	0.9
L_2	13.2	C_L	0.636
h	1	t	0.035

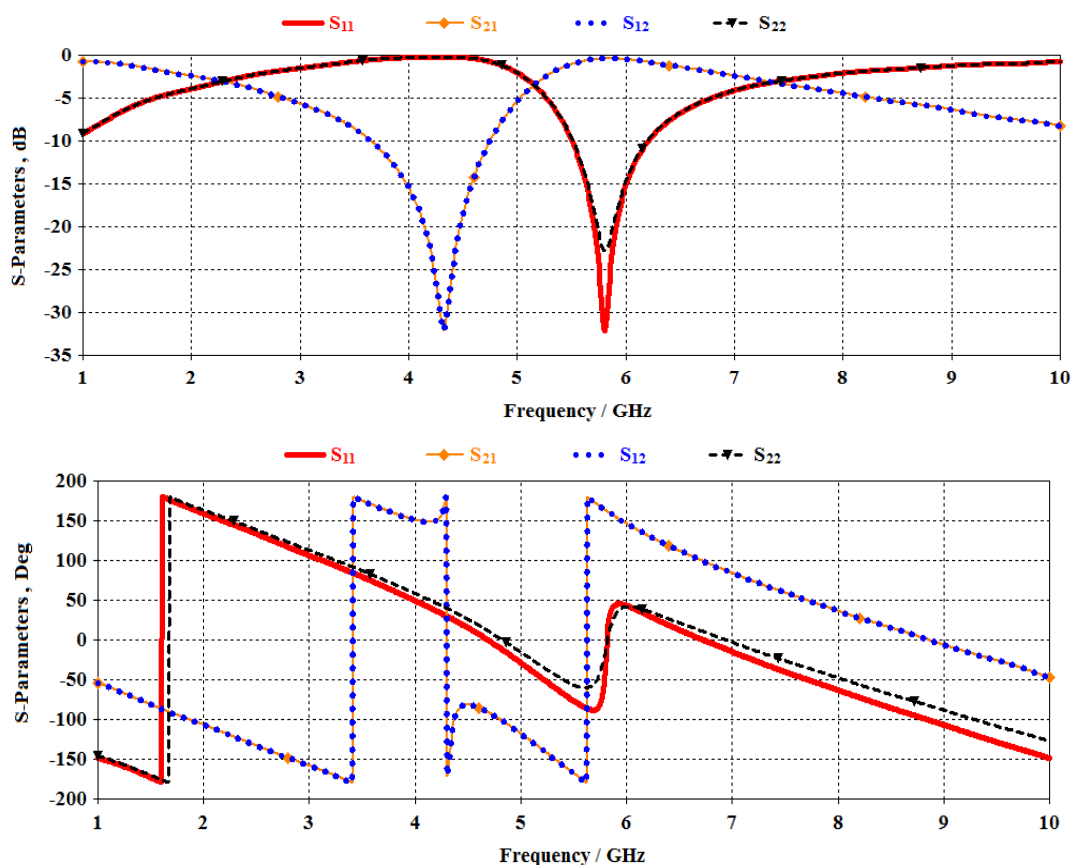
**Figure 7.** S-parameter results of the proposed unit cell MTM; (a) magnitude in dB, and (b) phase in degrees

Figure 8 introduces the μ_r and ϵ_r properties of the proposed unit cell. The proposed unit cell is characterized by a wide band of negative μ_r and ϵ_r at different frequencies. A negative permittivity ($-\epsilon_r$) is observed in the frequency band 2.51–4.56 GHz, with a maximum value of -28.52 at 2.73 GHz; a negative permeability ($-\mu_r$) is observed in the frequency band 7.91–10 GHz, with a maximum value of -6.56 at 8.25 GHz.

Figure 9 presents the refractive index (n) component of the proposed unit cell for real and imaginary parts. Dual bands of reflection are observed because of the high imaginary (n) part that appears in the bands of negative μ_r/ϵ_r . A high imaginary of the (n) component determines that no wave will be passed through the unit cell at these bands. The first band of reflection is 2.6 GHz, from 1.98 to 4.6 GHz, while the second band is 1.71 GHz, from 7.41 GHz to 9.1 GHz.

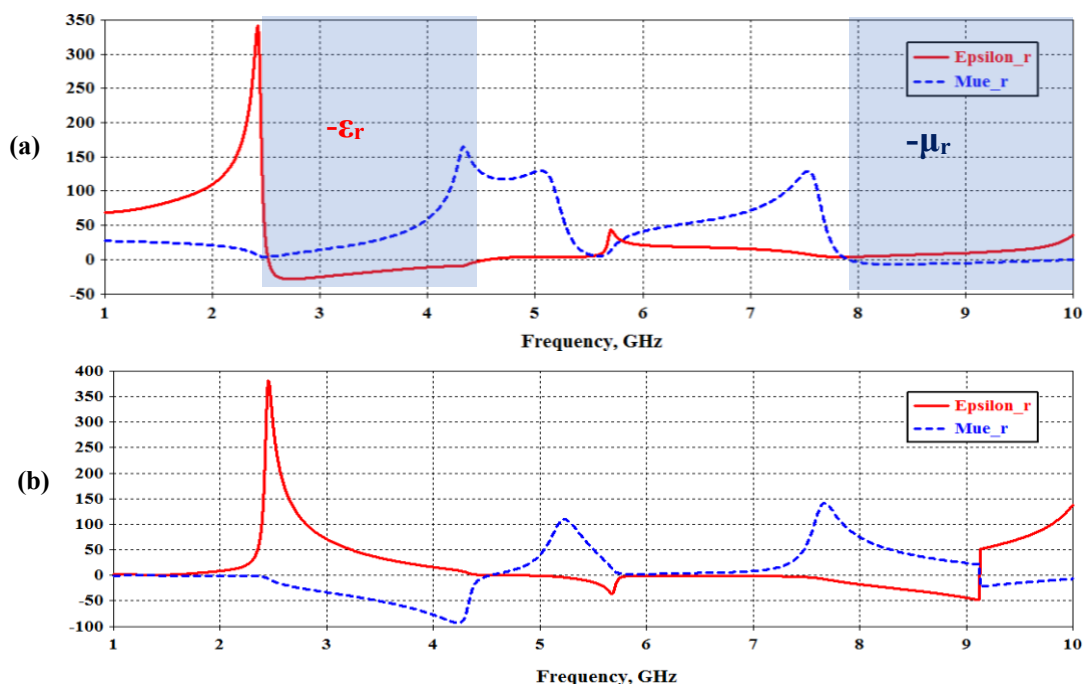


Figure 8. Constitutive parameters (ϵ_r and μ_r); (a) real part and (b) imaginary part

