1-1-2024

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Recommended Citation

Elwi, Taha A.; Taher, Fatma; Virdee, Bal S.; Alibakhshikenari, Mohammad; Zuazola, Ignacio J.Garcia; Krasniqi, Astrit; Kamel, Amna Shibib; Tokan, Nurhan Turker; Khan, Salahuddin; Parchin, Naser Ojaroudi; Livreri, Patrizia; Dayoub, Iyad; Pau, Giovanni; Aissa, Sonia; Limiti, Ernesto; and Sree, Mohamed Fathy Abo, "On the Performance of a Photonic Reconfigurable Electromagnetic Band Gap Antenna Array for 5G Applications" (2024). *All Works*. 6577.
https://zuscholars.zu.ac.ae/works/6577

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This article has been accepted for publication in IEEE Access. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2024.3392368

IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2017.Doi Number

On the Performance of a Photonic Reconfigurable Electromagnetic Band Gap Antenna Array for 5G Applications

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Dr. Mohammad Alibakhshikenari acknowledges support from the CONEX-Plus programme funded by Universidad Carlos III de Madrid and the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 801538. The authors also sincerely appreciate funding from Researchers Supporting Project number (RSP2024R58), King Saud University, Riyadh, Saudi Arabia.

ABSTRACT In this paper, a reconfigurable Multiple-Input Multiple-Output (MIMO) antenna array is presented for 5G portable devices. The proposed array consists of four radiating elements and an Electromagnetic Band Gap (EBG) structure. Planar monopole radiating elements are employed in the array with Coplanar Waveguide Ports (CWPs). Each CWP is grounded on one side to a reflecting L-shaped structure that has an effect of improving the antenna's directivity. It is shown that by inductively connecting Minkowski fractal structure of 1st order to the radiating element, the impedance matching is improved that results in enhancement in the array's bandwidth performance. The EBG structure is used to provide the isolation between antenna elements in the MIMO array. The fractal structure is connected to the L-shaped reflector through four photosensitive light dependent resistor (LDR) switches. The effect of various LDR switching configurations on the performance of the antenna is investigated. The proposed array provides a novel performance in terms of S-parameters with enhancements in the radiation properties. Such enhancements are achieved with low separation gaps between antenna elements (about $\lambda_o/16$ at 3.5 GHz). It is shown that the array's operational bands centered at 3.5 GHz and 4.65 GHz can be selected by activating certain LDR switches. The electromagnetic exposure of the array on the human body is investigated by determining the specific absorption rate (SAR). It is found that the proposed antenna shows lower SAR values compared to other antennas reported in literature. With the proposed EBG structure, the gain of the array is increased 7.5 dB (from -3.5 dBi to +4 dBi) at 3.5 GHz and by 14.3 dB (from -8.7 dBi to + 5.6 dBi) at 4.65 GHz. The average radiation efficiency between 3.5 GHz and 5.5 GHz increased by 42% from 20% to 62%. Excellent radiation characteristics of the EBG the array makes it suitable for 5G portable devices such as tablets.

INDEX TERMS Electromagnetic Band Gap (EBG), multiple-input multiple-output (MIMO), 5G system, antenna arrays, specific absorption rate (SAR), photosensitive light dependent resistor (LDR).

1. INTRODUCTION

Over the last decade, wireless communication technology has undergone rapid advancements, leading to increased demand for higher channel capacity and lower bit error rates [1]. Multiple-Input Multiple-Output (MIMO) is a crucial technology that has significantly contributed to address these demands [2]. These developments have improved various aspects of wireless communications including signal quality, enhanced throughputs, quality of service (QoS), minimizing fading effects, reduced latency, improved coverage, and energy efficiency [3-4]. The reconfiguration mechanism applied to the MIMO antenna permits wireless systems to dynamically adjust and adapt to different communication scenarios, frequencies, or conditions [5]. This flexibility offers several benefits and advantages in terms of frequency agility, spectrum efficiency, interference mitigation, and adaptive beamforming [6]. It should be noted that the surrounding environment of a MIMO antenna system plays a crucial role in determining its gain characteristics, particularly in the context of reconfigurable antennas [7].

Coplanar waveguide (CPW) antennas have the advantages of easy fabrication, low cost, compact size, and multiband operation [8]. Synthetic metamaterial surfaces such as soft and hard surface defects, frequency selective surfaces, artificial magnetic conductors, and Electromagnetic Band Gap (EBG) structures have been widely used to replace traditional conductors in most microwave structures [9]. These technologies are widely used for suppressing surface waves between antenna elements [10].

EBG structures are engineered periodic arrays of dielectrics or metals that exhibit photonic band gap ranges where electromagnetic waves are prohibited from propagating through the material. These structures are designed to control the behavior of electromagnetic waves by creating stopbands in the frequency spectrum [11-12]. EBG structures have been utilized for a variety of applications. Enhancing antenna gain and bandwidth are among the significant benefits they offer [13].

In 5G networks, 3GPP classifies the two main communication bands as FR1 (below 7.125 GHz) and FR2 (above 24.25 GHz) [14]. The use of millimeter-wave (mmW) spectrum results in significant reduction of antenna size because of the shorter wavelength and increase in bandwidth [15]. However, the propagation of mmW through buildings becomes extremely difficult since the skin depth and attenuation increase with increasing frequency [16-17]. Sub-6 GHz frequencies remain crucial for achieving reliable coverage, while higher-frequency millimeter waves offer high-capacity solutions for open areas [18,19].

In this paper, a reconfigurable MIMO antenna array with LDR switches is designed for 5G Applications. Isolation between the radiating elements of the MIMO array is enhanced by embedding EBG strips. The radiating elements consist of a monopole that is fed through a CPW structure, and the RF energy is launched through a matching load circuit and L-shaped reflector. By controlling the operation of LDR switches on the antenna, the proposed MIMO array provides reconfigurability and excellent radiation patterns.

2. ANTENNA ARRAY STRUCTURE

The proposed MIMO antenna array, which is shown in Fig.1, is designed to operate at sub-6GHz frequencies. Each antenna element consists of a monopole fed by a CPW port. The antenna ground-plane, which is an L-shaped reflector, is used to direct the radiation in a specific direction. An impedance matching structure, which is constructed from the first order Minkowski fractal, is inductively coupled to the radiating element to improve the array's bandwidth performance. The matching structure is attached to the L-shaped reflecting structure via four LDR switches that control the antenna surface current distribution and thereby its reconfigurability. All antenna elements were fabricated on an FR4 substrate having dielectric constant (ε_r) of 4.3 and loss-tangent ($\tan\delta$) of 0.025.

The physical size of the array is 64×64×1.6 mm^3 which is suitable for tablets and laptops. With LDR switches, the issues associated with wiring complexity are avoided. These switches do not require DC biasing circuitry. However, it is important to note that LDR switches have limitations too, such as slower response times compared

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to electronic switches, and sensitivity to ambient light conditions.

An EBG structure is printed on the upper surface of the antenna array to reduce the mutual coupling effects between the radiating elements and improve the radiation characteristics of the array. The proposed EBG structure consists of five elliptically shaped slots, as illustrated in Fig.2. Physical parameters defining the EBG strip are given in Table 1.

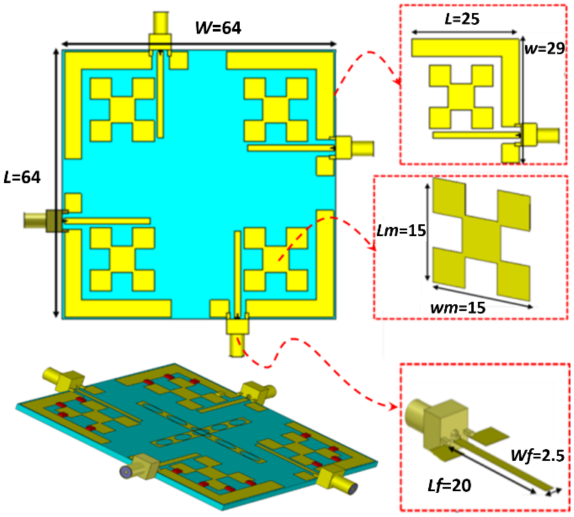

Fig. 1. Geometrical details of the MIMO antenna.

