A Massive MIMO Antenna Array Loaded with Quadruple Sequentially Rotated Square SRR for 5G Base Station

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Abstract. A 4 × 4 multiple input multiple output (MIMO) rectangular patch antenna array loaded with massive sequentially rotated split ring resonators (SRR) operating at 3.5 GHz is presented for 5G new radio (NR) frequency range 1 (FR1) n77 mid band base station application. SRR are placed in such a novel arrangement to avoid radiation pattern overlapping and improve overall gain of antenna array. Each sub array consists of three layers, top layer is made up of 2 × 2 patch elements each surrounded with four rings of sequentially rotated split ring resonators to support high port pattern isolation, middle layer act as ground plane, bottom layer consists of calculated corporate feeding network which feed antenna elements using via through ground plane at an optimized location to achieve impedance matching. More than 100 MHz impedance bandwidth, at least 14.47 dBi gain for any sub array, more than 90% of efficiency, 0.0027 of envelop correlation coefficient (ECC) and port isolation less than −25 dB is achieved using proposed MIMO array system. Overall, 20.6 dBi gain is achieved for whole array system. Leveraging a novel interlaced subarray topology, this work achieves superior port to port isolation and improved gain compared to prior state of the art MIMO designs. These optimistic results make proposed array an excellent candidate for 5G base station application.

Keywords: Massive MIMO · SRR (Split Ring Resonator) · NR (New Radio) · FR1 (Frequency Range 1) · High Efficiency · Port Isolation · High Gain

1 Introduction

Massive MIMO antenna arrays have emerged as a key technology for meeting the high data rate and reliability demands of next generation wireless communications [1, 2]. Integrating metamaterial split ring resonators into massive MIMO antenna arrays unlocks new potential for enhanced efficiency and reconfigurability. Researchers at LUND university in 2010 analyzed performance and practical feasibility of very large MIMO arrays

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at base station [3]. Up until mid of last decade massive MIMO was incorporated by 3GPP to standardize for 5G communication system. In 3GPP release 15 5G massive MIMO standards are specified [4]. Complementary split ring resonators (CSRR) are etched in ground plane [5] and also used co planar as radiating elements [6, 7] with defective ground plane [8, 9]. A variety of distinct designs are documented in the references [10–14]. Reported arrays show some notable deficiencies which need further research to optimize realized gain, unacceptable side lobe levels, manufacturability constraints for massive MIMO 5G base stations.

To address the limitations of prior works and meet the demanding requirements of massive MIMO systems, this paper presents a novel 4 × 4 antenna array with split ring resonators to enhance port isolation while maintaining broadside radiation with high efficiency, very low envelop correlation coefficient less than 0.0027 and high gain up to 20.5 dBi. Proposed antenna array system is designed using CST Studio Suit. Remaining sections of article is organized as follows. Section II gives details on design and optimization of antenna unit cell. Section III covers design and results comparison of 4 × 4 array. Finally, last section concludes the paper.

2 Design and Optimization of Antenna

2.1 Design of Unit Cell

A unit cell consists of three layers top layer is 2 × 2 rectangular linearly polarized elements surrounded by four sequentially rotated SRR, bottom layer is corporate feeding network and middle layer act as ground layer for both patch and feeding network. Four via from feeding network to patches through two layers of Rogers RT-5880 (dielectric constant 2.2, height 1.73) as shown in Fig. 1. The length and width of a single element is calculated using following Eq. 1 and 2 defined in [15].

$$\text{Width} = \frac{c}{2f_o\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{1}$$

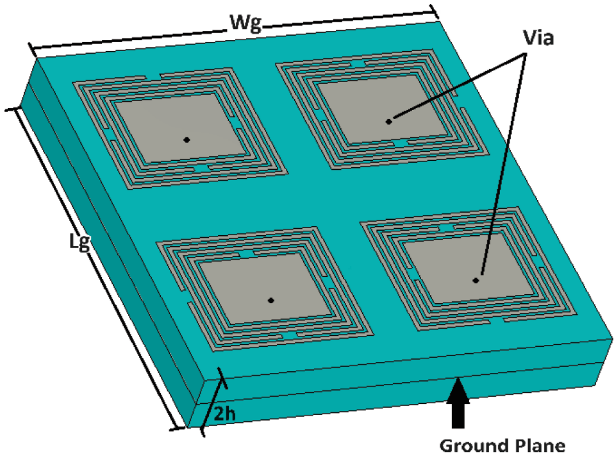
$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[\frac{1}{\sqrt{1+12\left(\frac{h}{W}\right)}}\right]$$

$$\text{Length} = \frac{c}{2f_{o\sqrt{\varepsilon_{eff}}}} - 0.824h\left(\frac{\left(\varepsilon_{eff}+0.3\right)\left(\frac{W}{h}+0.264\right)}{\left(\varepsilon_{eff}-0.258\right)\left(\frac{W}{h}+0.8\right)}\right) \tag{2}$$

