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Mutual Coupling Reduction in Antenna Arrays by Using Hexagonal Complementary Split Ring Resonator Metamaterial Structure in Comparison with Non-Metamaterial Antenna Array

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Abstract

Aim: The aim of this work is to reduce the mutual coupling by incorporating Hexagonal Complementary Split Ring Resonator (CSRR) into metamaterial structures in the novel two element antenna array. Mutual coupling values are measured for different frequencies and the values are compared with an antenna array without metamaterial structures. **Materials and Methods**: Mutual coupling in hexagonal shaped CSRR metamaterial is compared with that of antenna array without metamaterial. Each material has 10 samples. The mutual coupling values are measured by varying the operating frequency. The G power of the antenna array is 0.8 and the maximum acceptable error rate is 0.05. **Results:** The experimental results indicate a reduced mutual coupling using hexagonal-shaped CSRR metamaterial novel two element antenna array compared with the non-metamaterial array. The mean mutual coupling in hexagonal CSRR is -20.25 and in the non-metamaterial antenna array, it is -8.73 with the significance p = 0.0002. **Conclusion:** The hexagonal-shaped Complementary Split Ring Resonator (CSRR) metamaterial structure in a novel two element antenna array exhibits a better reduction in mutual coupling compared to the antenna array without the metamaterial loading.

Keywords

Mutual Coupling, Complementary Split Ring Resonator (CSRR), Novel two Element Antenna Array, Metamaterial, Radiation Pattern, High Frequency Structure Simulation (HFSS).

INTRODUCTION

A metamaterial antenna is an antenna that uses metamaterials to improve the performance of tiny (electrical) antennas (Haine 2004). The goal of these antennas, like any other electromagnetic antenna, is to propel energy into space Communication systems widely use antennas with microstrip arrays, which have unique properties and characteristics like their low profile, their lightweight, their compactness, and their conformability (Rabinovich and Alexandrov 2012). An array of microstrip elements, with single or multiple feeds, can also be used to achieve greater directivity, radiation pattern, and scanning capabilities. Arrays provide high directivity compared with single element.The noise factor is related to mutual coupling values (Bakouchi et al. 2012). The applications of reduced mutual coupling are useful in antenna array communications to avoid noise and improve the quality of the transmission (Abdallah 2006). The application of a complementary split-ring resonator (CSRR) is for biosensors to determine the concentration of glucose in an aqueous solution and also it is used for satellite communication (Craeye and Van 2021).

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 (Chaitanya et al. 2022). In addition, these metamaterials and radiation patterns offer the potential to realize superlenses or design passive microwave circuits like phase shifters, directional couplers, narrowband and wideband filters etc (Kim and Hopwood 2019). Metamaterial left-handed effect demonstrated with a hexagonal split ring resonator (Fu-Li et al. 2004). The electromagnetic parameters are analyzed to show that negative permeability bandwidths are present when simulated effects of SRR structural parameters are applied ((Pradeep and Bidkar 2018)). To understand the Complementary Split Ring Resonator (CSRR) electromagnetic behavior, the duality principle has to be applied to the Split Ring Resonator (SRR) structures. Magnetic materials based on SRR react to magnetic fields with vertical polarization (relative to the plane of the SRR). A balanced inductive-capacitive effect is produced by the induced electromotive force in the rings and gaps (Falcone et al. 2004). A balanced inductive-capacitive effect is produced by the induced electromotive force that generates current within the metallic rings and gaps (Falcone et al. 2004).

Previously our team has a rich experience in working on various research projects across multiple disciplines (Venu and Appavu 2021; Gudipaneni et al. 2020; Sivasamy, Venugopal, and Espinoza-González 2020; Sathish et al. 2020; Reddy et al. 2020; Sathish and Karthick 2020; Benin et al. 2020; Nalini, Selvaraj, and Kumar 2020).The lacunae of the existing research are the complexity and poor reduction in mutual coupling. The approach of using hexagonal CSRR yields a reduction in mutual coupling in a two-element antenna array. This work aims to reduce the mutual coupling to achieve high gain in a novel two-element array.