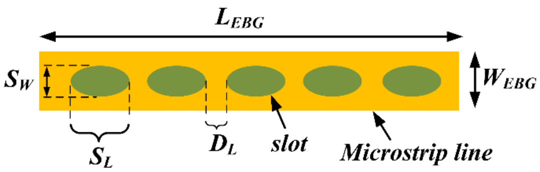

Fig. 2. Proposed EBG structure.

Table 1. Parameters of the EBG structure.

Parameter	Magnitude (mm)
L_{EBG}	38.0
W_{EBG}	3.0
D_L	1.5
S_L	6.0
S_W	2.6

3. CHARACTERIZATION OF EBG STRUCTURE

The defects on the copper strip of the EBG structure will have an influence on the array performance. Therefore, it is necessary to carry out a parametric study using numerical and analytical circuit modelling techniques to characterize the EBG structure.

A) NUMBER OF SLOTS

The number of slots on the EBG structure will have an impact on the resonance characteristics of the structure. The EBG structure was numerically analyzed using a commercially available full-wave analysis tool. The effect on the reflection and transmission coefficient responses is observed. An analysis is carried out by implementing the EBG on a 50-Ω microstrip transmission line, as shown in Fig.3. The transmission line is constructed on FR4 substrate. The propagating mode over the transmission line used is a quasi-Transverse Electromagnetic Mode (TEM) which is one of the primary modes of propagation in microstrip transmission lines.

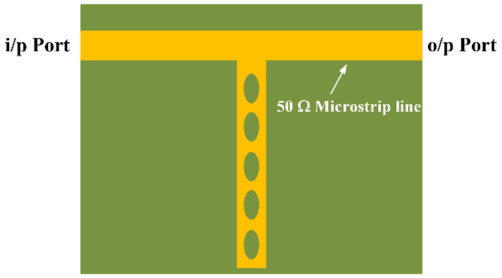

Fig. 3. Performance analysis scenario for the EBG structure. EBG defects are loaded to a transmission line structure.

The reflection coefficient (S_{11}) and transmission coefficient (S_{21}) responses as the function of frequency and number of slots (N) are given in Fig.4. It is observed that the EBG structure with N slots provides multiple resonances at sub-6 GHz band. The S_{11} response defines the resonance bands in the EM spectrum that are prone to mutual coupling effects.

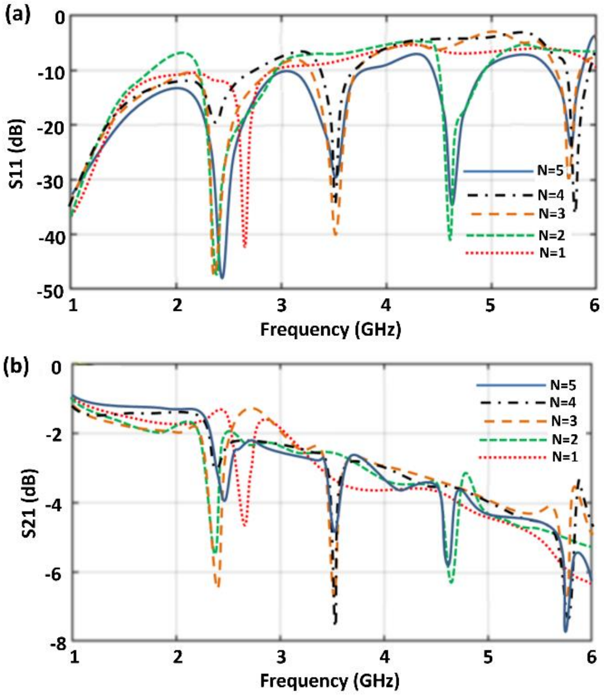

Fig. 4. Scattering parameters of the EBG structure with different number of slots, (a) S_{11}, and (b) S_{21}.

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The S_{21} response in Fig.4(b) indicates regions in the EM spectrum where rejection is the strongest. The EBG structure with five elliptically shaped slots impedes the propagation of surface waves, and this effect is observed in the transmission coefficient response with distinct attenuations at 2.45 GHz, 3.5 GHz, 4.65 GHz, and 5.8 GHz. The attenuation at 3.5 GHz and 4.65 GHz is instrumental in isolating EM interaction between the neighboring antennas in the proposed antenna array. EBG with 5 slots is considered in the proposed antenna array.

B) GEOMETRY OF THE SLOTS

An analysis for the slot geometry is carried out, considering various slot shapes, including elliptical, rectangular, and circular. The effects of slot shape on transmission and reflection characteristics are shown in Fig. 5. The analysis results reveal that the elliptical slot exhibits exemplary matching performance compared to circular and rectangular-shaped slots. This is attributed to the motion of the currents at the edges of the elliptical slot, which effectively reduces reactance of the structure in comparison to the other geometries.

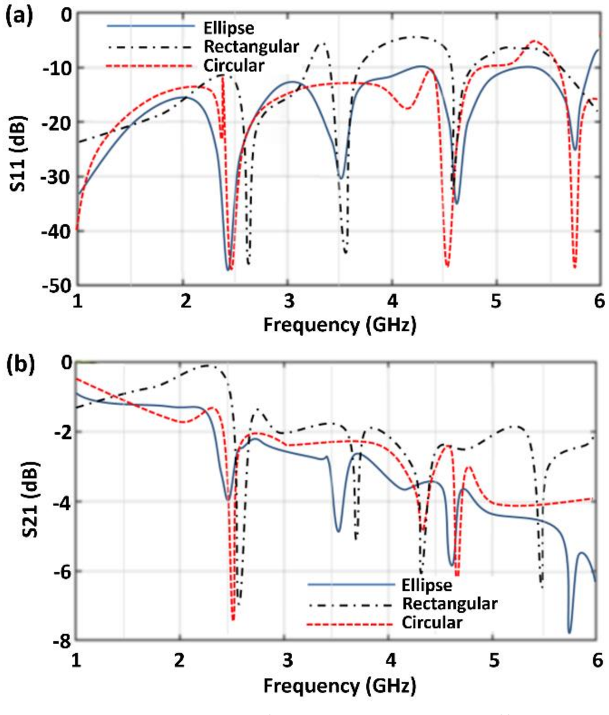

Fig. 5. Scattering parameters of the EBG structure with different slot shapes, (a) S_{11}, and (b) S_{21}.

C) CIRCUIT MODEL

The performance of the proposed EBG is validated by analyzing its equivalent circuit model. The model is verified with two commercially software, Advanced Design System (ADS) by Keysight Technologies and High Frequency Structure Simulator (HFSS), which is a full-wave 3D electromagnetic (EM) simulation software by Ansys. Fig.6 shows the electrical circuit model of the transmission line EBG structure. The microstrip stub of the T-shaped structure consists of parallel $C_T L_T$ circuit in series with parallel LCR circuit that represent the slots embedded in the stub. The coupling effect between the slots in the stub is represented by reactive elements C_T and L_T. The values of the circuit elements are determined using ADS and are listed in Table 2. S-parameter responses of the equivalent circuit model along with the responses from ADS and HFSS are shown in Fig.7. The excellent correlation in the S-parameter responses of the circuit model with ADS and HFSS confirms the accuracy of the electrical model.

