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# Enhanced 4-Port MIMO Antenna Based on Electromagnetic Mutual Coupling Reduction Using CSRRs Metamaterials for Sub-6 GHz 5G Applications

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A multi-input multi-output (MIMO) antenna is presented in this paper. The proposed antenna is formed by four (04) radiating patch elements of different sizes and shapes (rectangular and circular). These elements are excited by four feed ports, each port is parallel to three other adjacent ports. All elements are etched on the upper face of the FR4_Epoxy dielectric substrate for electrical dimensions $1.26\lambda_0 \times 1.05\lambda_0 \times 0.019\lambda_0$ ($\lambda_0$ is calculated at an operating frequency of 3.75 GHz). In order to improve the performance of our MIMO antenna, nine (09) complementary metamaterial resonators (CSRRs) of compact sizes are printed on the ground plane of the overall structure. These symmetrical rectangular and circular CSRRs act as an isolator between the radiating elements which contributes to the reduction of the mutual coupling between these adjacent elements. The obtained results reveal that the proposed sub-6 GHz antenna operates in the 5G band at 3.61 GHz (3.3-4.2 GHz) with high port isolation (lower than 28 dB). In addition, the antenna loaded with CSRRs demonstrates good MIMO performance with an envelope correlation coefficient (ECC) of less than 0.07, more than 1360 MHz bandwidth, negligible mutual coupling, and a gain of 15.79 dB. The suggested MIMO sub-6 GHz antenna is suitable for 5G applications.

**Keywords:** Envelope correlation coefficient (ECC), CSRRs, Metamaterial, MIMO antenna, Sub-6 GHz.

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## 1. INTRODUCTION

With the rapid (fast) development of the telecommunications market, significant competition has emerged at the level of mobile operators. As a result, the number of users has experienced a remarkable growth rate globally. For mobile phone operators, multi-input multi-output (MIMO) systems represent indispensable means of solving communication problems due to the high number of users, which is justified by the intense interest in the third (3G) and fourth (4G) generations. However, with this growth in the number of users, some defects and deficiencies appear in these two generations, especially in terms of interference and channel capacities. Recently, the fifth generation (5G) showed several advantages over previous generations including reported 5G MIMO antenna systems for single or dual operational bands [1-5]. Three working bands of 5G new radio (NR) have been started by generation partnership project (3GPP) [6]. These bands are useful for applications in 3.3-3.8 GHz, 3.3-4.2 GHz and 4.4-5.0 GHz which represent N78, N77 and N79, respectively.

Several studies have been conducted to develop and activate 5G; the majority of them target the electrical performance of MIMO systems. In [7], Huy et al. proposed a MIMO antenna with low profile and circular polarization. The realized antenna provided a bandwidth of 13.7 % and isolation less than – 20 dB. A 4-port MIMO antenna was reported in [8], the defective ground structure (DGS) technique was used for the design of this antenna operated in 25.5-29.6 GHz. The radiating elements used for this design have a rectangular shape. A non-planar 16-port MIMO antenna was realized in [9], Shabbir et al. introduced metamaterial resonators with a near-zero index (NZI) to achieve the decoupling of the radiating elements. This compact antenna showed remarkable performance such as a wide bandwidth of 3.35-3.65 GHz and envelope correlation coefficient ECC < 0.1. In [10], Ghazaoui et al. proposed a dual-band MIMO antenna operated at 29/39 GHz. The chosen shape for the four radiating elements was the flower. This antenna provided a gain of 3.04 and 8.11 dB on two bands 28.9-30.5 GHz and 38.43-40.76 GHz, respectively. An integrated massive MIMO (mMIMO) antenna system was reported in [11]. Al-Bawri et al. made 32 radiating elements spread over eight sub-arrays. On the upper face of the used substrate, 40 metamaterial resonators (SRRs) were etched to achieve the necessary decoupling. The realized system showed isolation more than 35 dB and a peak gain of 10.6 dBi for 250 MHz wide bandwidth. In [12], a compact 4-port MIMO antenna was proposed for WLAN/WiMAX applications. The designed antenna was based on 4 circular patches of the same size, the study was made for two possible feed configurations: parallel and orthogonal. The obtained results show a wide bandwidth (2540 MHz) and isolation more than 25 dB.