MATERIALS AND METHODS

This study was conducted in the Antenna Lab, Department of Electronics and Communication Engineering at Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, India. This project was done using High Frequency Structure Simulation (HFSS). It consists of two groups, one is 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 calculation Pretest g power is fixed as 0.8 and an acceptable error rate of 0.05 is used.

In the sample preparation for group 1 hexagonal CSRR metamaterial novel 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 novel two-element antenna arrays are chosen. It has no multi-band performance, In this group,10 samples are taken and the mutual coupling values will be obtained by varying the operating frequency.

For this work, the High Frequency Structure Simulation (HFSS) tool is used to simulate the design. The proposed Multiple Input Multiple Output (MIMO) novel two element antenna array is loaded with hexagonal CSRR two-element metamaterial structure created with this tool with FR4 as substrate. The dimensions of the ground are 34 mm and the patch dimension is 8.5 mm and 11 mm. The line feed has a dimension of 6 mm and thickness is 1.3 mm. The dimension of the total hexagonal CSRR metamaterial structure is 11 mm and 5 mm. 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 CSRR structure dimensions.

Statistical Analysis

The statistical software used in SPSS (Mohammed et al. 2019). The obtained values from the simulation tool are extracted into 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 CSRR structure and dimension.

RESULTS

The experimental results indicate a reduced mutual coupling using hexagonal-shaped CSRR metamaterial novel two element antenna array compared with the non-metamaterial array. The mean mutual coupling in hexagonal CSRR is -20.25 and in the non-metamaterial antenna array, it is -8.73 with the significance p = 0.0002. The results show that the hexagonal-shaped CSRR metamaterial novel two-element antenna array exhibits a better reduced mutual coupling compared to the non-metamaterial antenna array. The proposed work is successfully implemented by using a hexagonal CSRR metamaterial structure. From the simulation results, it has been observed that the metamaterial antenna array exhibits mutual coupling better than 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 the metamaterial has a higher significance ($p < 0.05$) in comparison with the array without metamaterial. Fig. 1. and Fig. 2. shows the representation of a nonel hexagonal CSRR loaded array and array without metamaterial CSRR structure respectively. Better isolation is provided by CSRR structure etched on the ground plane. Fig. 3. shows the output graph for 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 -26.6875 dB and the graph is obtained by varying the operating frequency. The peak gain of the hexagonal CSRR antenna is 6.4 dB. The mutual coupling values for both groups are obtained by varying the frequency. The mutual coupling is -13.6259 dB for group 2 as shown in Fig.4. The radiation pattern of the novel two-element antenna array with and without CSRR is presented in Fig. 5. and Fig. 6. 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 hexagonal CSRR antenna. The mean values are -20.25 for hexagonal CSRR and -8.73 for without CSRR. It is evident from the results that the mean value is high for a reduction in hexagonal CSRR compared to without CSRR.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 found to be 0.0002. Hence it is declared that group 1 (mutual coupling with CSRR antenna array) and group 2 (mutual coupling without 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 hexagonal CSRR) and group 2 (without hexagonal CSRR) mutual coupling mean value with error bars. The error bars are set to 95% CI and +/-1 SD. This work shows a reduction in mutual couling in the novel two element antenna array with hexagonal CSRR compared with the two element antenna array without CSRR.

DISCUSSION

The characteristics of a Novel two-element antenna array can be determined by varying the operating frequency from 0-14 GHz. The mean mutual coupling in hexagonal CSRR is -20.90 dB.and in the non-metamaterial antenna array is -8.73 dB with significance p = 0.0002.

