Original Article

Mutual Coupling Reduction in Antenna Arrays using Circular Complementary Split Ring Resonator Metamaterial Structure in Comparison with Non-Metamaterial Antenna Array

Sai charith.G[1], Sheela.D[2]

[1]Research Scholar, Department of Electronics and Communication Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, Tamilnadu, India, Pincode: 602105
[2]Project guide, CorrespondingAuthor, Department of Electronics and Communication Engineering, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, Tamilnadu, India, Pincode:602105

Abstract

Aim: The aim of this work is to reduce mutual coupling by incorporating circular CSRR into metamaterial structures. Mutual coupling values are measured for different frequencies and the values are compared with the antenna array without the metamaterial structures. **Materials And Methods**: Mutual coupling in circular-shaped CSRR metamaterial is compared with that of antenna array without metamaterial. Each group has 10 samples. The mutual coupling values are measured by varying the operating frequency. The G power calculation is 0.8. **Results:** The experimental results indicate a reduced mutual coupling using the circular-shaped CSRR metamaterial in the two element antenna array compared with the non-metamaterial array. The mean mutual coupling in circular CSRR is -14.36 and in the non-metamaterial antenna array, it is -8.73 with the significance p = 0.023. **Conclusion:** The circular-shaped CSRR metamaterial structure in the two element antenna array exhibits a better reduction in mutual coupling compared to the antenna array without the metamaterial structure.

Keywords: Mutual Coupling, Complementary Split Ring Resonator (CSRR), Novel two element antenna array, Metamaterial, Radiation Pattern, High Frequency Structure Simulation (HFSS).

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INTRODUCTION

A Metamaterial is a material that is created artificially but has properties different from those of naturally occurring materials. Near the magnetic resonance frequencies, metamaterials show negative magnetic permeability. This allows for the miniaturization and enhancement of the radiation properties of metamaterial antennas (Cho and Yoon 2021). Multiple Input Multiple Output (MIMO) antennas can be made more efficient by decreasing the mutual coupling between elements using metamaterials. As the distance between individuals receiving wire components decreases, however, they will suffer from a solid common coupling, which degrades the performance of these wires, similar to a reduction in gain and radiation for metamaterial structure (Rezapour et al. 2019). This circular Complementary Split Ring Resonator (CSRR) array is used for satellite communication, telemedicine, navigation, WiMAX, and radar applications. To improve performance and the efficiency of the antennas, mutual coupling reduction is a critical problem. There have been many methods of using metamaterials to enhance isolation and performance of mutual coupling but a few strategies have been described. A few examples of such metamaterials are Split Ring resonators (SRR) and Complementary Split Ring Resonators (CSRR). There are two enclosed loops in a unit cell SRR that have splits at opposite ends. Copper or gold loops have a small gap in between them and are made of a non-magnetic metal (Chandu DS, Karthikeyan, and Phani Kumar 2015).

On mutual coupling in antenna arrays prediction in recent years nearly 600 articles were published in Google scholar, In IEEE Xplore 300 articles were published. In this study, a new method is proposed by introducing a CSRR based antenna array that is examined for multiband operation and radiation pattern. To boost the performance and make it a metamaterial, the proposed construction incorporates a Complementary Split Ring Resonator (CSRR) loaded in the base of the antenna. Metamaterials have qualitatively new electromagnetic response functions that aren't seen anywhere else in nature. (Chipouline and Küppers 2018). The CSRR loaded base allows many frequencies to be used at the same time. The CSRR structure is the dual of SRR, located alng the axis in the waveguide. Depending on the width of the slot (W), the gap between the slots (s), and the outer loop radius (Rout), the metamaterial's resonant frequency can be determined (Bird 2021). Complementary Split Ring Resonators (CSRR) are used in between the two patches. A magnetic flux penetrating the metal rings will induce rotating currents in the rings, which enhance or oppose the incident field and radiation pattern. (Pradeep and Bidkar 2019). According to the literature, the metamaterial Complementary Split Ring Resonator (CSRR) antenna gives better performance and has a high multiband width and radiation pattern. So mutual coupling can be reduced by using advanced metamaterial CSRR (Yaduvanshi and Parthasarathy 2015). The application of Complementary Split Rng Resonator (CSRR) based biosensor is to determine the glucose concentration in an aqueous solution and also it is used for satellite communication (Lai et al. 2021).