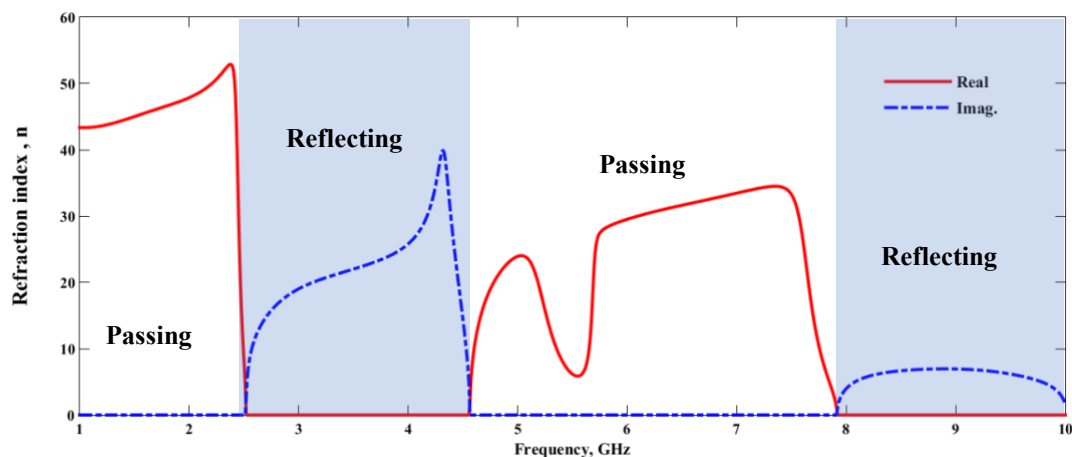


Figure 9. Refraction index (n) of the proposed unit cells, real and imaginary

2.2. Reconfigurable Reflectarray Structure-Based Antenna

In Figure 10, a modified Vivaldi antenna (MVA) is proposed to generate the incident of electromagnetic waves on the reflectarray structure. The MVA dimensions are $45 \times 35 \text{ mm}^2$ with a thickness of 1 mm. Slitlines are etched out from the antenna's outer radiator edges to reduce the surface current in these edges. These slitlines can provide better impedance matching for wider bandwidth achievement, higher gain and a more directive beam due to side lobe reduction and surface current distribution change, enhancing antenna performance. Table 2 provides more details about the optimized MVA geometry.

The modified and conventional antennas are simulated, where their performances are presented. The modified antenna is simulated, where the test results show that it can cover a range of frequencies beginning at 3 GHz and can exceed 12 GHz with $S_{11} < -10 \text{ dB}$ for 5G applications, while the conventional antenna

covers a range of frequencies from 4.27 GHz to 12 GHz, as seen in Figure 11 (a). A wider bandwidth is achieved by using slitlines, which enhance the impedance matching.

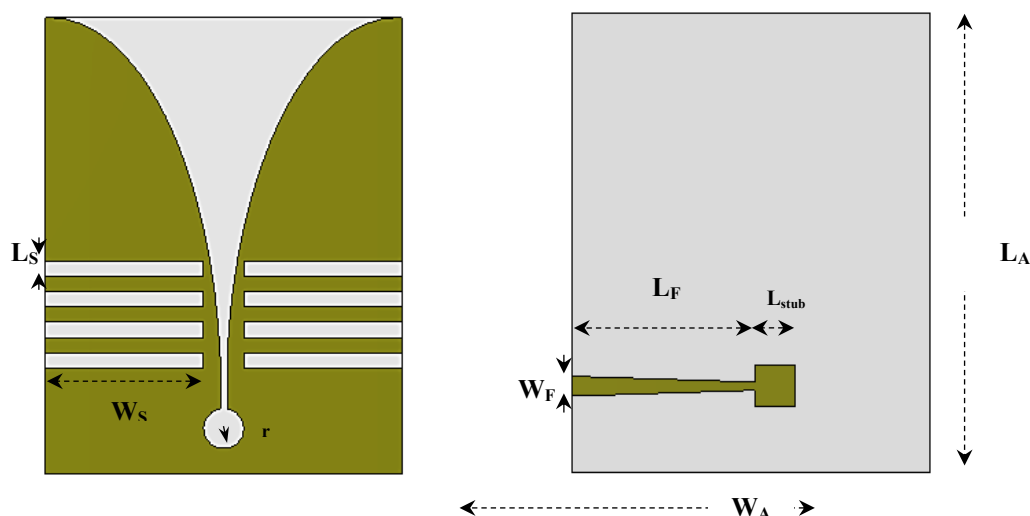


Figure 10. MVA structure geometry

Table 2. Optimized antenna parameters in mm

Parameter	Value (mm)	Parameter	Value (mm)
L_A	45	L_{stub}	4
W_A	35	L_S	1.5
L_F	17.86	W_S	15.5
W_F	1.945	r	2

Moreover, the gain spectra of both antenna models are evaluated. The modified antenna shows a gain enhancement of approximately 1.31 dB compared to the conventional antenna. The gain of the modified antenna varies from 4.29 dB to 8.55 dB in the desired band, with a maximum value of 8.55 dB at 8 GHz, as seen in Figure 11 (b). Furthermore, the radiation pattern of the modified antenna compared with the conventional structure is presented in Figure 11 (c), which shows that the modified structure has a more directive beam due to the current surface reduction in the outer edges.

Finally, Figure 12 presents the efficiency of the modified antenna, showing that the modified antenna has a good efficiency value varying from 80% to 92.6% in the Sub-6 band.

An array of reflectarray MTM-based reconfigurable behavior is designed and located vertically on the propagated wave direction, as seen in Figure 13. The separated distance (d) between the MVA and the reflectarray structure is optimized to 20 mm.

For reconfigurable pattern achievement, PIN diodes are inserted among unit cells. The array of PIN diodes is divided into four groups, as seen in Figure 12 (c). Reconfiguring the unit cells changes the phase distribution across the proposed surface structure, which controls the direction and beam shape of the reflected wave.