The derived effective characteristics of the unit cell demonstrate that both bands are related to the structure's negative permittivity response (Zhang et al. 2019), (Vishvaksenan et al. 2017). A row of EBG structures reduced mutual coupling by 16.4dB at the designated resonant frequency, and the average decrease in the antenna's

operating band was 7.57 dB (Ma and Zhao 2014). When vertically polarized electric fields are present, the Complementary Split Ring Resonator (CSRR) exhibits resonant behavior (Wang, Fang, and Ge 2009). Therefore, such structures have proven to be particularly useful in electromagnetic fields with relatively vertically polarized electric fields and reduce the mutual coupling effectively. Through the introduction of a novel CSRR cell, mutual coupling between two patch antennas is reduced (Bakouchi et al. 2012). A metamaterial is an artificial material that has distinct properties, namely negative permeability, negative permittivity, and good radiation pattern ((Quevedo-Teruel, Sipus, and Rajo-Iglesias 2011). This enables the antennas to achieve a wider band of frequencies and reduce their size and work in novel microwave circuits (Smith et al. 2000). In this case, the CSRR structure is the dual of SRR, located longitudinally in the waveguide. The most significant parameters of the structure and their effects on the resonance frequency (frequency in which the S12 is maximum) and the relative bandwidth of frequency response (Alici and Ozbay 2007). According to the literature, the metamaterial CSRR antenna gives better performance and has a high multiband width. The effect of mutual coupling can be reduced using advanced metamaterial CSRR (Rezapour et al. 2019).
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 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 research demonstrates a significant improvement in performance and reduced mutual coupling for the loaded hexagonal complementary split ring resonator (CSRR) based on metamaterials compared with without metamaterial CSRR. The mean value for the reduction in mutual coupling in a loaded novel two element antenna array with metamaterial (-20.25) is significantly better than the two element antenna array without the metamaterial loaded (-8.73).

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 hexagonal CSRR and corresponding mutual coupling values. The maximum mutual coupling values are obtained for the Hexagonal CSRR antenna array at (1-14 GHz).

S.No	Group 1	Frequency (GHz)	Mutual coupling for the antenna array with hexagonal CSRR (dB)	Group 2	Frequency (GHz)	Mutual Coupling for the antenna array without metamaterial(dB)
1	1	1	-26.68	2	1	-13.62
2	1	1.13	-25.16	2	1.13	-12.31
3	1	1.26	-23.69	2	1.26	-11.10
4	1	1.39	-22.62	2	1.39	-9.79
5	1	1.52	-20.85	2	1.52	-8.92
6	1	1.65	-19.46	2	1.65	-7.93

 ISSN 2029-0454
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7	1	1.78	-18.09	2	1.78	-7.011
8	1	2.04	-15.42	2	2.04	-5.421
9	1	3.08	-9.07	2	3.08	-3.747
10	1	4.12	-22.9	2	4.12	-8.423
11	1	5.03	-23.29	2	5.03	-12.69
12	1	6.07	-24.6	2	6.07	-14.88
13	1	7.11	-23.1	2	7.11	-12.87
14	1	8.02	-24.88	2	8.02	-11.02
15	1	9.06	-35.99	2	9.06	-10.03
16	1	10.10	-25.2	2	10.1	-11.06
17	1	11.01	-11.55	2	11.01	-12.67
18	1	12.05	-18.05	2	12.05	-14.37
19	1	13.09	-20.16	2	13.09	-11.27
20	1	14.00	-22.99	2	14	-12.15

Table 2. The t-Test analysis of Mean and Standard deviation of antenna array with hexagonal CSRR metamaterial and array without metamaterial. The mean value of mutual coupling for hexagonal CSRR antenna (-20.25) is higher than the mutual coupling without metamaterial (-8.73). The Independent sample t-test results that hexagonal 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 hexagonal CSRR antenna array	10	-20.25	4.213	1.332
Mutual coupling	Without Metamaterial antenna array	10	-8.73	2.997	0.948

Table 3. T-test comparison of mutual coupling value for metamaterial loaded hexagonal Cplementary Split Ring Resonator (CSRR) based antenna array and mutual coupling value for without metamaterial-based antenna array. Independent sample t-test shows statistical significance (p = 0.0002).