Our team has extensive knowledge and research experience that has translate into high quality publications (Bhansali et al. 2021; Jayanth et al. 2021; Sudhakar, Ravel, and Perumal 2021; Sathiyamoorthi et al. 2021; Deepanraj et al. 2021; Raju et al. 2021; Arun Prakash et al. 2020; Kamath et al. 2020; Shanmugam et al. 2021; Rajasekaran et al. 2020; Adhinarayanan et al. 2020; Rajesh et al. 2020; Aurtherson et al. 2021)(Bhansali et al. 2021; Jayanth et al. 2021; Sudhakar et al. 2021; Sathiyamoorthi et al. 2021; Deepanraj et al. 2021; Raju et al. 2021; Arun Prakash et al. 2020; Kamath et al. 2020; Shanmugam et al. 2021; Rajasekaran et al. 2020; Adhinarayanan et al. 2020; Rajesh et al. 2020; Aurtherson et al. 2021). The lacunae of the existing research are the complexity and poor reduction in mutual coupling. The approach of using circular CSRR yields a reduction in mutual coupling in a novel two element antenna array. This work aims to reduce the mutual coupling to achieve high gain in a two element antenna array.

Materials And Methods

This study was conducted in the Antenna Lab, Department of Electronics and Communication Engineering at Saveetha School of Engineering, SIMATS, Chennai, India. This project was done using High Frequency Structure Simulation (HFSS). It consists of two groups, one is the antenna array with metamaterial and the other is without meta metamaterial with a sample size of 20 respectively. The specified sample analysis is completed using G power calculations. Pretest g power is fixed as 0.8 and the maximum acceptable error rate of 0.05 is used.
In the sample preparation for group 1 circular CSRR metamaterial two element antenna arrays are chosen. In this group, 10 samples are taken and the mutual coupling values will be obtained by varying the operating frequency.
In the sample preparation for group 2 non metamaterial two element antenna arrays are chosen. It has no multiband performance and the bandwidth is less. In this group, 10 samples are taken and the mutual coupling values will be obtained by varying the operating frequency.
For this research work, the High Frequency Structure Simulation (HFSS) tool is used to simulate the design. The proposed MIMO novel two element antenna array is loaded with a circular CSRR metamaterial. This structure is created with FR4 as a substrate. The dimensions of the ground are 34 mm and the patch dimensions are 8.5mm and 11mm. The line feed has a dimension of 6mm and thickness is 1.3mm. The dimension of the total circular CSRR metamaterial structure is 11mm and 5mm. Graphs are obtained using the High Frequency Structure Simulation (HFSS) tool and data values are extracted. The independent variables are input power and frequency. The dependent variables are mutual coupling and CSRR structure and dimensions.

Statistical Analysis

The statistical software used in SPSS (Mohammed et al. 2019). The observed values from the simulation tool are given to SPSS to calculate the mean, standard deviation, and significance. In this research work, the independent variables are input power and frequency. The dependent variables are mutual coupling and Complementary Split Ring Resonator (CSRR) structure and dimensions.