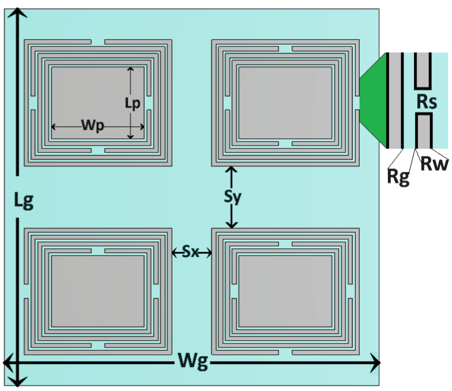
Detailed parameters and corresponding values to design unit cell and full array is mentioned in Table 1, while size of unit cell with two layers of substrate is 137 × 137 × 3.46.

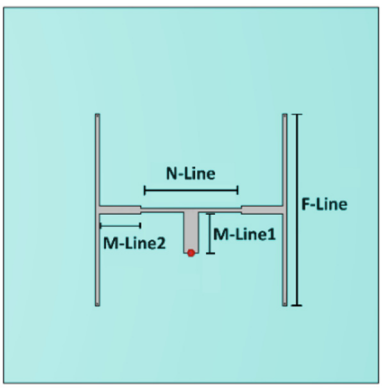
Table 1. Unit cell and 4 × 4 array values and dimensions.

Parameter	Value (mm)	Parameter	Value (mm)	Element	Dimension (mm^2)
Wp	33.86	Rs	5	N-Line	36.73 × 1.55
Lp	26.04	Rg	1	F-Line	70.08 × 1.55
Wg	137.05	Rw	1.5	M-Line1	14.88 × 5.34
Lg	137.05	L	274.1	M-Line2	15.12 × 3.06
Sx	14.67	W	274.1		
Sy	22.48	h	1.73		



(a)





(b) (c)

Fig. 1. Unit Cell structure. (a) Side view (b) Top View (c) Bottom View

Figure 2 presents a comprehensive comparison of the results in terms of achieving the required bandwidth, efficiency, and gain. The analysis reveals that when employing the Split Ring Resonator (SRR) antenna, a total efficiency exceeding 90% is attained across the entire band of concern. Furthermore, within the specified band, the SRR antenna exhibits an enhanced gain of 1 to 1.5 dBi compared to its counterpart without the SRR. Figure 3 illustrates the radiation patterns, where (a) and (b) depict the 3D radiation patterns of the unit cell with and without the incorporation of SRR, respectively. Additionally, Fig. 3(c) provides a detailed comparison of the 2D radiation patterns for the unit cell with and without the SRR implementation.

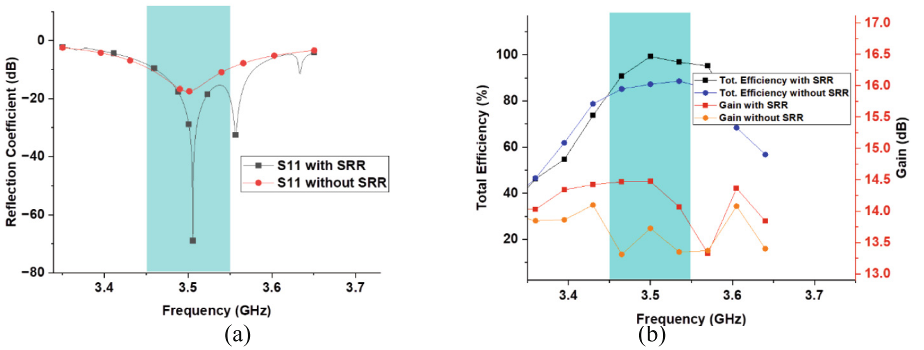


Fig. 2. (a) Reflection Coefficient with and without SRR (b) Efficiency and Gain plot with and without SRR

To further enhance the gain and efficiency each surrounding SRR was rotated by 90 degrees relative to the preceding one. Table 2 provides a comprehensive rationale for the utilization of SRR rotation within the base structure, elucidating the associated gains in terms of improved gain, augmented efficiency, and reduced side lobe levels at centered frequency. Notably, it was observed that as the number of SRRs increased and they were subjected to further rotation, both the peak gain and efficiency exhibited substantial improvements, while the side lobe levels (SLLs) remained unaffected.