Independent sample Test		
	Levene's Test for equality of	**t-test for Equality of means**

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2022

	variances								
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	1.567	.227	-7.051	18	.0002	-11..528	1.635	-14.964	-8.093
Equal variances not assumed			-3.616	16.251	.0.0002	-11.528	1.635	-14.990	-8.067

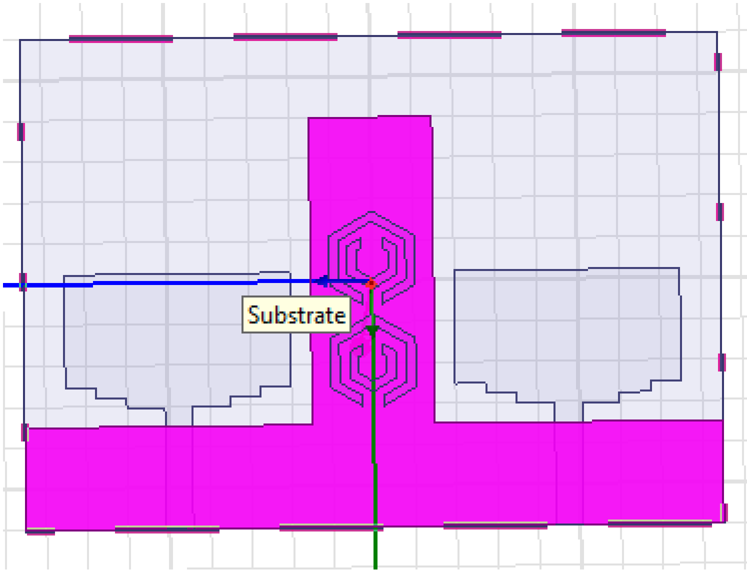

Fig. 1. Design of Novel two element antenna array with loaded metamaterial hexagonal Complementary Split Ring Resonator (CSRR) using High Frequency Structure Simulation (HFSS) (X-axis: width of the feed line and substrate, Y-axis: Length of the substrate, and Z-axis: the thickness of the substrate.

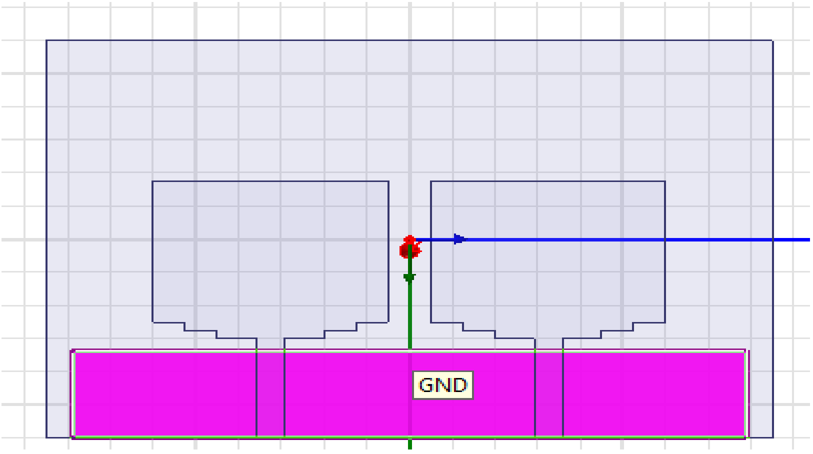

Fig. 2. Design of Novel two element antenna array without metamaterial using High Frequency Structure Simulation (HFSS) (X-axis: width of the feed line and substrate, Y-axis: Length of the substrate, and Z-axis: the thickness of the substrate).