Results

The experimental results indicate a reduced mutual coupling using the circular-shaped CSRR metamaterial in the two element antenna array compared with the non-metamaterial array. The mean mutual coupling in circular CSRR is -14.36 and in the non metamaterial antenna array, it is -8.73 with the significance $p = 0.023$. The results show that the circular shaped CSRR metamaterial novel two element antenna array exhibits a better reduction in mutual coupling compared to the non-metamaterial antenna array. The proposed work is successfully implemented by using a circular CSRR metamaterial structure. From the simulation results, it has been observed

that metamaterial-based antenna arrays exhibit a better reduction in mutual coupling than the arrays without metamaterial.
The results from Table 1 are collected by varying the frequency for both groups. From the analysis, it is shown that the performance of metamaterial-based two element antenna arrays has significance ($p = 0.023$) in comparison with the arrays without metamaterial. Fig. 1. and Fig. 2. shows the representation of a novel two element antenna array with loaded circular CSRR and without metamaterial CSRR structure respectively. CSRR structure is grown on the ground to provide better isolation. Fig. 3. shows the output graph for the group 1 values using the High Frequency Structure Simulation (HFSS) software. From Fig. 3., it is observed that the mutual coupling measured by (dB) has the least value of -20.87123 dB and the graph is obtained by varying the operating frequency. The peak gain of the circular CSRR Novel two element antenna array is 5.9 dB. The mutual coupling values for both groups are obtained by operating frequency. The CSRR structure provides better isolation for the fields from the individual antenna elements thereby reducing the mutual coupling between them. Fig. 4. shows the plotted graph for group 2 values. Fig. 5. and Fig. 6. shows the radiation pattern of the two-element antenna array with and without CSRR respectively. Fig. 7. discusses the bar chart that shows the comparison of reduction in mutual coupling between an antenna array with metamaterial loaded and the antenna array without metamaterial.
Table 2 gives the statistical values of 10 samples taken from without metamaterial antenna and with metamaterial circular CSRR antenna. The mean values are -14.36 for circular CSRR and -8.73 for without CSRR. It is evident from the results that reduction in mutual coupling is better in circular CSRR compared to without CSRR metamaterial structure.Table 3 shows the independent sample t-test which contains Levene's Test for equality of variances and t-test for Equality of means. Based on this table the significance value is 0.023 which is less than the standard significance value of 0.05. Hence it is declared that group 1 (mutual coupling with circular CSRR antenna array) and group 2 (mutual coupling without circular CSRR antenna array) are highly significant to each other.

The graphical representation of statistical analysis is shown in Fig. 7. which represents the comparison of group 1 (with circular CSRR) and group 2 (without circular CSRR) mutual coupling with error bars. In this graph, the error bars are set to 95 % CI and +/-1 SD. This graph concludes that a novel two element antenna array with square Complementary Split Ring Resonator (CSRR) has better reduced mutual coupling with less error bar compared with a novel two element antenna array without square CSRR.