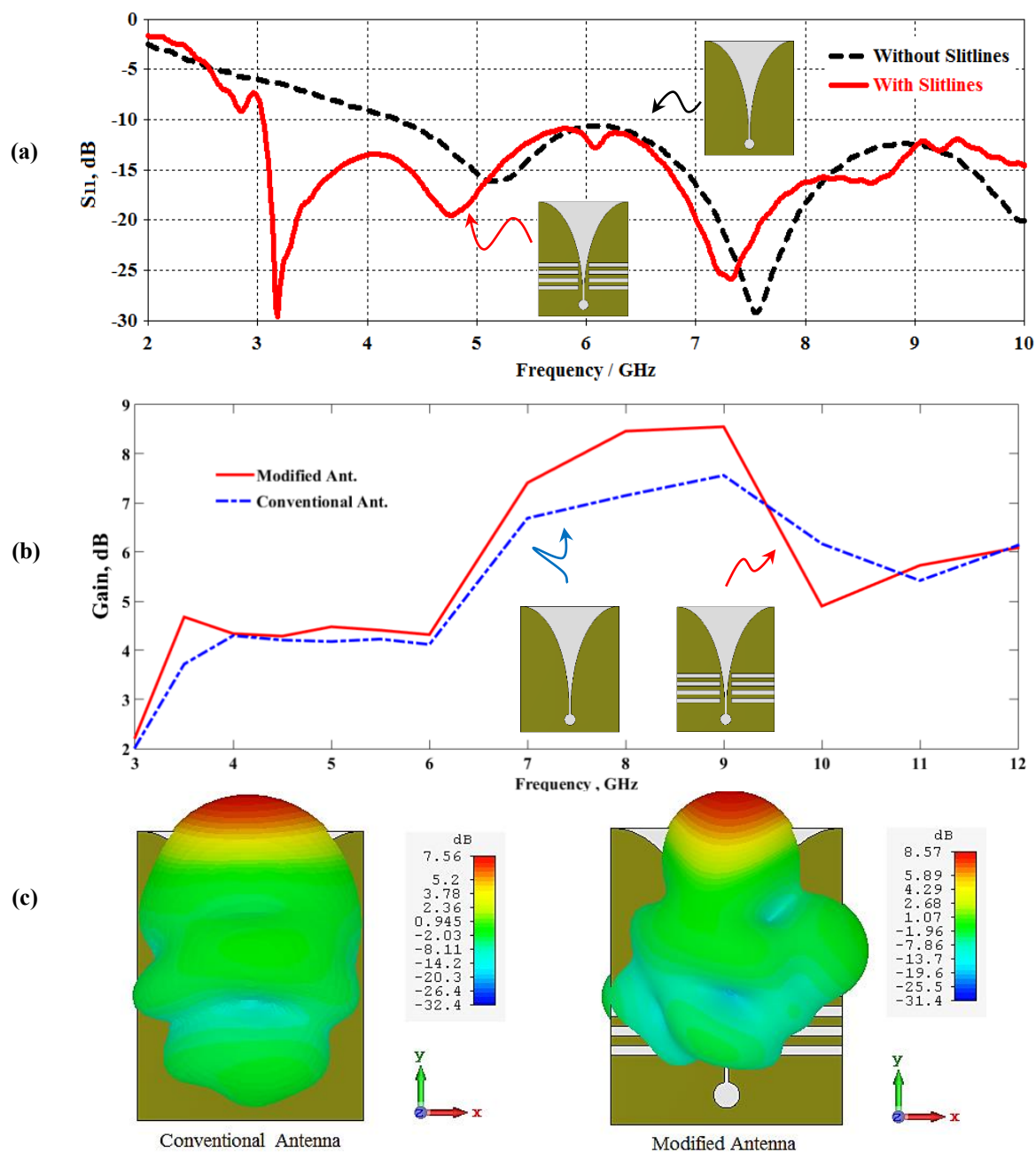


Figure 11. Conventional and modified antenna results; a) reflection coefficient, b) gain versus frequency, and c) radiating patterns