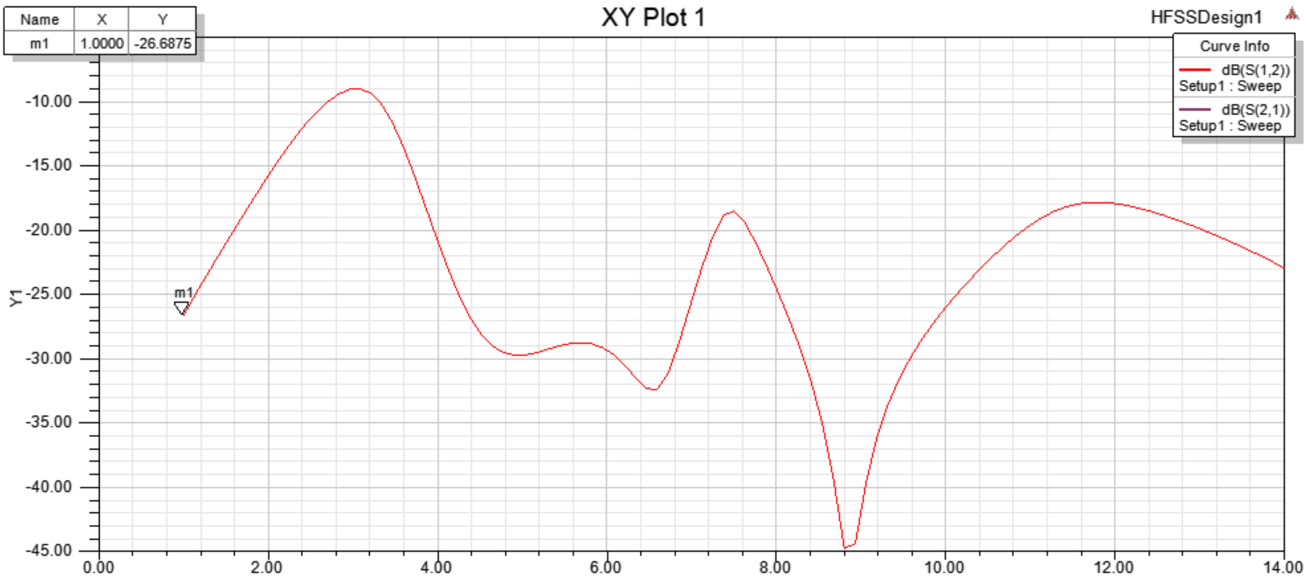

Fig. 3. Results of the Mutual Coupling test on a hexagonal complementary split ring resonator (CSRR) antenna array using metamaterials up to 14 GHz. Mutual coupling at-26.6875 dB.