Discussion

The characteristics of a circular Novel two element antenna array can be determined by varying the operating frequency from 0-14 GHz. The mean mutual coupling in square CSRR is -14.36 dB and in the non metamaterial antenna array, it is -8.7dB with a significance of $p = 0.023$. It is evident from the comparison of metamaterial with circular CSRR antenna array and without metamaterial antenna array that the mean reduction in mutual coupling is better for the antenna array loaded with metamaterial compared to the array without metamaterial.
The rapid growth of electromagnetic applications, as well as the lack of a theoretical model to estimate resonance frequency motivated to perform a comparative study of mutual coupling effects with this geometry (Najafy and Bemani 2020). By constraining the array's beamforming capabilities and ultimately limiting its communication range, mutual coupling impacts its performance. An array with two elements has several parameters that describe the mutual coupling effect. S21, also called the isolation coefficient, is one of the most fundamental forms of evaluating the effects. An analysis is performed for both cases based on the S21 responses with varying the gap between antenna elements (Pradeep and Bidkar 2019). The CTBGCSRR (Compact Triple-Band Gap Complementary Split Ring Resonator) unit cell has been presented for use in Wireless Local Area Network (WLAN) applications based on two microstrip-fed antennas to reduce mutual coupling and better radiation pattern in the triple-band. MIMO antennas have improved front-to-back ratios due to the compact size of the unit cell, which also improved the proximity of the two antennas (Vishvaksenan et al. 2017). A comparative examination of Circular Split Ring Resonators for Mutual Coupling Effect minimization is performed (Afsar et al. 2021). A 1x2 patch antenna loaded with a Circular Split Ring Resonator construction is also designed and analyzed. It is discovered that an array of two radiating patches with 5.43 dB and 5.40 dB directivity is isolated by about 13.3 dB using the Hexagonal Split Ring Resonator (HSRR) and CSSR structures, respectively (Zhang et al. 2019).
Frequency Selective Surfaces (FSS) structures based on graphene have been proposed for reducing the mutual coupling effects of multiband MIMO antenna arrays. Multi-band coverage is achieved by carefully selecting different Fermi energy levels in graphene. An FSS structure mounted between the elements of a MIMO array reduces mutual coupling effects. As a next step, the electromagnetic waves in the substrate are blocked by the FSS decoupling structure. FSS decoupling structure has been shown to eliminate both coupled electric and magnetic fields (Wu, Yuan, and Wu 2018). Furthermore, it has been demonstrated that the radiation performance of nano-antennas is not significantly affected by the FSS. The Modified Split Ring Resonator (MSRR) metamaterial structure carries a large current, which helps to reduce the mutual coupling of the antenna array to

improve performance and the efficiency of the antennas and to minimize array phase errors, mutual coupling reduction is a critical problem (Zakrajsek et al. 2017). There have been many methods of using metamaterials to enhance isolation and performance of mutual coupling but a few strategies have been described. A metamaterial-based antenna loading exhibits resonant bands at 1 GHz and 14 GHz with reflection coefficients of - 25 dB and - 22 dB respectively. For perfect impedance matching over the operating band, the width of the splits (S1 and S2) in the resonators is crucial. A comparison of different splits (S1 and S2) is provided. (Yang, Chu, and Mao 2016). Literature on the role of metamaterial in reducing the mutual coupling outnumbers the works with other approaches. Therefore, this work proceeded with antenna arrays loaded with metamaterial. The Complementary Split Ring Resonator (CSRR) can be used as a small LC circuit due to its limitations. Frequency resonators provide high noise characteristics. In the future, combinations of CSRR with other metamaterials will be investigated and their effectiveness in reducing mutual coupling will be evaluated.

Conclusion

This work demonstrates a significant improvement in performance by reducing the mutual coupling in a two element antenna array by loading circular CSRR metamaterials compared with without metamaterial CSRR. The mean value in the mutual coupling reduction in the metamaterial loaded Novel two element antenna array (-14.36) is significantly better than the two element antenna array without the metamaterial loaded (8.73) with an acceptable significant value of 0.023.

DECLARATION

Conflict of Interest

No conflict of interest in this manuscript.

Author Contribution

Author GS was involved in data collection, data analysis, manuscript writing. Author DS was involved in the conceptualization, guidance, and critical review of the manuscript.

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TABLES AND FIGURES

Table 1. Comparison for both the groups loaded metamaterial circular CSRR and without metamaterial and corresponding mutual coupling values are noted. The maximum mutual coupling values are obtained for the circular CSRR antenna array at (1-14GHz).

S.No	Group 1	Frequency (GHz)	Mutual coupling values for the antenna array with metamaterial-based circular CSRR (dB)	Group 2	Frequency (GHz)	Mutual Coupling Values for the antenna array without metamaterial(dB)
1	1	1	-20.87	2	1	-13.62