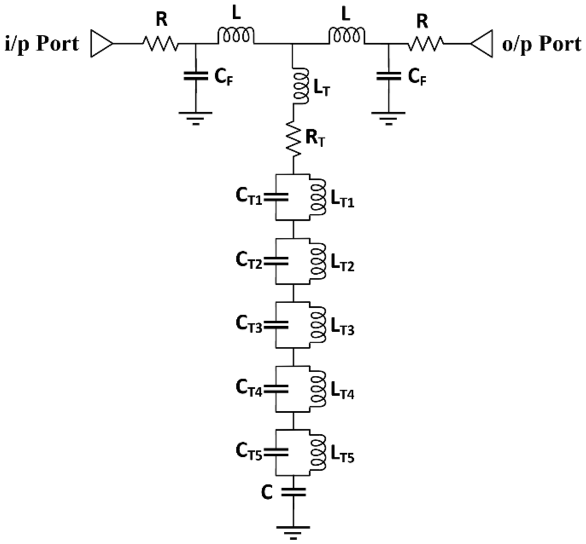

Fig. 6. Equivalent circuit model of the five slot EBG structure.

Table 2. Circuit elements of the equivalent circuit model.

Lumped element	Value	Lumped element	Value
R	50 Ω	C_{T3}	0.64 pF
L	0.1 nH	L_{T3}	2.06 nH
L_T	42.6 nH	C_{T4}	1.04 pF
R_T	50 Ω	L_{T4}	0.64 nH
C_{T1}	0.45 pF	C_{T5}	2.04 pF
L_{T1}	1.94 nH	L_{T5}	0.2 nH
C_{T2}	1.54 pF	C	0.08 pF
L_{T2}	1.42 nH	C_F	0.2 pF

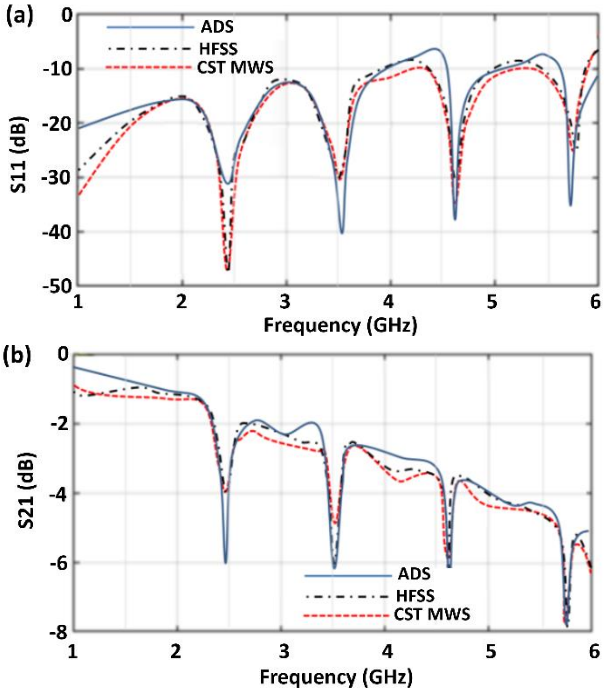

Fig. 7. Equivalent circuit model analysis results, (a) S_{11}, and (b) S_{21}.

4. ANTENNA PERFORMANCE

The EBG structure, which is located at the center of the 2×2 MIMO antenna array, has a great impact on the antenna performance. In this section, firstly, the effect of the EBG structure on the radiation characteristics is investigated. Then, a beam switching implementation is demonstrated using LDR switches.

A) PERFORMANCE WITHOUT EBG

This section presents the numerical analysis results of the antenna array without the EBG structure obtained using CST Studio Suite [15], which is a high-performance 3D electromagnetic analysis software. The reflection coefficient response of the antenna array and radiation patterns in the E and H orthogonal planes are given in Fig.8. The reflection coefficient response shows that the proposed antenna array resonates more strongly at 3.5 GHz and 4.8 GHz. It is lower than -10 dB within the range of 3.4-3.6 GHz and 4.25-5.2 GHz. Moreover, at 3.5 GHz the radiation patterns in both E- and H-planes can be approximated to an oval shape, and at 4.65 GHz the array in the E-plane radiates approximately omnidirectionally whereas in the H-plane it is bidirectional firing at angles of 25 and 155 degrees, as shown in Fig.8(b) and (c), respectively.

The transmission coefficient response of the antenna array is given in Fig.9(a). The isolation between the ports is better than 15 dB in the 1-6 GHz frequency range. Antenna gain and radiation efficiency of the array are shown in Fig.9(b) and (c), respectively. Fig.9(b) shows that the gain of the array over 3-6 GHz varies between -8.7 dBi and -2.5 dBi. Fig.9(c) shows that the radiation efficiency of the array without EBG varies between 15% and 21%. The poor gain and radiation efficiency is due to the detrimental effects of mutual coupling between the radiating elements of the array. Effective design and mitigation strategies are therefore essential to counteract these effects and achieve the desired array performance.

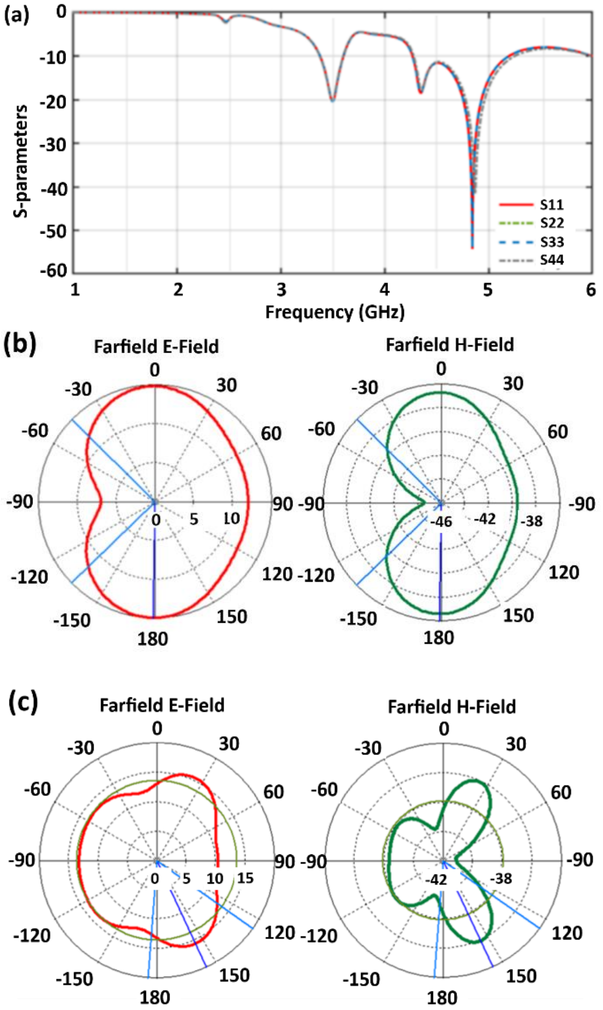

Fig. 8: (a) Reflection coefficient response without EBG structure, (b) far-field radiation patterns of the antenna array without EBG structure in the E-plane and H-plane at 3.5 GHz, and (c) far-field radiation patterns of the antenna array without EBG structure in the E-plane and H-plane at 4.65 GHz.