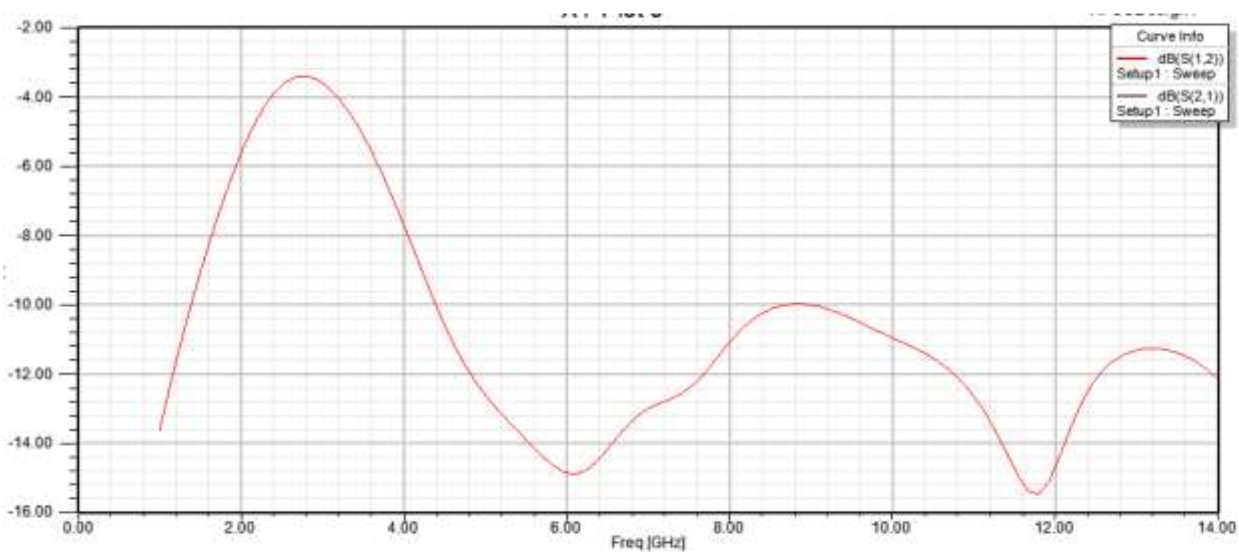

Fig. 4. Results of the Mutual Coupling test on a without Complementary Split Ring Resonator (CSRR) antenna array using metamaterials up to 14 GHz. Mutual coupling at -13.6259 dB.

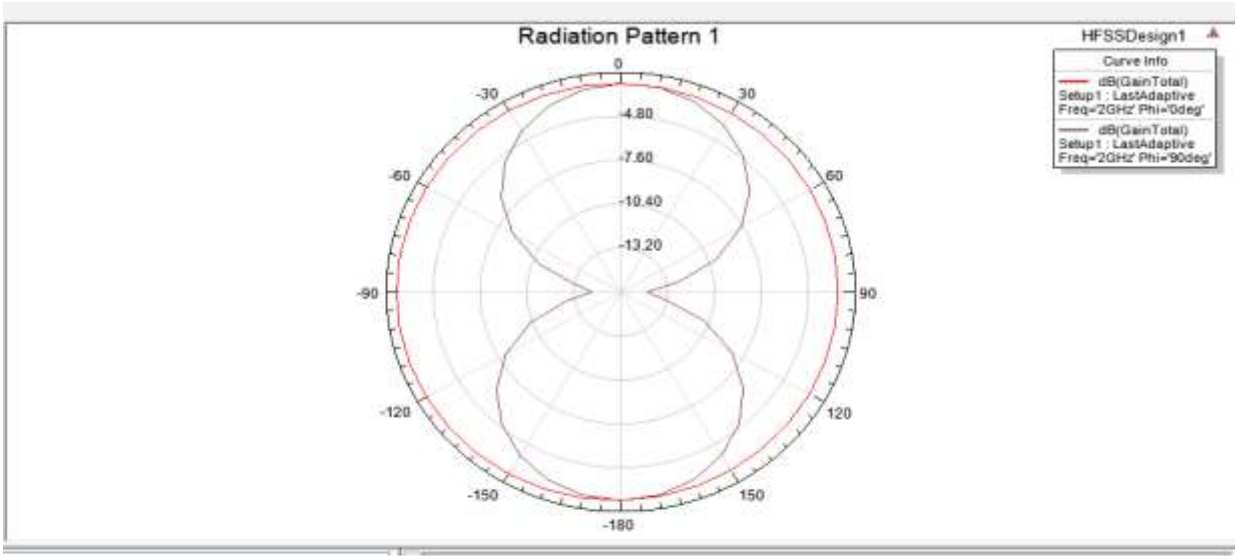

Fig. 5. Radiation pattern of the antenna with CSRR using High Frequency Structure Simulation (HFSS).

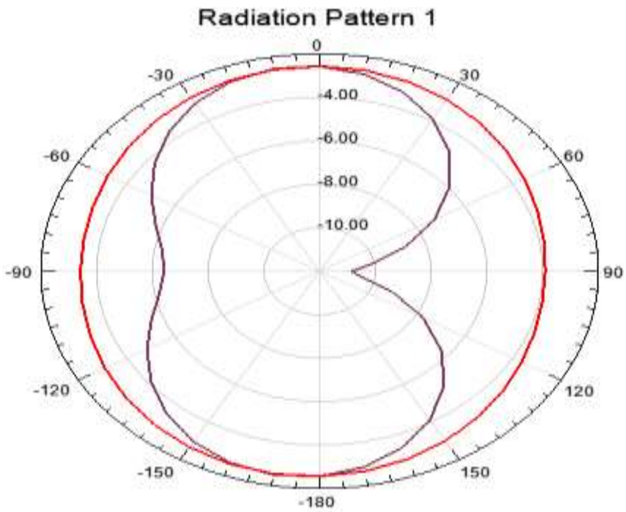

Fig. 6. Radiation patterns of the antenna without CSRR using High Frequency Structure Simulation (HFSS).