2	1	1.13	-19.28	2	1.13	-12.31
3	1	1.26	-17.76	2	1.26	-11.10
4	1	1.39	-16.28	2	1.39	-9.79
5	1	1.52	-14.84	2	1.52	-8.92
6	1	1.65	-13.44	2	1.65	-7.93
7	1	1.78	-12.09	2	1.78	-7.011
8	1	2.04	-9.64	2	2.04	-5.421
9	1	3.08	-5.21	2	3.08	-3.747
10	1	4.12	-9.80	2	4.12	-8.423
11	1	5.03	-18.71	2	5.03	-12.69
12	1	6.07	-27.22	2	6.07	-14.88
13	1	7.11	-22.93	2	7.11	-12.87
14	1	8.02	-18.79	2	8.02	-11.02
15	1	9.06	-17.41	2	9.06	-10.03
16	1	10.1	-17.87	2	10.1	-11.06
17	1	11.01	-14.49	2	11.01	-12.67
18	1	12.05	-12.92	2	12.05	-14.37
19	1	13.09	-14.88	2	13.09	-11.27
20	1	14	-14.94	2	14	-12.15

Table 2. The t-Test analysis of Mean and Standard deviation of antenna array with metamaterial circular CSRR and antenna array without CSRR. The mean value of the reduction in mutual coupling for circular CSRR antenna (-14.36) is higher than the reduction in mutual coupling without metamaterial (-8.73). The Independent sample t-test results that circular CSRR demonstrated better reduced mutual coupling in comparison with without metamaterial antenna were analyzed using IBM SPSS Software version.

Parameter	**Group**	**N**	**Mean**	**Std.Deviation**	**Std. Error mean**
Mutual coupling	Metamaterial-based circular CSRR antenna array	10	-14.36	4.165	1.317
Mutual coupling	Without Metamaterial antenna array	10	-8.73	2.997	.898

Table 3. T-test comparison of reduction in mutual coupling value for metamaterial loaded circular CSRR based antenna array and reduction in mutual coupling value for without metamaterial-based antenna array. Independent sample t-test shows statistical significance (p=0.023).

Independent sample Test									
	Levene's Test for equality of variances		**t-test for Equality of means**						
Mutual Coupling	**F**	**Sig.**	**t**	**df**	**significance (2 tailed)**	**Mean difference**	**Std.Error Difference**	**95% Confidence Interval of the Difference**	
								Lower	**Upper**
Equal variances assumed	1.503	.0236	-3.474	18	.003	-5.637	1.623	9.046	-2.22
Equal variances not assumed			-3.474	16.349	.003	-5.637	1.623	-9.071	-2.203

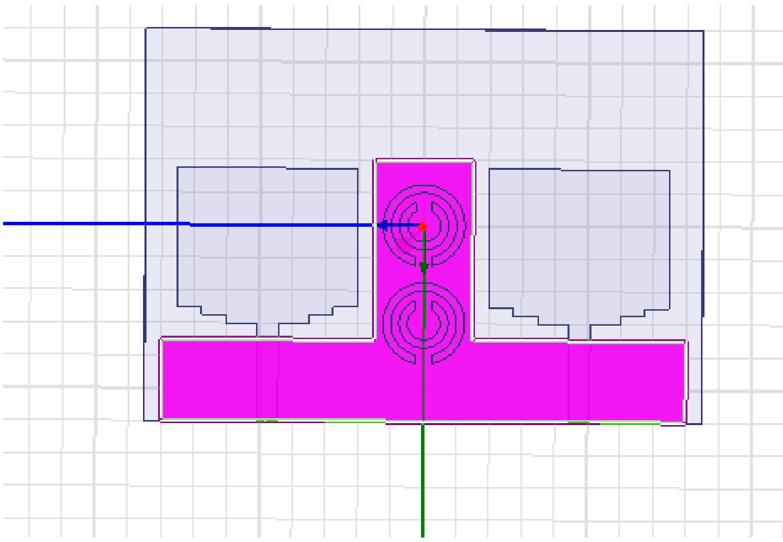

Fig. 1. Design of Novel two element antenna array with loaded metamaterial circular CSRR using High Frequency Structure Simulation (HFSS) (X-axis: width of the feed line and substrate, Y-axis: Length of the substrate, and Z-axis: the thickness of the substrate).