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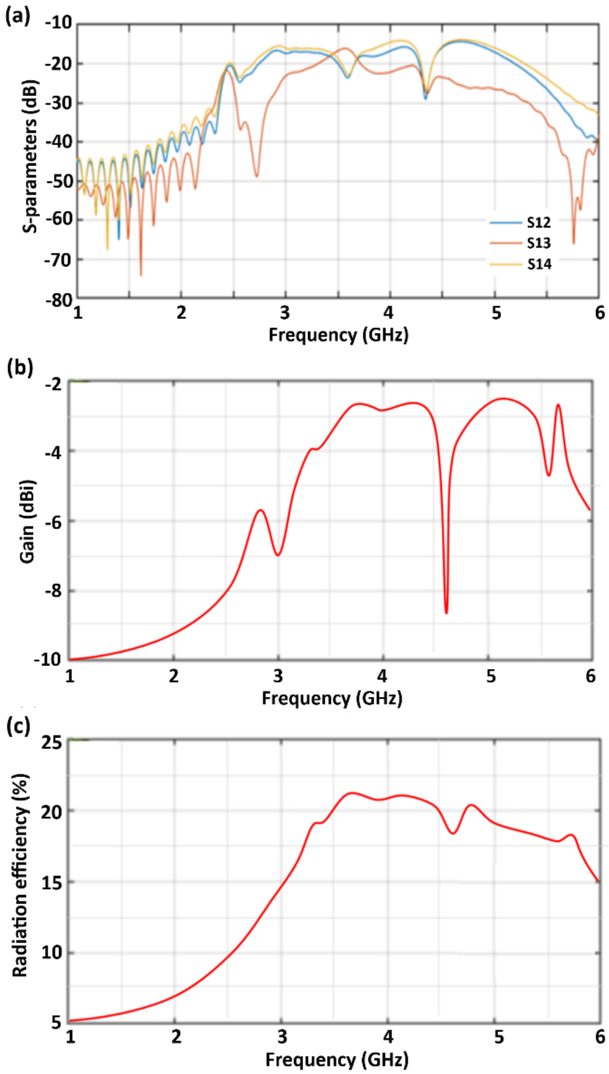


Fig. 9. Transmission coefficient response of the antenna array without EBG structure, (b) antenna gain without EBG structure, and (c) radiation efficiency without EBG structure.

B) PERFORMANCE WITH EBG

EBG structure is implemented between the radiating elements to prevent the electromagnetic interference between adjacent antenna elements in an array. The proposed EBG structure also prevents propagation of the surface waves which are generated by reflections and interactions with the ground plane. These surface waves can also degrade the performance of the antenna system by interfering with the desired radiation pattern and causing scattering. Fig.10 shows that by inserting the EBG between the radiating elements, significant improvement in the reflection coefficient response and radiation patterns is obtained. The reflection coefficient is lower than -10 dB in the range of 3.4-3.6 GHz and 4.25-5.2 GHz. At 3.5 GHz, the reflection coefficient is -27 dB, and at 4.65 GHz it is -22 dB. The proposed EBG structure creates a more conducive electromagnetic environment around the antenna elements, which in turn contributes to mitigating factors that improve impedance matching. The radiation patterns at 3.5 GHz in E- and H-planes are approximately oval shaped, and at 4.5 GHz the radiation in the E- and H-planes is approximately omnidirectional but with a pinch off at 90^{o}.

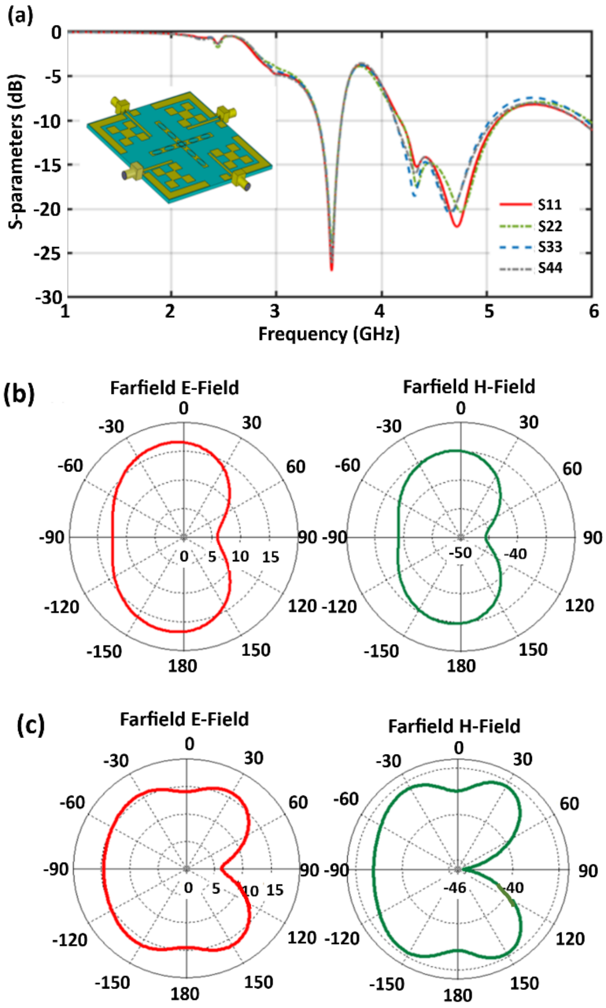


Fig. 10. Antenna performance: (a) Return loss with EBG structure, (b) Far-field radiation patterns in the E- and H-planes at 3.5 GHz, and (c) Far-field radiation patterns in the E- and H-planes at 4.65 GHz.

The transmission coefficient response of the antenna array with EBG structure is given in Fig.11(a). It shows that the isolation between the ports is better than 21 dB in the 1-6 GHz frequency range. Fig.11(b) shows gain of the array over 3-6 GHz varies between 1 dBi and 5.6 dBi. The radiation efficiency of the array, shown in Fig.11(c), varies between 37.5% and 61% over the 3-6 GHz band. The significant characteristics of the antenna array without and with EBG structure at 3.5 GHz and 4.65 GHz are summarized in Table 3.

Table 3. Comparison of performance parameters of the array with and without EBG.

	S_{11} (dB)	Gain (dBi)	Eff. (%)
Without EBG @3.5 GHz	-20	-3.5	20
Without EBG @4.65 GHz	-12	-8.7	20
With EBG @3.5 GHz	-27	4	63
With EBG @4.65 GHz	-22	5.6	61

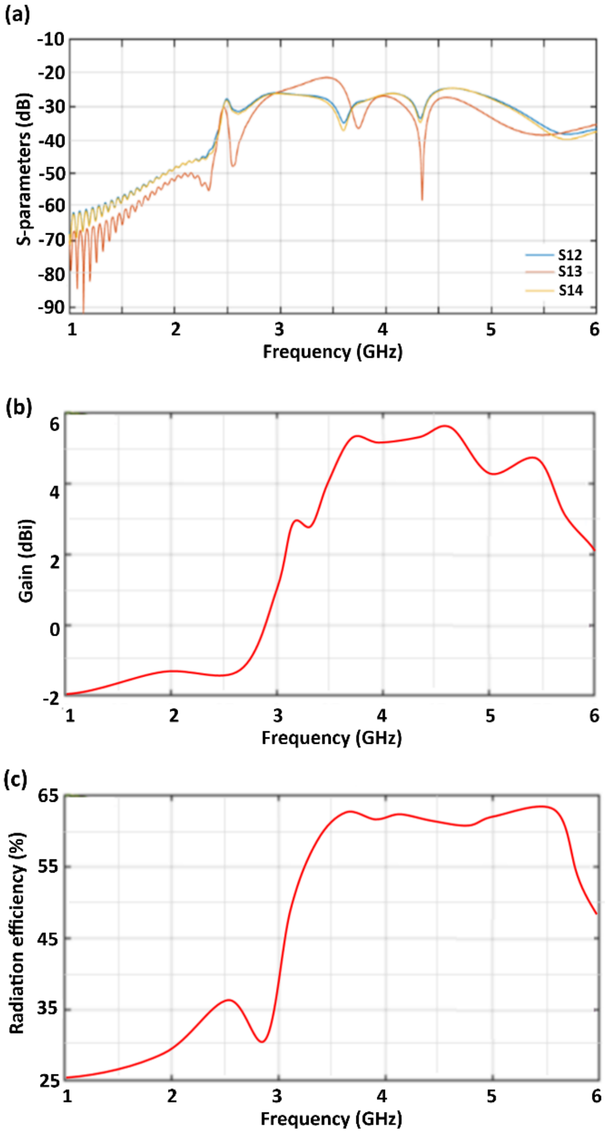
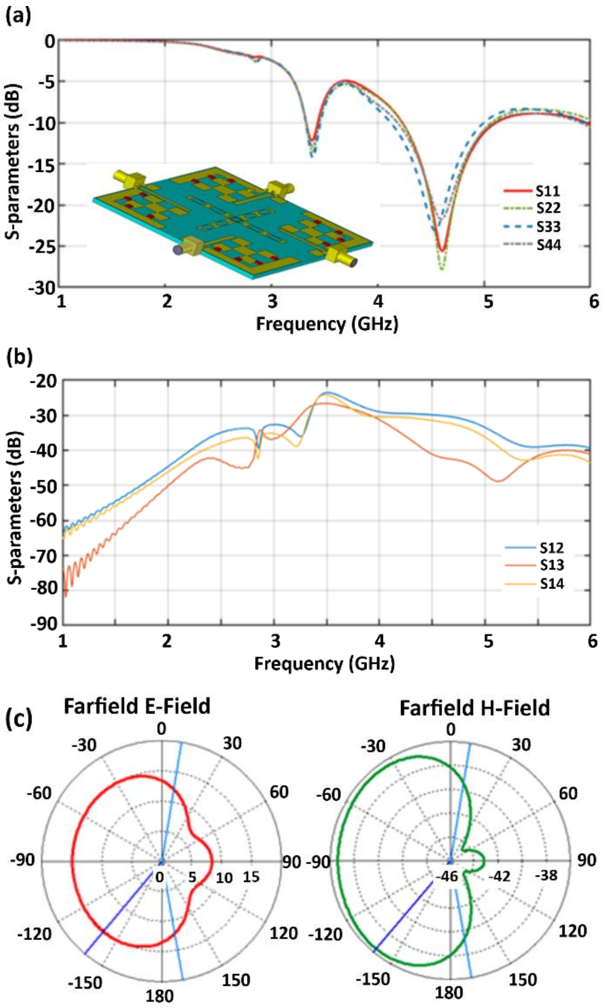