Table 2. Impact of Number and Orientation of Split Ring Resonators on Antenna Array Performance Parameters.

Rings in SRR	Without rotation			With rotation		
	Peak Gain dBi	Efficiency	SLL	Peak Gain dBi	Efficiency	SLL
1	12.567	86	−9.5	13.256	91	−9.6
2	13.4014	86	−9.5	14.4499	92	−9.6
3	12.7798	87	−9.6	14.3805	94	−9.7
4	13.5364	87	−9.6	14.4774	98	−9.7

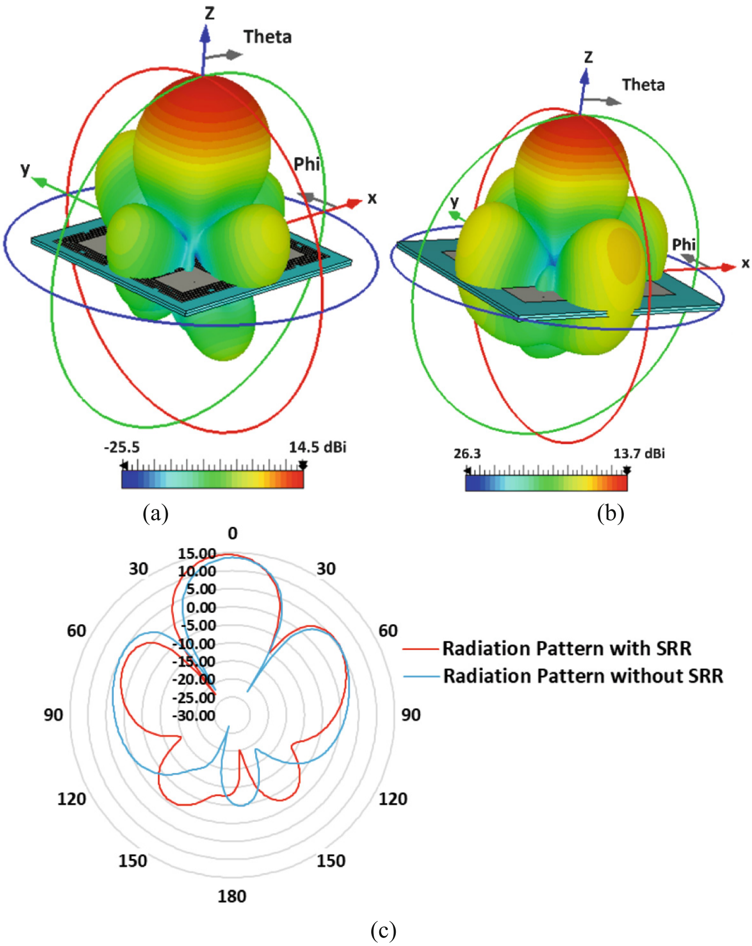
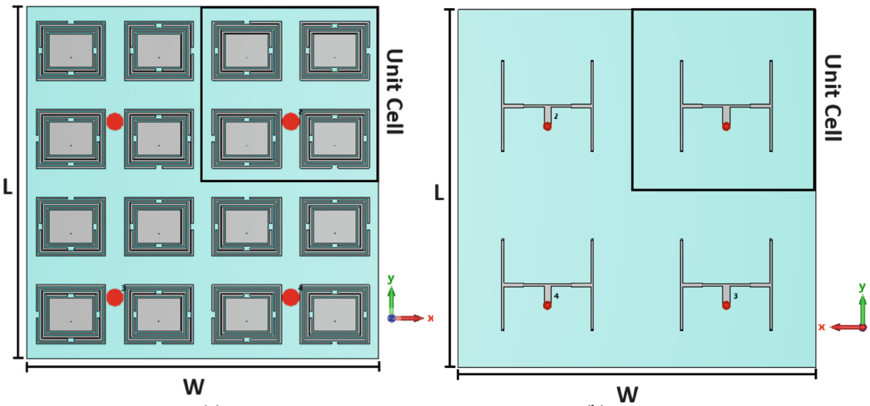