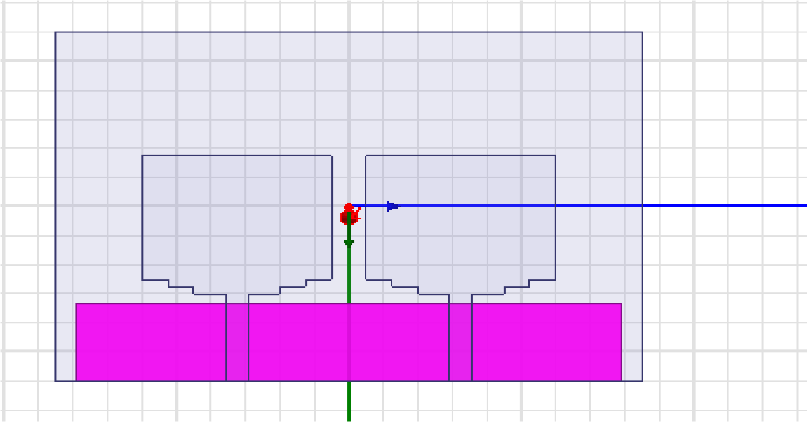

Fig. 2. Design of Novel two element antenna array without metamaterial using High Frequency Structure Simulation (HFSS) (X-axis: width of the feed line and substrate, Y-axis: Length of the substrate, and Z-axis: the thickness of the substrate).

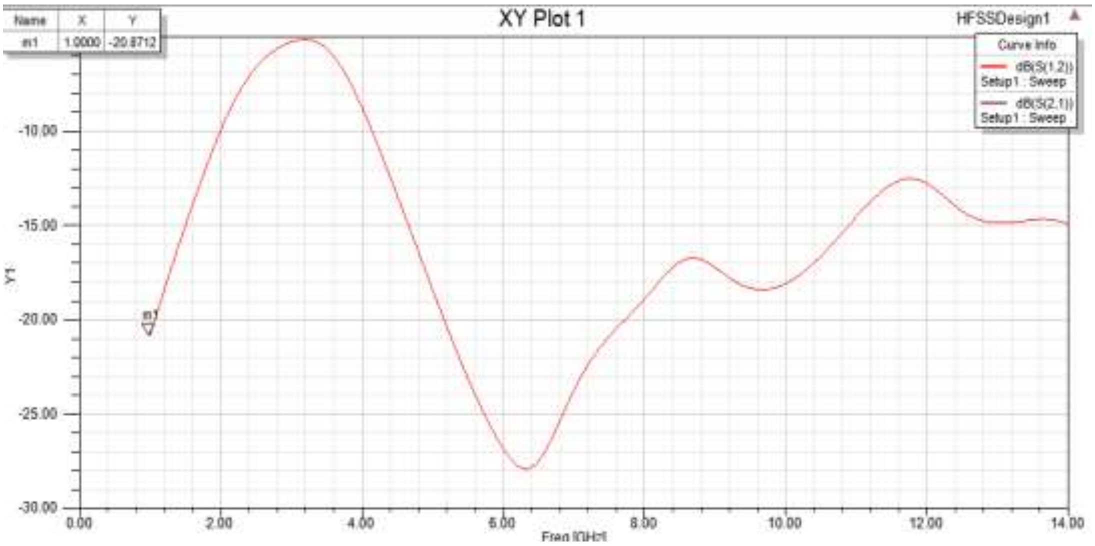

Fig. 3. Results of the Mutual Coupling test on a circular CSRR antenna array using metamaterials up to 14 GHz. Mutual coupling at -20.87123 dB.