Fig. 11. Antenna array performance with EBG structure, (a) Transmission coefficient response, (b) Antenna gain, and (c) Radiation efficiency.

C) EFFECTS OF LDR SWITCHING

Four light dependent resistor switches are added to each fractal structure as shown in Fig.12(a). In this application the LDR was either fully activated or deactivated. In this scenario the LDR were not used in a quasi-ON/OFF mode. By activating or deactivating the LDR switches, each radiating element in the array can be controlled. The simulated reflection and transmission coefficient responses when LDR switches are activated (ON status) are shown in Fig.12(a) and (b), respectively. The reflection coefficient is better than -10 dB across 3.3-3.5 GHz and 4.3-5.1 GHz. At 3.5 GHz, the reflection coefficient is -14 dB, and at 4.65 GHz it is -25 dB. The isolation between the ports is better than 21 dB within 1-6 GHz frequency range. The radiation patterns in the E- and H-planes are shown in Fig.12(c) at 3.5 GHz and 4.65 GHz. The array radiates over 0° to -180° in both the E- and H-planes at 3.5 GHz. At 4.65 GHz, it radiates in the opposite direction over 0° to +180° in both the E- and H-planes. When the LDR switches are deactivated (OFF state) the performance of the antenna array is identical to those shown in Fig.10.



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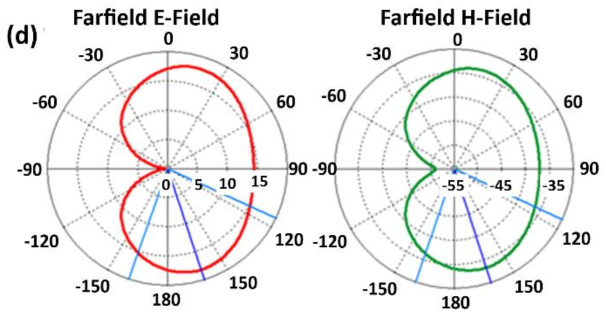


Fig. 12. Performance of the reconfigurable MIMO antenna, (a) Reflection coefficient response, (b) Transmission coefficient response, (c) Radiation patterns at 3.5 GHz, and (d) Radiation patterns at 4.65 GHz.

By turning certain elements ON or OFF using the LDR switches, the overall radiation pattern of the antenna array can be controlled. This enables the ability to electronically steer the direction of the main beam, which is very useful for applications like radar, wireless communication, and satellite communication.

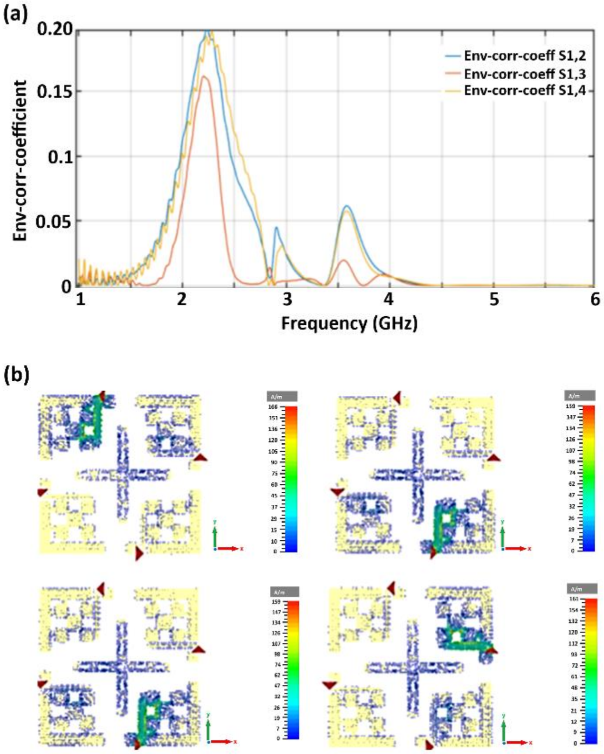
Traditional mechanical steering mechanisms require moving parts, which can be bulky and have limitations in terms of speed and accuracy. LDR-based beamforming eliminates the need for such mechanisms, reducing the complexity and maintenance requirements of the antenna system.

Envelope Correlation Coefficient (ECC) is a parameter used to characterize the performance of MIMO antenna arrays [14]. It measures the correlation between the envelope of the signals received by the various antennas in a MIMO system. ECC values close to zero indicate that the signals received by different antennas are relatively uncorrelated, which is beneficial for achieving the full potential of MIMO technology, including improved spatial diversity and higher data rates. Fig.13(a) shows the magnitude of the ECC of the proposed MIMO antenna array over the frequency span of interest is less than 0.2. These results can be explained by studying the surface current density distribution over the antenna array at 3.5 GHz and 4.65 GHz. The surface current distribution of the antenna array at these frequencies is shown in Fig.13(b) and (c). It shows the effectiveness of the EBG structure in blocking mutual coupling between the radiating elements. The EBG structure induces a phase difference in the propagation of electromagnetic waves between neighboring radiating elements, leading to an amplification of current intensity along the edges of the substrate.

5. MEASURED RESULTS AND DISCUSSION

The prototype of the MIMO antenna array shown in Fig.14 is fabricated on FR4 substrate. Its S-parameters and radiation patterns are measured using Agilent PNA 8720 Network Analyzer. The measured results are compared with the results obtained by CST Studio Suite to verify the accuracy and effectiveness of the simulation tool. The LDR switches were covered with an opaque lid so that they were inactive during the measurements. The radiation patterns were measured inside an RF anechoic chamber in the two principal planes.

The reflection and transmission coefficient responses of the antenna array with LDR switches OFF are shown in Fig.15(a) and (b), respectively. The measured reflection coefficient is better than -10 dB across 3.3-3.6 GHz and 4.2-5.1 GHz. At 3.5 GHz, the reflection coefficient is -25 dB, and at 4.65 GHz it is -25 dB. The isolation between the radiating elements is better than 35 dB within 1-6 GHz range. The radiation patterns in the E- and H-planes at 3.5 GHz and 4.65 GHz are shown in Fig.15(c) and (d). At 3.5 GHz, the array radiates over 0^{o} to -180^{o} in the E-plane and in the H-plane the array radiates over 0^{o} to $+180^{o}$. At 4.65 GHz the array radiates bidirectionally at 27^{o} and 158^{o} in the E-plane, and at over 0^{o} to $+180^{o}$ in the H-plane. There is excellent agreement between simulated and measured results. The discrepancies between simulated and measured results are attributed to manufacturing tolerances and environmental conditions.