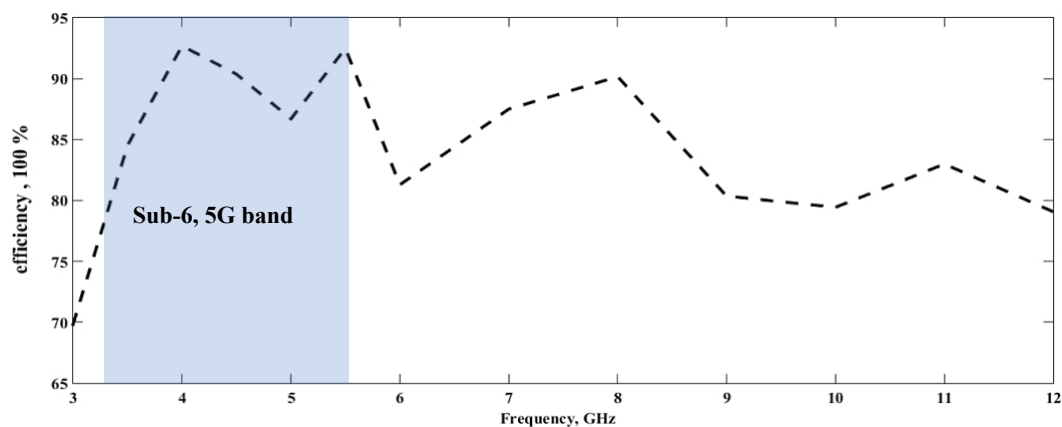


Figure 12. Efficiency of the modified antenna

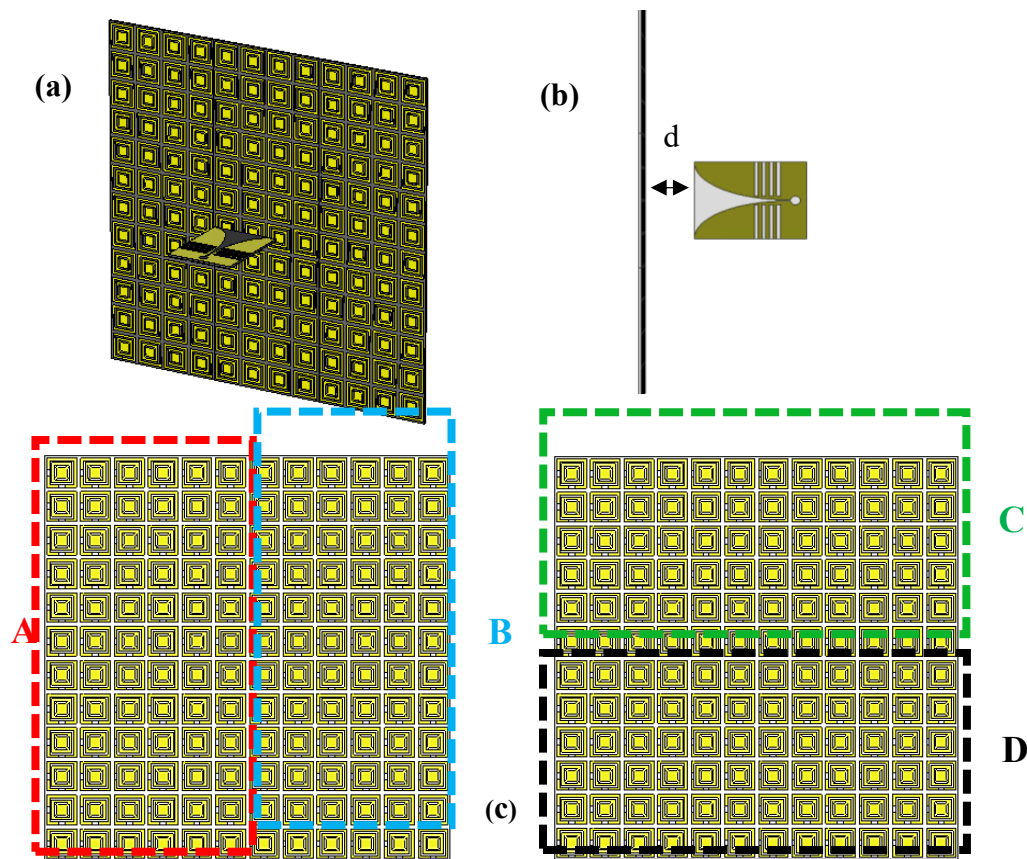


Figure 13. Reconfigurable reflectarray structure; a) 3D view, b) top view, and c) front view

In this section, the radiation patterns of the reconfigurable reflectarray structure based on MVA are tested and analyzed. When all diodes are in the ON state, the radiation pattern of the proposed structure is presented in 3D, top, and side views, as shown in Figure 14. The results demonstrate that the MTM array reflects all the incident waves across the entire 5G bands, with no waves *transmitted* through the reflectarray structure.

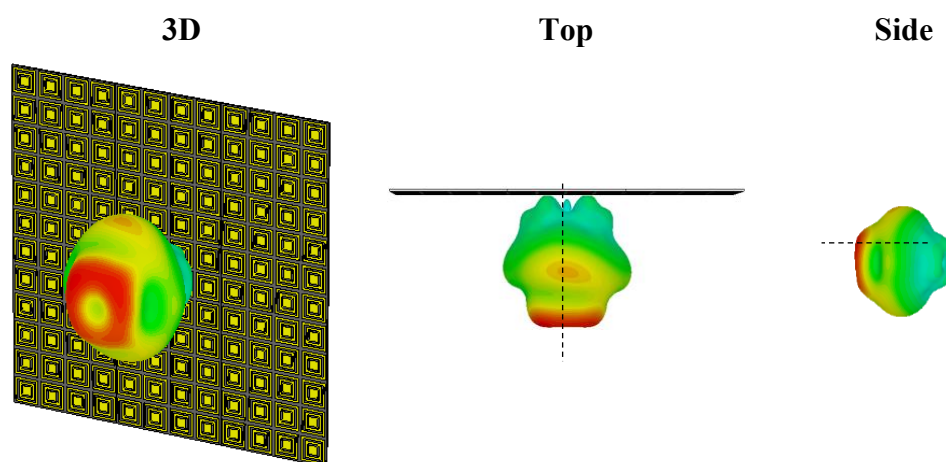


Figure 14. Radiation pattern of the proposed structure when all diodes are in the ON state

Figure 15 shows the radiation pattern of the proposed structure when Group A of the diodes is in the ON state. The results indicate that the incident waves are reflected at a 20° angle to the left side. When Group B of diodes is activated and other groups remain inactive, the incident waves are reflected at a 21° angle to the right side, as seen in Figure 16. When only Group C is activated, the results indicate that the reflected waves are directed in an upper direction with an angle of 30° , as seen in Figure 17. Furthermore, the reflected waves are directed in a lower direction at an angle of 37° when Group D is activated, as seen in Figure 18. Depending on which diode group is activated (in the ON state), the incident waves will be reflected and redirected at different angles. Figure 19 presents the 2D radiation patterns of the proposed structure for all diode configurations.

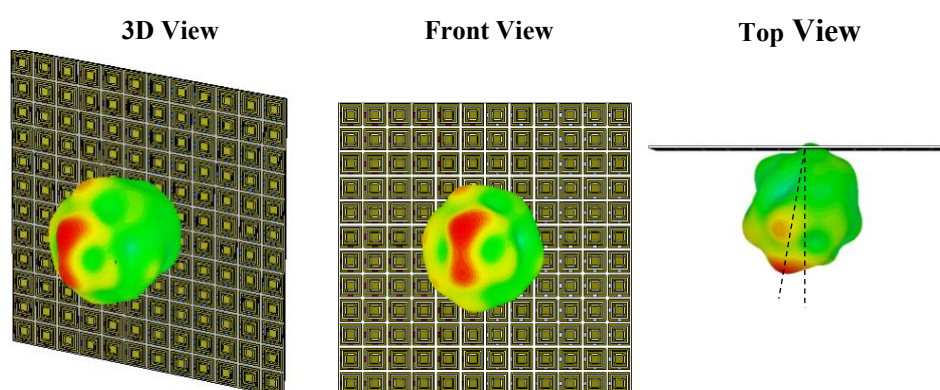


Figure 15. Radiation pattern of the proposed structure when Group A is in the ON state

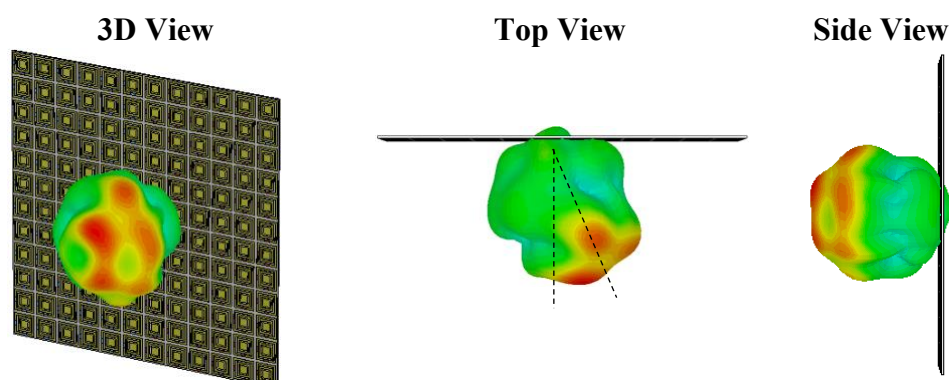


Figure 16. Radiation pattern of the proposed structure when Group B is in the ON state