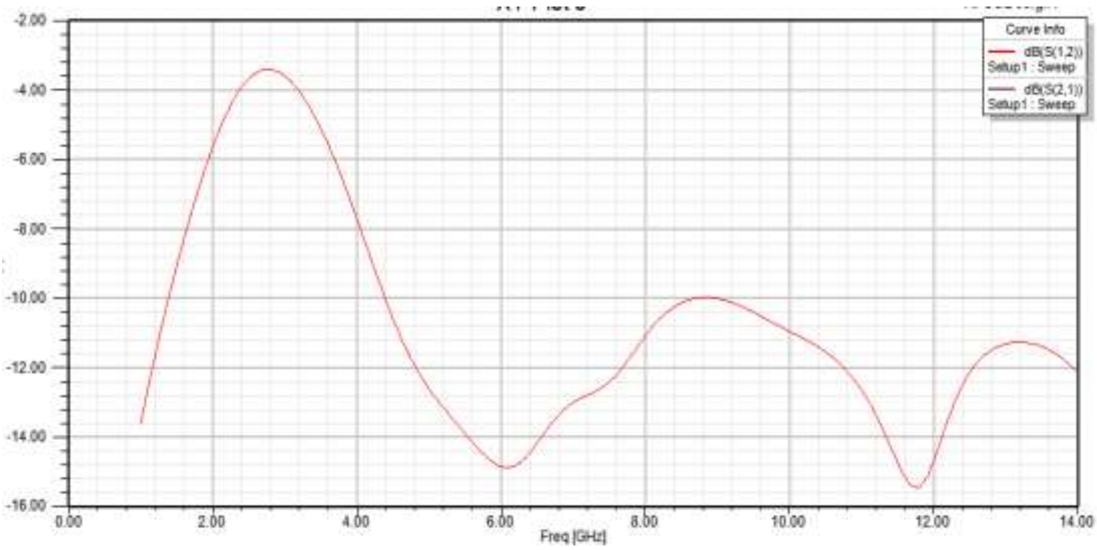

Fig. 4. Results of the Mutual Coupling test on a without CSRR antenna array using metamaterials up to 14 GHz. Mutual coupling at -13.6259 d

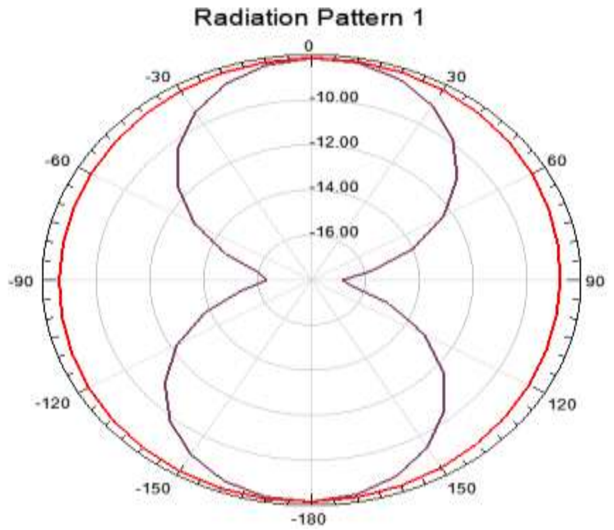

Fig. 5. Radiation patterns of the antenna with CSRR using High Frequency Structure Simulation (HFSS).