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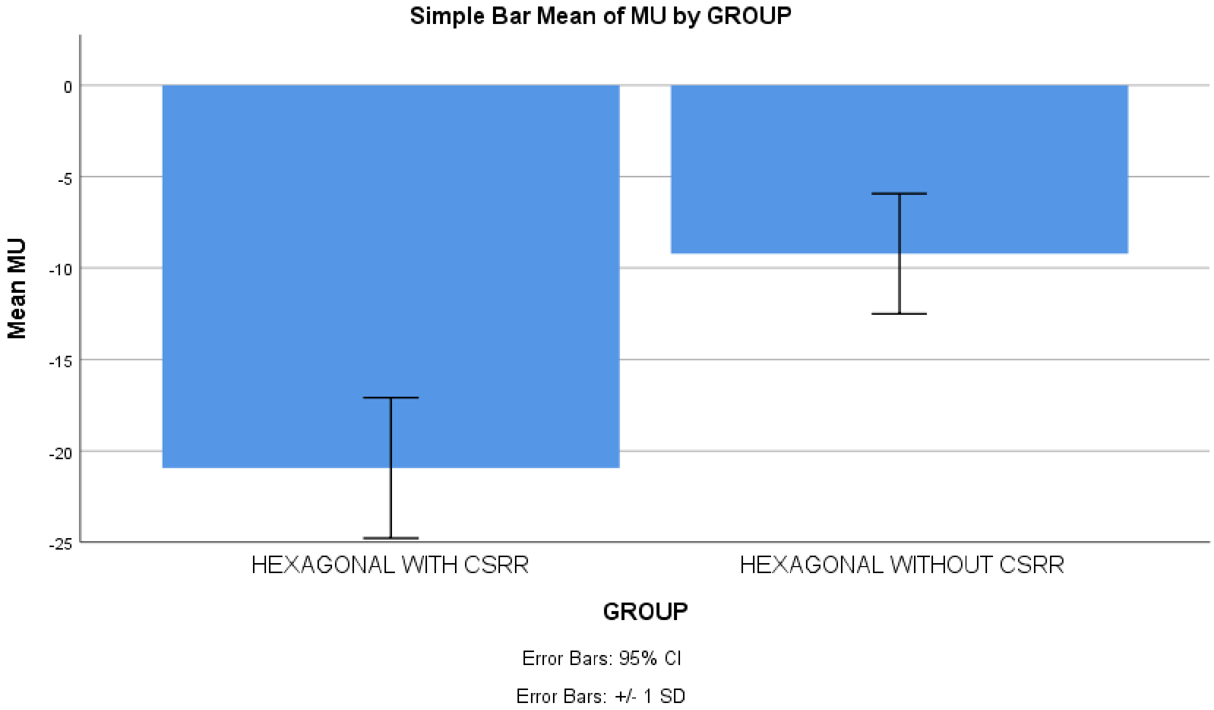

Fig. 7. Bar chart comparing the mean (+/-1SD) reduction in the mutual coupling of a metamaterial-based hexagonal CSRR antenna array and without metamaterial CSRR. The mean reduction in the mutual coupling of metamaterial-based hexagonal CSRR antenna array is better than without metamaterial antenna array X-Axis: Group 1 (antenna array with metamaterial hexagonal CSRR) and 2 (antenna array without metamaterial antenna array) Y-Axis: Mutual coupling.