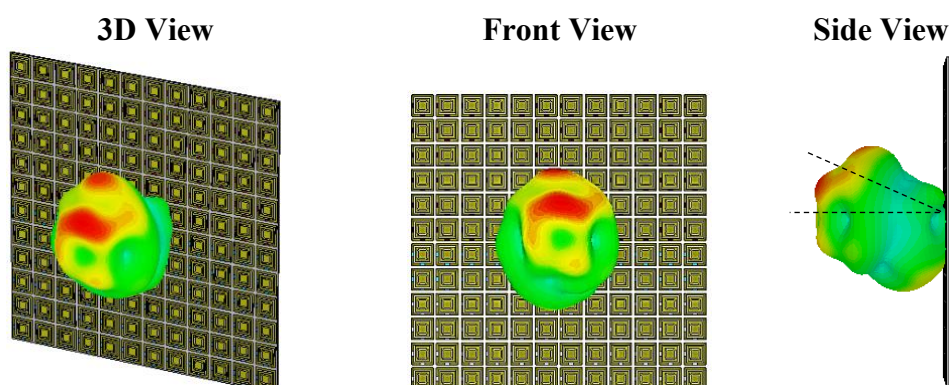


Figure 17. Radiation pattern of the proposed structure when Group C is in the ON state

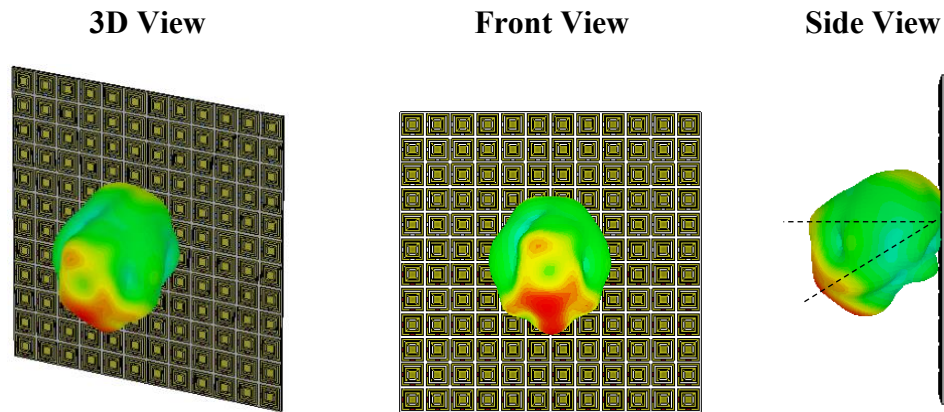
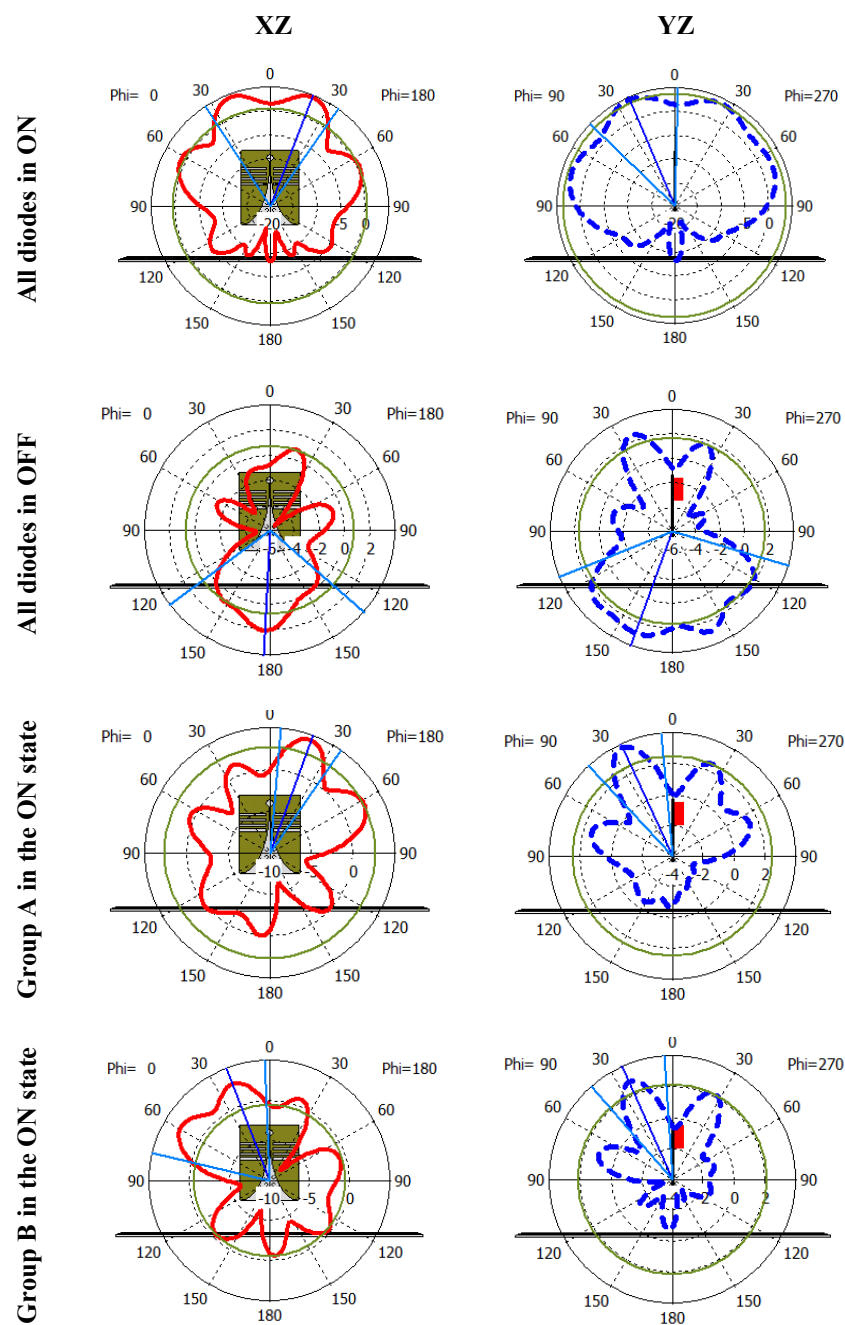