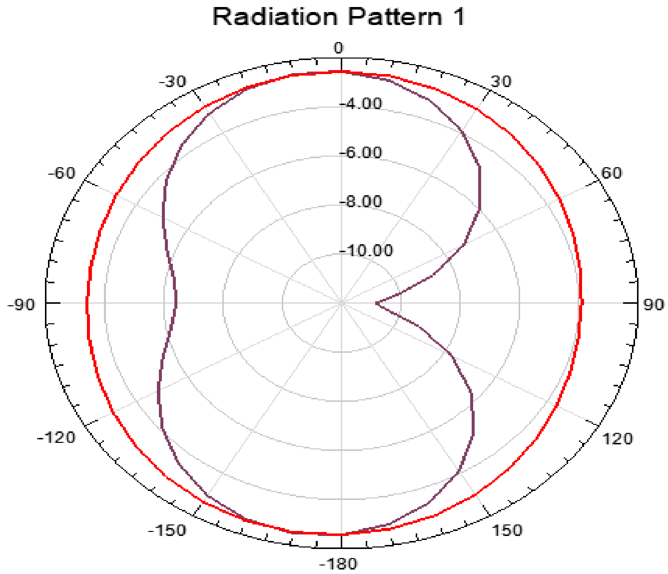

Fig. 6. Radiation patterns of the antenna without metamaterial CSRR using High Frequency Structure Simulation (HFSS).

GGraph

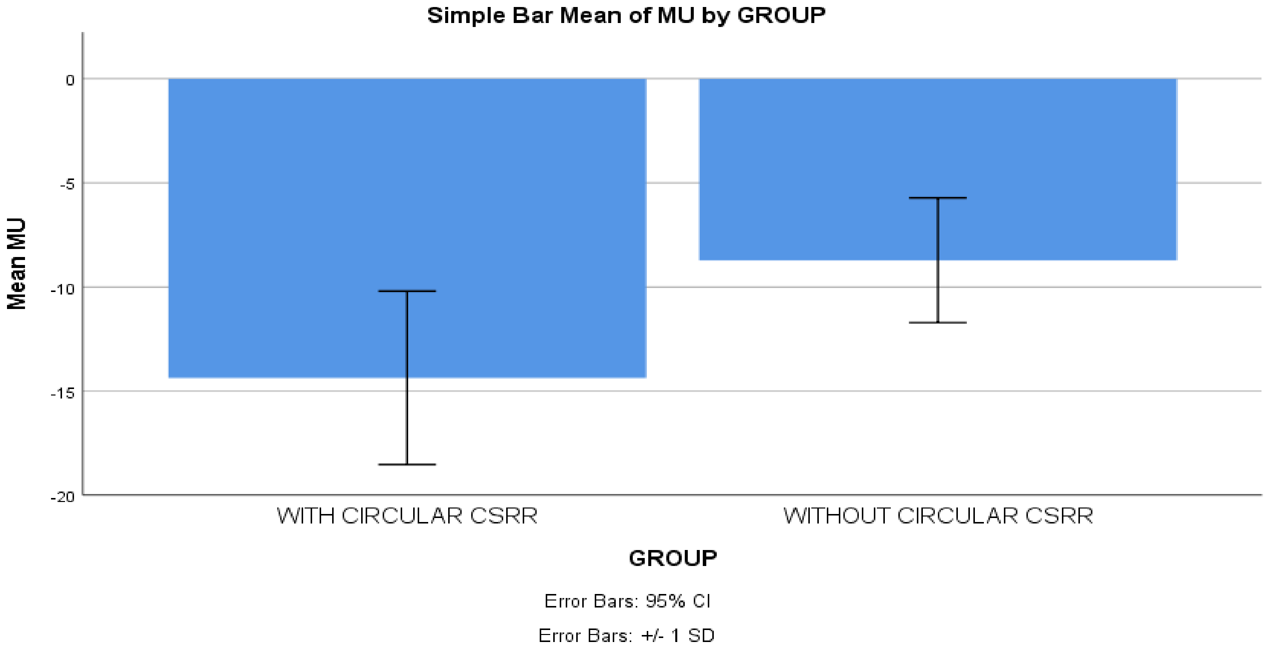

Fig. 7. Bar chart comparing the mean (+/- 1SD) reduction in the mutual coupling of a metamaterial-based circular CSRR antenna array and antenna array without metamaterial CSRR. The mean reduction in the mutual coupling of metamaterial-based circular CSRR antenna array is better than without metamaterial antenna array X-Axis: with metamaterial circular CSRR antenna array Vs without metamaterial antenna array Y-Axis: Mutual coupling.