Fig. 3. 3D radiation pattern at 3.5 GHz a) with SRR b) without SRR c) 2D Radiation pattern comparison

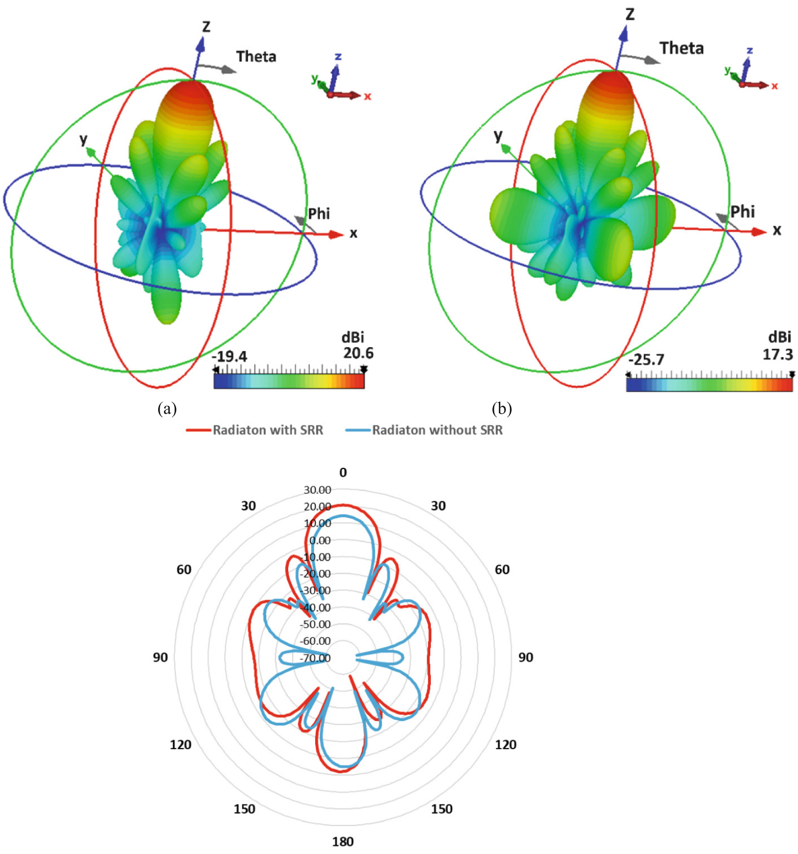
2.2 Design of Array

The proposed antenna array is configured as a 4 × 4 element rectangular lattice, comprising 4 ports arranged in a 2 × 2 layout. Each port and its associated feeding network are responsible for exciting four antenna elements, with each element being encircled by four rectangular, sequentially rotated split ring resonators (SRRs). Figure 4 illustrates the top and bottom views of the complete array model. Furthermore, Fig. 5 depicts the 3D and 2D radiation patterns of the full array with and without the incorporation of SRRs at the centered frequency of 3.5 GHz. It is evident from the analysis that the implementation of SRRs around the rectangular patch antenna array results in a substantial enhancement of the gain.



(a) (b)

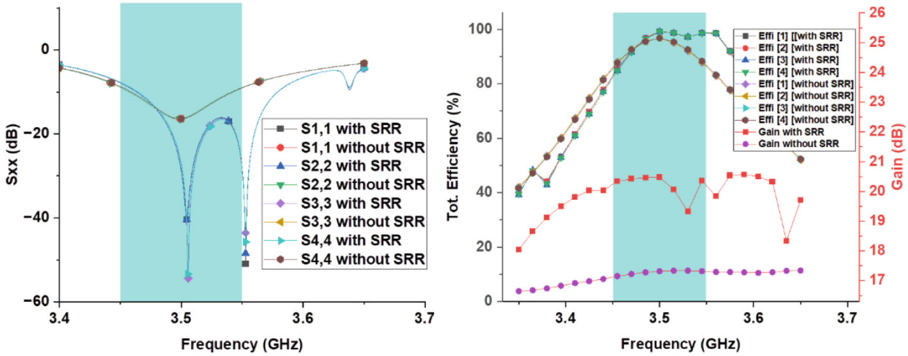
Fig. 4. 4x4 Array(a) Top view (b) Bottom view



(a) (b) (c)

Fig. 5. Array factor (a) 3D radiation pattern with SRR (b) 3D radiation pattern without SRR (c) 2D radiation pattern comparison

Figure 6 presents a comparative analysis of the reflection coefficient, efficiency, and overall gain of the full MIMO array, both with and without the incorporation of SRRs. Port isolation and the envelope correlation coefficient (ECC) are regarded as the most crucial MIMO parameters for evaluating the array's performance.