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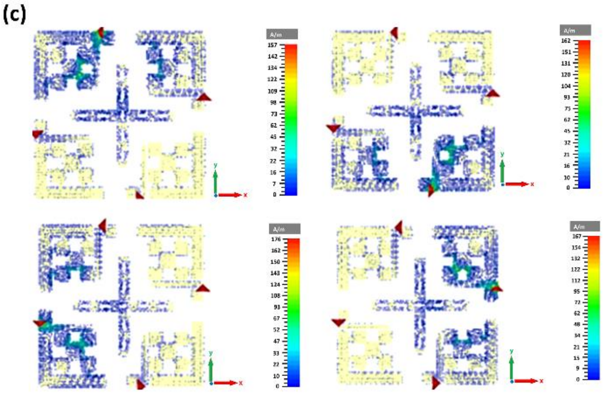
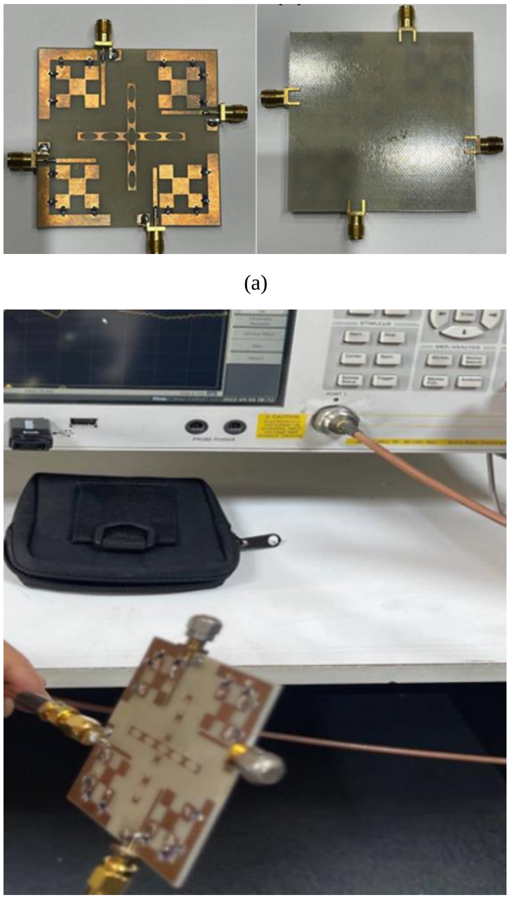


Fig. 13. Performance of the proposed reconfigurable MIMO array, (a) ECC response, (b) Current density distribution over the antenna array at 3.5 GHz, and (c) Current density distribution over the antenna array at 4.65 GHz.



(a)

(b)

Fig. 14. Fabricated prototype of the reconfigurable MIMO antenna (a) Top and bottom view, (b) Prototype in the measurement setup.

The MIMO antenna array's performance was evaluated when all LDR switches were activated ON. Fig.16 shows the measured reflection and transmission responses of the array. S_{11} is lower than -10 dB between 3.25-3.5 GHz and 4.2-5.1 GHz. At 3.4 GHz, S_{11} is -15 dB, and at 4.65 GHz it is -30 dB. The S_{21} between the radiating elements is greater than 38 dB over 1-6 GHz. At 3.5 GHz, the array radiates over 0° to -180° in the E-plane and bidirectionally at angles of -30° and -160° in the H-plane. At 4.65 GHz the array radiates over 0° to +180° in the E-plane, and in the H-plane it radiates over 0° to +180°.

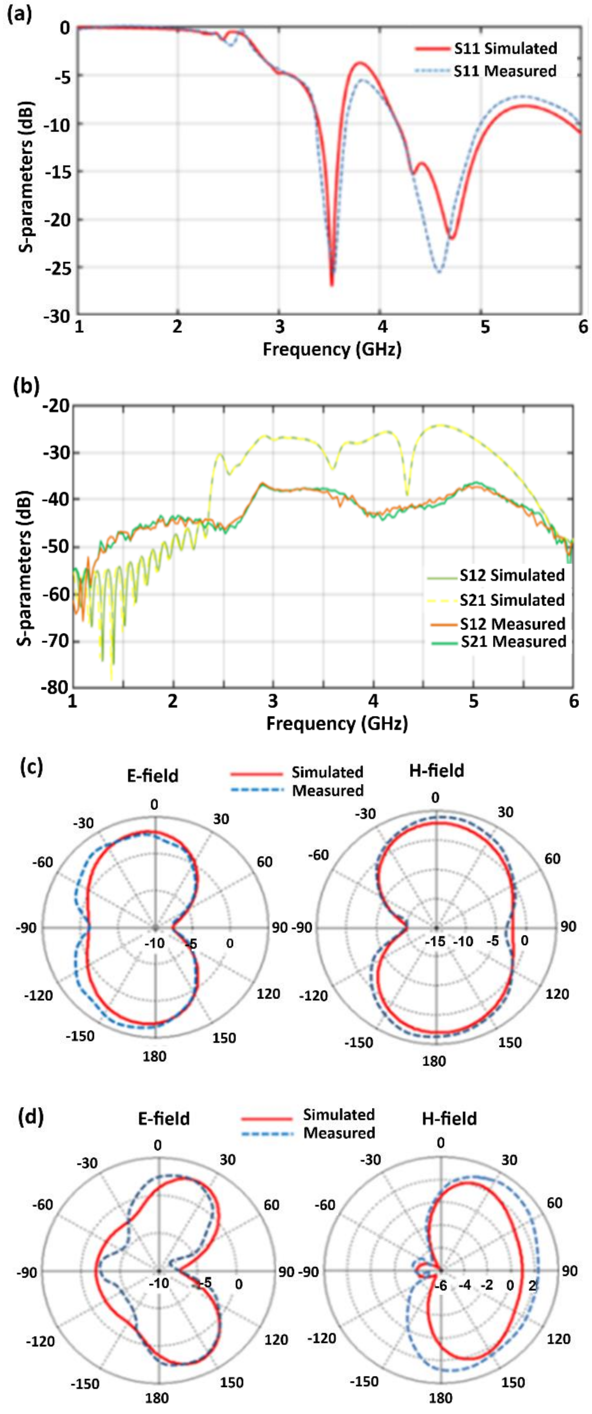


Fig. 15. Antenna performance when all LDR switches are switched 'OFF', (a) Reflection coefficient, (b) Transmission coefficient, (c) Radiation patterns at 3.5 GHz, and (d) Radiation patterns at 4.65 GHz.