Figure 18. Radiation pattern of the proposed structure when Group D is in the ON state



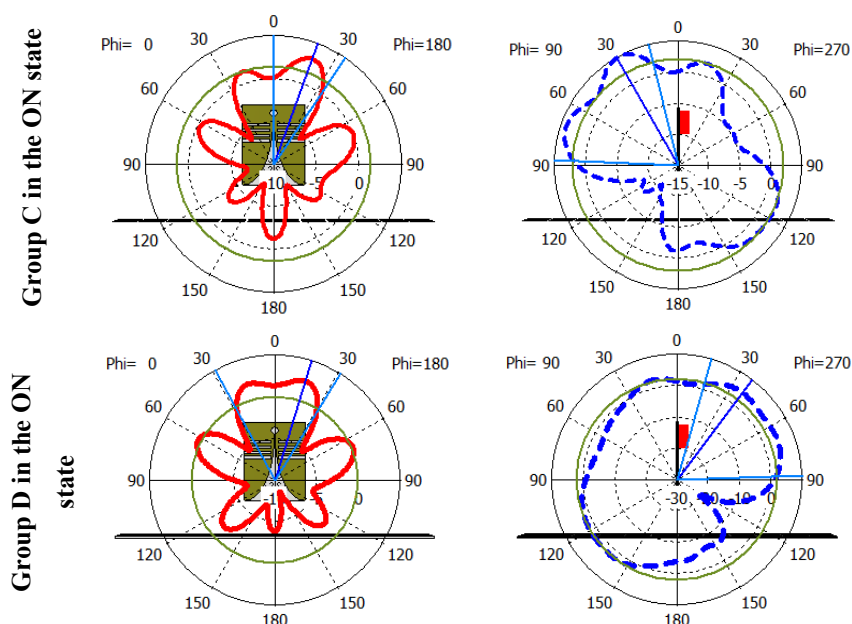


Figure 19. Radiation patterns of the proposed structure for different diode states

3. Fabrication and Measurement

Figure 20 shows the fabrication of the proposed structures using an LPKF ProtoMat S100 CN Machine. Figure 20 (a) presents the MVA prototype, and Figure 20 (b) presents the reflectarray structure. The vector network analyzer (VNA) and anechoic chamber are involved in testing and measuring the performance of the proposed structures, as shown in Figure 21. Figure 22 shows how the measured S_{11} of the proposed structures are obtained and compared with those from the simulation. Figure 23 presents the simulated and measured radiation patterns of the proposed structures. A good agreement is observed between the simulated and measured results, with insignificant differences. Such differences mainly arise from copper loss, irregular soldering defects, substrate loss, and errors in the fabrication process.

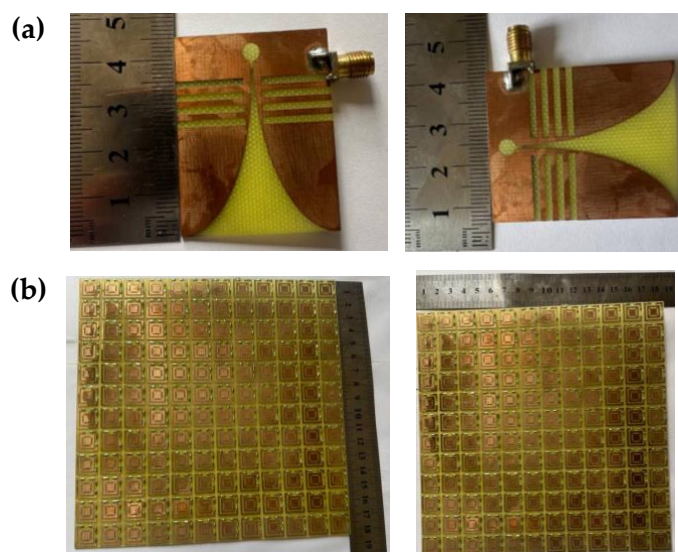


Figure 20. Proposed structure prototypes; (a) MVA structure, (b) reflectarray structure