(a) (b)

Fig. 6. 4x4 Array (a) Reflection Coefficient (b) Efficiency and Gain

ECC quantifies the statistical correlation between the signal envelopes received by the individual antennas. Mutual coupling in antenna arrays represents the electromagnetic interaction between the individual antenna elements. Figure 7 illustrates a comparison of port isolation and ECC for the full array, with and without the utilization of SRRs. Notably, it is observed that the mutual coupling remains below −25 dBi across the band of concern, spanning from 3.45 to 3.55 GHz. Furthermore, the MIMO antenna array employing SRRs exhibits a lower ECC in comparison to its counterpart without SRRs, indicating an improved performance. Table 3 presents a comparative analysis of the proposed antenna and MIMO system with previously reported base station antennas, evaluating critical performance parameters. The results demonstrate that the proposed antenna exhibits superior performance across the majority of the considered parameters, evidencing its enhanced capabilities.

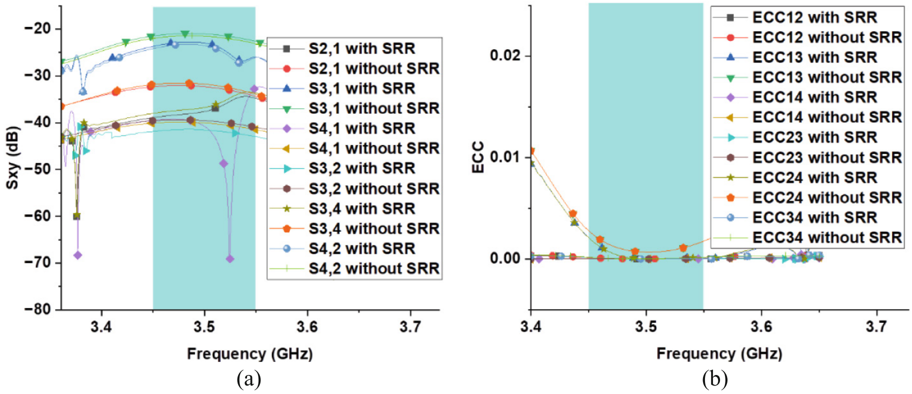


Fig. 7. 4x4 Array (a) Mutual Coupling (b) ECC comparison

Table 3. Comparison of proposed structure with previously reported MIMO antenna arrays.

Ref.	Operating Band (GHz)	MIMO Model	Array Size (mm3)	Elements per port	Max. Gain per port (dBi)	Total Gain Array (dBi)	Total Efficiency	Port Isolation (dB)	ECC
[10]	2.8–4	4 × 4	200 × 200 × 32	-	–	9.1	-	−27	-
[12]	3.3–3.87	4 × 4	147.41 × 147.41 × 3.2	2 × 2	8.1	8.72	> 92	<−32	0.001
[13]	3.1–11	1 × 2	26 × 31 × 0.8	1	–	5.67	85.5	<−25	0.001
[16]	3.3–5	4 × 4	76.2 × 76.2 × 13.9	1	–	7.9	>90	<−30	<0.1
[17]	3.35–3.65	2 × 8	8(36 × 23 × 1.5)	1 × 2	–	6.5	65	28	<0.1
This work	3.45–3.55	4 × 4	274.1 × 274.1 × 3.46	2 × 2	14.473	20.5	>91	<−25	<0.0027

3 Conclusion

In this research endeavor, a 4 ports 16 elements antenna array has been designed on a Rogers 5880 substrate, incorporating a corporate feeding network in which each port excites four radiating elements surrounded with rotating SRR to operate within the frequency range of 3.45 to 3.55 GHz. Each unit cell exhibits a peak gain of 14.47 dBi and achieves a total efficiency surpassing 90% across the band of concern, spanning from 3.45 to 3.55 GHz. For the full 16 elements array, a directional beam is formed, attaining a high gain of 20.5 dBi, low mutual coupling up to -25 dB and an exceptionally low ECC below 0.0025 have been realized within the band of concern. Overall, antenna array possesses attractive features for next generation 5G base stations.

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Data Availability. The data used to support the findings of this study are included within the paper.

Conflict of Interest. The authors declare that they have no conflicts of interest.

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