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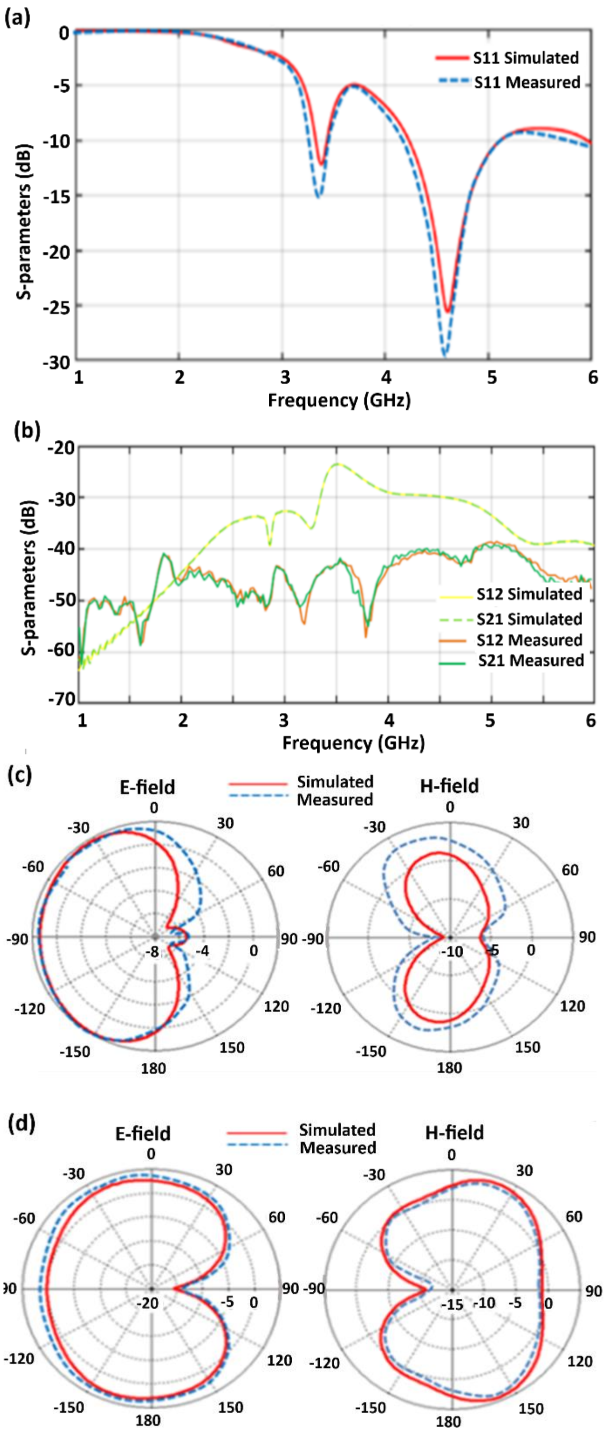

Fig. 16. Antenna performance when all LDRs switches are switched 'ON', (a) Reflection coefficient, (b) Transmission coefficient, (c) Radiation patterns at 3.5 GHz, and (d) Radiation patterns at 4.65 GHz.

The reflection and transmission coefficients of the antenna array with all LDR switches either activated or deactivated are compared in Table 4. In the 'ON' condition the antenna is receptive to 4.65 GHz and in the 'OFF' state it is receptive to both 3.5 GHz and 4.65 GHz.

Table 4. Comparison of antenna array parameters with LDR in the 'ON' and 'OFF' states.

	S_{11} (dB)	S_{21} & S_{12} (dB)
LDR switched OFF @3.5 GHz	-25	-38
LDR switched OFF @4.65 GHz	-25	-42
LDR switched ON @3.5 GHz	-15	-42
LDR switched ON @4.65 GHz	-30	-40

A) SAR ANALYSIS

Specific Absorption Rate (SAR) quantifies the pace at which body tissues absorb electromagnetic energy. It is quantified in terms of watts per kilogram (W/kg). SAR analysis is carried out on the proposed MIMO antenna array. Radiation effects are numerically evaluated by analyzing the SAR using HUGO which is standardized anatomical model of the head in CST Studio Suite. HUGO represents the human head and its internal structures with high anatomical accuracy. Radiation absorption from the proposed antenna array is evaluated on HUGO in the ON/OFF state at 3.5 GHz and 4.65 GHz. In the proposed simulation scenario, the antenna array is located 10 mm away from HUGO's face. The power transmitted from the antenna array is 20 dBm, which falls within the Federal Communications Commission's (FCC) maximum permissible limit. The results of this simulation are shown in Fig.17.

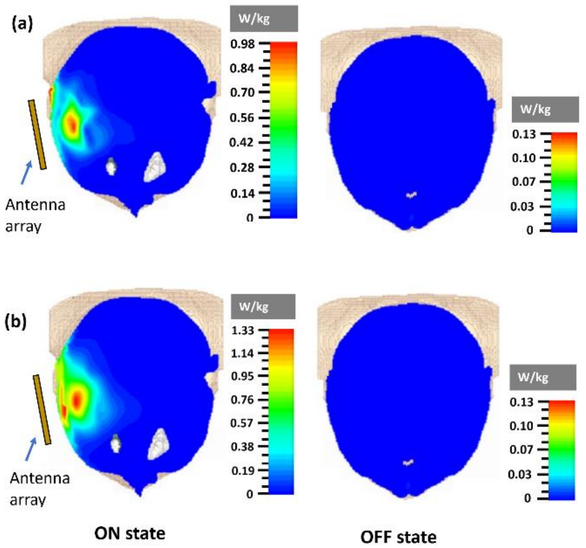

Fig. 17. Problem definition for the SAR analysis. Far-field radiation and SAR values at (a) 3.5 GHz, and (b) 4.65 GHz.

When the LDR switches are in the 'OFF' state the peak value of the SAR is computed to be 0.15 W/kg at 3.5 GHz and 0.21 W/kg at 4.65 GHz. In the 'ON' state the SAR peak value is 1.25 W/kg at 3.5 GHz and 0.94 W/kg at 4.65 GHz. The magnitude of SAR is well below the limit permitted by the FCC in United States, which is 1.6 W/kg averaged over 1 gram of tissue for both head and body exposure. In the European Union, the limit is generally 2.0 W/kg averaged over 10 grams of tissue for head exposure and 2.0 W/kg averaged over 10 grams of tissue for body exposure.

B) COMPARISON WITH OTHER MIMO ANTENNA ARRAYS

The performance of the proposed antenna array is compared with the other MIMO antenna arrays reported in literature in Table 5. Compared to the other antenna arrays, the proposed antenna array exhibits better performance in terms of antenna gain, inter-radiating element isolation, and ECC. Moreover, the gap between the radiating elements and the overall array size is significantly smaller. Unlike other antenna arrays, the performance of the proposed array can be reconfigured with LDR switches without the need for DC biasing.

6. CONCLUSION

The proposed sub-6 GHz MIMO antenna array with EBG structure is shown to provide high element isolation. The reconfigurability property of the antenna array is also demonstrated using LDR switches. With the proposed EBG structure, the antenna gain of the array is increased by 7.5 dB to +4 dBi at 3.5 GHz and by 14.3 dB to + 5.6 dBi at 4.65 GHz. The radiation efficiency at 3.5 GHz and 4.65 GHz are increased to 63% to 61%. This demonstrates the effectiveness of the proposed EBG structure. Moreover, the array exhibits excellent radiation characteristics with EBG. SAR of the antenna array was evaluated on HUGO which is standardized anatomical model of the head in CST Studio Suite. When the LDR switches on the antenna array were either switched 'ON' or 'OFF', the SAR peak value was well below 1.6 W/kg, which is the limit set by the FCC in United States.

Table 5. Comparison with other MIMO antenna arrays published in literature.

Ref.	Size (λ_o^2)	No. radiating elements	Freq. (GHz)	Gain (dBi)	Isolation (dB)	ECC	Gap
[20]	2.4×1.8	8	5.15/5.95	2.1	15	0.05	λ/1.9
[21]	2.75×1.4	4	5.15/5.85	1.9	16	0.06	λ/2
[22]	2.5×1.1	8	5.15/5.95	1.9	10	0.09	λ/2
[23]	2.5×1.2	12	4.8/5.1	2.6	12	---	λ/2.1
[24]	2.78×1.5	8	5.17/5.95	2.2	10	0.11	λ/2.3
[25]	2×2	4	3.3/5.8	1.1	15	0.10	λ/2.1
[26]	3×1.3	2	5.6/5.67	12	30	0.06	λ/1.4
This work	0.87×0.87	4	3.5/4.65	5.6	42	0.01	λ/8