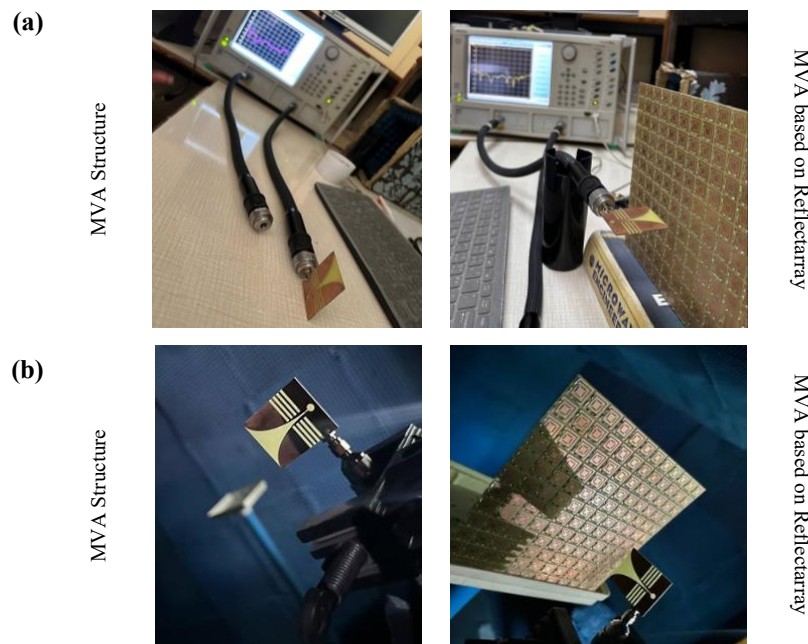


Figure 21. Measurement setup; (a) VNA, (b) anechoic chamber

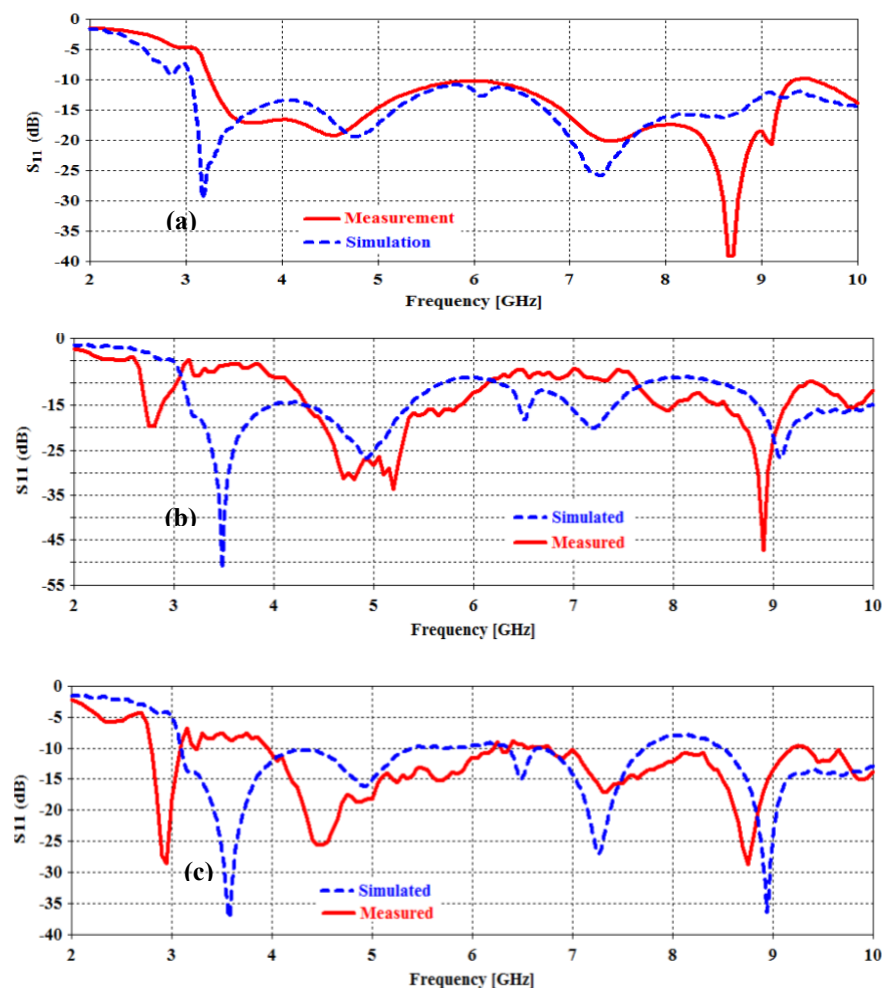


Figure 22. The simulated and measured S_{11} ; (a) MVA, (b) MVA based on a reflectarray structure when all diodes are in the OFF state, (c) MVA based on a reflectarray structure when all diodes are in the ON state

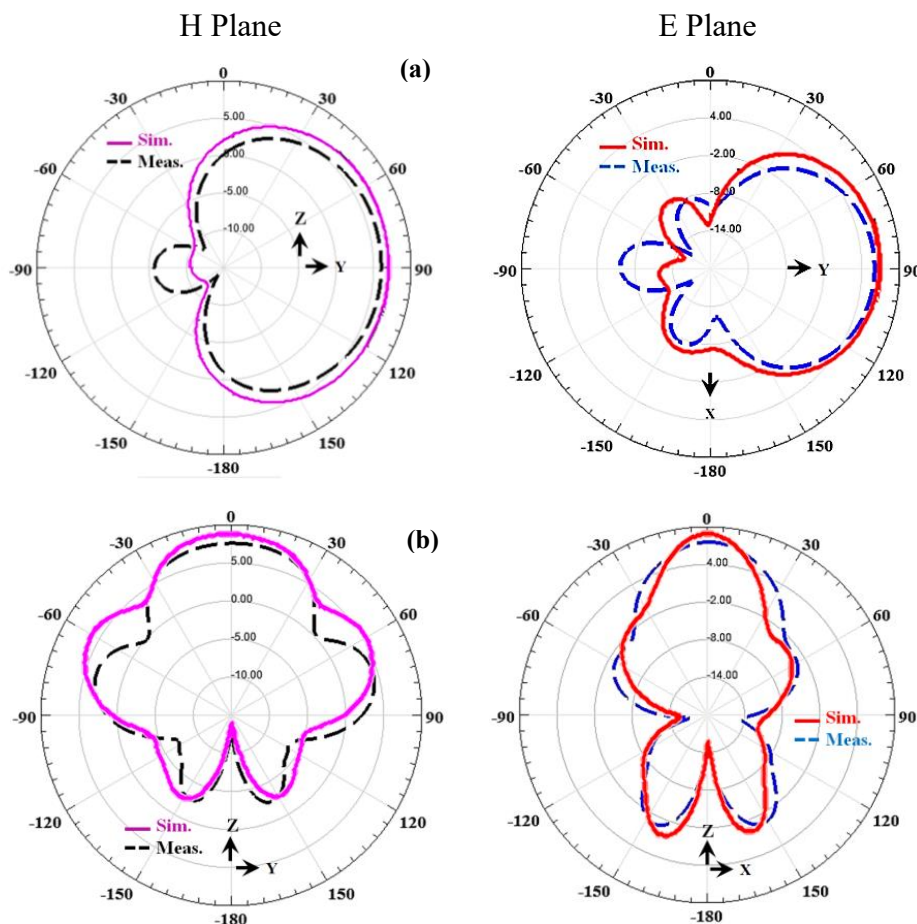


Figure 23. Simulated and measured radiation patterns at 3.5 GHz; (a) MVA, (b) MVA based on a reflectarray structure

4. Conclusions

This work introduced a reconfigurable reflectarray structure based on metamaterials. An MVA was employed to generate the incident electromagnetic waves. By etching out slitlines along the outer edges of the antenna, the bandwidth and gain were enhanced by 1.27 GHz and 1.31 dB, respectively, achieving a maximum efficiency of 92.6%. A single layer based on a multi-concentric square rings unit cell in the reflectarray structure was proposed. A single layer was provided with a $-\epsilon_r/-\mu_r$ while multiple square rings provided wide reflection bands. Dual bands of reflection were observed; the first band of reflection was found from 1.98 GHz to 4.6 GHz, while the second band was from 7.41 GHz to 9.1 GHz. A reflection at different angles was achieved depending on the state of the integrated diodes. Finally, a good agreement was found between the measurement results and those from the simulation.

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Declaration of Competing Interest: The authors declare they have no known competing interests.

Research Involving Human/Animal Participants: This article does not involve any studies conducted by authors on animals or human participants.

References

- [1] O. Luukkonen, S. I. Maslovski, and S. A. Tretyakov, "A stepwise Nicolson–Ross–Weir-based material parameter extraction method," *IEEE antennas and wireless propagation letters*, vol. 10, pp. 1295-1298, 2011, doi: <https://doi.org/10.1109/LAWP.2011.2175897>.
- [2] A. R. Azeez, S. K. Ahmed, A. M. Zalzal, Z. A. Abdul Hassain, and T. A. Elwi, "Design of High Gain UWB Vivaldi Antenna with Dual Band-Notches Characteristics," *International Journal on Engineering Applications (IREA)*, vol. 11, no. 2, pp. 128-136, 2023, doi: <https://doi.org/10.15866/irea.v11i2.22177>.
- [3] B. Gallas *et al.*, "Silver square nanospirals mimic optical properties of U-shaped metamaterials," *Opt. Express*, vol. 18, no. 16, pp. 16335-16344, 2010, doi: <https://doi.org/10.1364/OE.18.016335>.
- [4] C. Caloz and T. Itoh, *Electromagnetic metamaterials: transmission line theory and microwave applications*. John Wiley & Sons, 2005. <https://doi.org/10.1002/0471754323>
- [5] N. P. Johnson, A. Z. Khokhar, H. M. H. Chong, R. M. D. L. Rue, and S. McMeekin, "Characterisation at infrared wavelengths of metamaterials formed by thin-film metallic split-ring resonator arrays on silicon," *Electronics Letters*, vol. 42, no. 19, pp. 1117-1119, 2006, doi: <https://doi.org/10.1049/el:20062212>.
- [6] B. Sauviac, C. R. Simovski, and S. A. Tretyakov, "Double Split-Ring Resonators: Analytical Modeling and Numerical Simulations," *Electromagnetics*, vol. 24, no. 5, pp. 317-338, 2004, doi: <https://doi.org/10.1080/02726340490457890>.
- [7] J. D. Baena, R. Marqués, F. Medina, and J. Martel, "Artificial magnetic metamaterial design by using spiral resonators," *Physical Review B*, vol. 69, no. 1, p. 014402, 2004, doi: <https://doi.org/10.1103/PhysRevB.69.014402>.
- [8] H. Chen *et al.*, "Left-handed materials composed of only S-shaped resonators," *Physical Review E*, vol. 70, no. 5, p. 057605, 2004, doi: <https://doi.org/10.1103/PhysRevE.70.057605>.
- [9] M. R. I. Faruque, M. T. Islam, and N. Misran, "Analysis of Electromagnetic Absorption in Mobile Phones Using Metamaterials," *Electromagnetics*, vol. 31, no. 3, pp. 215-232, 2011, doi: <https://doi.org/10.1080/02726343.2011.558457>.
- [10] J. Huang and J. A. Encinar, *Reflectarray antennas*. New York: John Wiley & Sons, 2007. doi: <https://doi.org/10.1002/9780470178775>
- [11] S. Oh, "Broadband reflectarray composed of gap coupled elements with linear phase response," *Microwave and Optical Technology Letters*, vol. 59, no. 5, pp. 1045-1047, 2017, doi: <https://doi.org/10.1002/mop.30464>.
- [12] D. M. Pozar, S. D. Targonski, and H. Syrigos, "Design of millimeter wave microstrip reflectarrays," *IEEE transactions on antennas and propagation*, vol. 45, no. 2, pp. 287-296, 1997, doi: <https://doi.org/10.1109/8.560348>
- [13] M. Karimipour and N. Komjani, "Bandwidth enhancement of electrically large shaped-beam reflectarray by modifying the shape and phase distribution of reflective surface," *AEU - International Journal of Electronics and Communications*, vol. 70, no. 5, pp. 530-538, 2016, doi: <https://doi.org/10.1016/j.aeue.2015.12.007>.
- [14] H. Bodur, S. Ünal, S. Çimen, and G. Çakır, "A Novel Reflectarray Antenna with Reduced RCS," (in en), *Kocaeli Journal of Science and Engineering*, vol. 1, no. 1, pp. 11-14, 2018, doi: <https://doi.org/10.34088/kjose.399389>.
- [15] M. M. Fakharian, P. Rezaei, and A. A. Orouji, "A Reflectarray based on the folded SIR patch-slot configuration backed on FSS for low RCS," *Progress In Electromagnetics Research Letters*, vol. 47, pp. 119-124, 2014, doi: <https://doi.org/10.2528/PIERL14061803>.
- [16] H. Bodur and S. Cimen, "Reflectarray antenna design with double cutted ring element for X-band applications," *Microwave and Optical Technology Letters*, vol. 62, no. 10, pp. 3248-3254, 2020, doi: <https://doi.org/10.1002/mop.32436>.

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- [17] F. Xue, H. J. Wang, M. Yi, and G. Liu, "A broadband KU-band microstrip reflectarray antenna using single-layer fractal elements," *Microwave and Optical Technology Letters*, vol. 58, no. 3, pp. 658-662, 2016, doi: <https://doi.org/10.1002/mop.29637>.
- [18] K. Lele, A. A. Desai, A. A. Kadam, and A. A. Deshmukh, "Reflectarray antennas," *International Journal of Computer Applications*, vol. 108, no. 3, pp. 21 - 28, 2014, doi: <https://doi.org/10.5120/18891-0173>
- [19] S. Mezaal, S. Khaleel, A. A. Al-Hillal, A. Azeez, M. Hemza, and M. Al-Majdi, "State of art on microstrip resonators, filters, diplexers and triplexers," *Journal of Mechanics of Continua and Mathematical Sciences*, vol. 19, no. 2, pp. 1-24, 2024, doi: <https://doi.org/10.26782/jmcms.2022.02.00001>.
- [20] L. Li *et al.*, "Frequency selective reflectarray using crossed-dipole elements with square loops for wireless communication applications," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 1, pp. 89-99, 2010, doi: <https://doi.org/10.1109/tap.2010.2090455>
- [21] A. R. Azeez, T. A. Al-Sharify, O. Abdullah, Z. Salam, H. H. Al-khaylani, and T. Oleiwi, "High Gain Tapered Slot Antenna Based on Offset Radiation Characteristic for 5G Wireless Applications," in *2024 4th International Conference on Artificial Intelligence and Signal Processing (AISP)*, 2024: IEEE, pp. 1-5, doi: <https://doi.org/10.1109/aisp61711.2024.10870648>
- [22] CST. "CST Microwave Studio." SIMULIA. <https://www.3ds.com/products/simulia/cst-studio-suite> (accessed 10/1, 2025).