REFERENCES

1. Constantine A. Balanis, Antenna Theory Analysis and Design, 2013.
2. I, Ishteyaq., & K. Muzaffar, "Multiple Input Multiple Output (MIMO) and Fifth Generation (5G): An Indispensable Technology for Sub-6 GHz and Millimeter Wave Future Generation Mobile Terminal Applications," Int. Journal of Microwave and Wireless Technologies, 14(7), 2021:1-17.
3. C.G. Christodoulou, Y. Tawk, S.A. Lane, S.R. Erwin, "Reconfigurable Antennas for Wireless and Space Applications," 100(7), 2012:2250-2261.
4. K. Bagadi et al., "Detection of Signals in MC–CDMA Using a Novel Iterative Block Decision Feedback Equalizer," IEEE Access, 10, 2022:105674-105684.
5. M. H. Jwair et al., "Intelligent Metasurface Layer for Direct Antenna Amplitude Modulation Scheme," IEEE Access, 11, 2023: 77506-77517.
6. W. Kim, M.F. Iskander, "A New Coplanar Waveguide Continuous Transverse Stub (CPW-CTS) Antenna for Wireless Communications," IEEE Antennas and Wireless Prop., Letters, 4:172-174.
7. A.I. Imran, T.A. Elwi, and A.J. Salim, "On the Distortionless of UWB Wearable Hilbert-Shaped Metamaterial Antenna for Low Energy Applications," Progress in Electromagnetics Research M, 101, 2021:219-239.
8. W. Dorothy and R. Joos, "The PIN Diode Circuit Designers' Handbooka," Watertown, 617, 1998.
9. S. Zahra, et al., "Electromagnetic Metasurfaces and Reconfigurable Metasurfaces: A Review," Frontiers in Physics, 8, 2021:1-16.
10. Bai, T. and Heath, R.W., "Coverage and Rate Analysis for Millimeter-Wave Cellular Networks.," IEEE Transactions on Wireless Communications, 14(2), 2014:1100-1114.
11. J.-y. Lee, et al., "Reduction of Mutual Coupling in Planar Multiple Antenna by Using 1D EBG and SRR Structures," IEEE Transactions on Antennas and Propagation, 63(9), 2015:4194-4198.
12. A.S. Kamel, A.S.A. Jalal, "Novel Reconfigurable Monopole-Based Matching Circuitry Design for 5G and Modern Wireless Communication Systems," Int J Commun. Syst. 35(14), 2022: e5252. doi:10.1002/dac.5252.
13. A. Azeez, et al., "Design and Analysis of a Novel Concentric Rings Based Crossed Lines Single Negative Metamaterial Structure," Int. Journal Eng. Science and Technology, 20(3), 2017:1140-1146.
14. R. Dilli, "Analysis of 5G Wireless Systems in FR1 and FR2 Frequency Bands," 2nd International Conference on Innovative Mechanisms for Industry Applications (ICIMIA), 2022:1-6.
15. The Homepage of CST Microwave Studio. Available: http://www.cst.com/.
16. K.A. Ansal, and T. Shanmuganatham, "ACS-fed Wide Band Antenna With L-shaped Ground Plane for 5.5 GHz WLAN Application," Progress in Electromagnetics Research Letters 49, 2014:59-64.
17. K.A. Ansal, T. Shanmuganatham, "Compact ACS-fed monopole antenna with CRR defect for triple band application," AEU - International Journal of Electronics and Communications, 127; 153487; 2020.
18. K. Le, et al., "Compact ACS-Fed Monopole Antenna With Rectangular SRRs for Tri-Band Operation," Electronics letters 50(16); 2014:1112-1114.
19. M.H. Jwair, T.A. Elwi, "Steerable Composite Right–Left-Hand-Based Printed Antenna Circuitry for 5G Applications," Microw. Opt. Technol. Lett. 2023: 1-8.
20. Y. Li, et al., "Eight-Element MIMO Antenna Array for 5G/Sub-6GHz Indoor Micro Wireless Access Points," Proceedings of the IEEE International Workshop on Antenna Technology (iWAT), 2018:1-4.
21. Z. Ren, S. Wu, A. Zhao, "Triple Band MIMO Antenna System for 5G Mobile Terminals," Proceedings of the IEEE International Workshop on Antenna Technology (iWAT), 2019:163-165.
22. C. Sim, H. Liu, C. Huang, "Wideband MIMO Antenna Array Design for Future Mobile Devices Operating in the 5G NR Frequency Bands n77/n78/n79 and LTE band 46," IEEE Antennas Wirel. Propag. Lett. 19, 2020: 74-78.
23. Y. Li, et al., "12-Port 5G Massive MIMO Antenna Array in Sub-6GHz Mobile Handset for LTE Bands 42/43/46 Applications," IEEE Access, 6, 2017:344-354.
24. J. Guo, L. Cui, C. Li, B. Sun, B, "Side-Edge Frame Printed Eight-

Port Dual-Band Antenna Array for 5G Smartphone Applications,” IEEE Trans. Antennas Propag. 66;2018:7412-7417.

25. W.M. Abdulkawi et al., „Design of a Compact Dual-Band MIMO Antenna System with High-Diversity Gain Performance in Both Frequency Bands,” Micromachines. 12(4), 2021:p.383,
26. J.S.U. Khan, et al., “A Sub-6 GHz MIMO Antenna Array for 5G Wireless Terminals,” Electronics, 10(24);2021:12-18.
27. W. Yu, S. Yang, C.-L. Tang, D. Tu, "Accurate Simulation of the Radiation Performance of a Mobile Slide Phone in a Hand-Head Position," IEEE Antennas and Propagation Magazine, 52(2), 2010: 168-177.
28. J. Krogerus, C. Icheln, P. Vainikainen, "Effect of Human Body on 3-D Radiation Pattern and Efficiency of Mobile Handsets," IEEE Instrumentation and Measurement Technology Conference Proceedings, 2005:.271-276.
29. J. Krogerus, C. Icheln, P. Vainikainen, "Experimental Investigation of Antenna Performance of GSM phones in Body-Worn and Browsing Use Positions," European Conference on Wireless Technology, 2006: 330-333.

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This article has been accepted for publication in IEEE Access. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2024.3392368

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This article has been accepted for publication in IEEE Access. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2024.3392368

research line is oriented to small-signal, noise, and large signal modelling. Regarding passive devices, equivalent-circuit models have been developed for interacting discontinuities in microstrip, for typical MMIC passive components (MIM capacitors) and to waveguide/coplanar waveguide transitions analysis and design. For active devices, new methodologies have been developed for the noise characterization and the subsequent modelling, and equivalent-circuit modelling strategies have been implemented both for small and large-signal operating regimes for GaAs, GaN, SiC, Si, InP MESFET/HEMT devices. The second line is related to design methodologies and characterization methods for low noise circuits. The focus is on cryogenic amplifiers and devices. Collaborations are currently ongoing with the major radioastronomy institutes all around Europe within the frame of FP6 and FP7 programmes (RadioNet). Finally, the third line is in the analysis methods for nonlinear microwave circuits. In this line, novel analysis methods (Spectral Balance) are developed, together with the stability analysis of the solutions making use of traditional (harmonic balance) approaches. The above research lines have produced more than 250 publications on refereed international journals and presentations within international conferences. Ernesto Limiti acts as a referee of international journals of the microwave and millimeter wave electronics sector and is on the steering committee of international conferences and workshops. He is actively involved in research activities with many research groups, both European and Italian, and he is in tight collaborations with high-tech italian (Selex - SI, Thales Alenia Space, Rheinmetall, Elettronica S.p.A., Space Engineering …) and foreign (OMMIC, Siemens, UMS, …) companies. He contributed, as a researcher and/or as unit responsible, to several National (PRIN MIUR, Madess CNR, Agenzia Spaziale Italiana) and international (ESPRIT COSMIC, Manpower, Edge, Special Action MEPI, ESA, EUROPA, Korrigan, RadioNet FP6 and FP7 …) projects. Regarding teaching activities, Ernesto Limiti teaches, over his istitutional duties in the frame of the Corso di Laurea Magistrale in Ingegneria Elettronica, “Elettronica per lo Spazio” within the Master Course in Sistemi Avanzati di Comunicazione e Navigazione Satellitare. He is a member of the committee of the PhD program in Telecommunications and Microelectronics at the University of Roma Tor Vergata, tutoring an average of four PhD candidates per year.