In this paper, we propose a 4-port MIMO antenna. To improve the performance of this antenna, we use the mutual coupling reduction principle between adjacent patches. For this reason, we introduce CSRRs of different sizes and shapes. Nine CSRRs are engraved on the ground plane, three of which (rectangular) are used to achieve the decoupling between ports 1 and 2 on the one hand and, on the other hand, three CSRRs are engraved between ports 3 and 4. Between ports 2 and 3, we place 3 circular CSRRs with four gaps to obtain the necessary isolation. To show the influence of CSRRs, we study the MIMO antenna without CSRRs (with 4

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separate ground planes), then we study the antenna with 9 CSRRs. The novelty of this work is that the proposed antenna is compact, of a simple design which uses 4 different patches for a parallel configuration. In addition, the proposed antenna produces a bandwidth of more than 1360 MHz for an envelope correlation coefficient (ECC) of less than 0.07.

## 2. DESIGN PROCEDURE

### 2.1 Single Element Antenna

For the basic antenna, we use two differently shaped patches. The chosen shapes are rectangular and circular because these two types of patches are simple to design and easy to integrate into a dielectric substrate. For the rectangular patch of effective length $L_{eff}$ and width $W$, the dimensions are calculated from the transmission line model [13]:

$$W = \frac{C_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}}\,, \tag{1}$$

$$L_{eff} = \frac{C_0}{2f_r\sqrt{\varepsilon_{eff}}} - 2\Delta L\,, \tag{2}$$

where $\varepsilon_{eff}$ represents the effective permittivity of the inhomogeneous medium (substrate and air), $c_0$ is the speed of light,

$$\begin{cases} \varepsilon_{eff} = \dfrac{\varepsilon_r + 1}{2} + \dfrac{\varepsilon_r - 1}{2}\left[1 + 12\left(\dfrac{h}{W}\right)\right]^{-1/2}, \\ \dfrac{\Delta L}{h} = 0.412\dfrac{\left(\varepsilon_{eff} + 0.3\right)\left(\dfrac{W}{h} + 0.264\right)}{\left(\varepsilon_{eff} - 0.258\right)\left(\dfrac{W}{h} + 0.8\right)}. \end{cases} \tag{3}$$

The design process of a conventional circular patch starts with the evaluation of the patch radius $a$ which is expressed by the following expression [14]:

$$a = \frac{F}{\sqrt{1 + \dfrac{2h}{\pi\varepsilon_r F}\left[ln\left(\dfrac{\pi F}{2h}\right) + 1.7726\right]}} \tag{4}$$

with

$$F = \frac{8.791 \times 10^9}{f_r\sqrt{\varepsilon_r}}\,. \tag{5}$$

For both types of patches, the feed line impedance is selected as 50 Ω.

### 2.2 Configuration without CSRRs

The proposed MIMO antenna (of length $X$ and width $Y$) is formed by two rectangular patches and two others of a circular shape. On the lower surface of the used substrate (FR4_Epoxy with relative permittivity of 4.4, loss tangent of 0.02 and thickness $h = 1.52$ mm), we print four ground planes separated from each other (each GND associated with a patch). The four patches and the four ground planes are printed on both sides of the substrate by copper for a thickness $t = 35$ μm. The overall antenna configuration before the use of CSRRs is shown in Fig. 1.

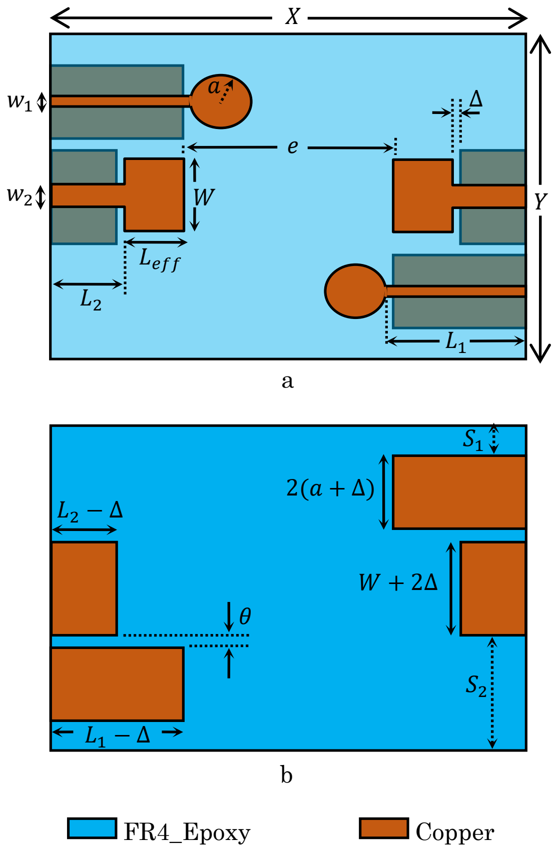


**Fig. 1** – Proposed MIMO antenna without CSRRs: (a) top view, (b) bottom view

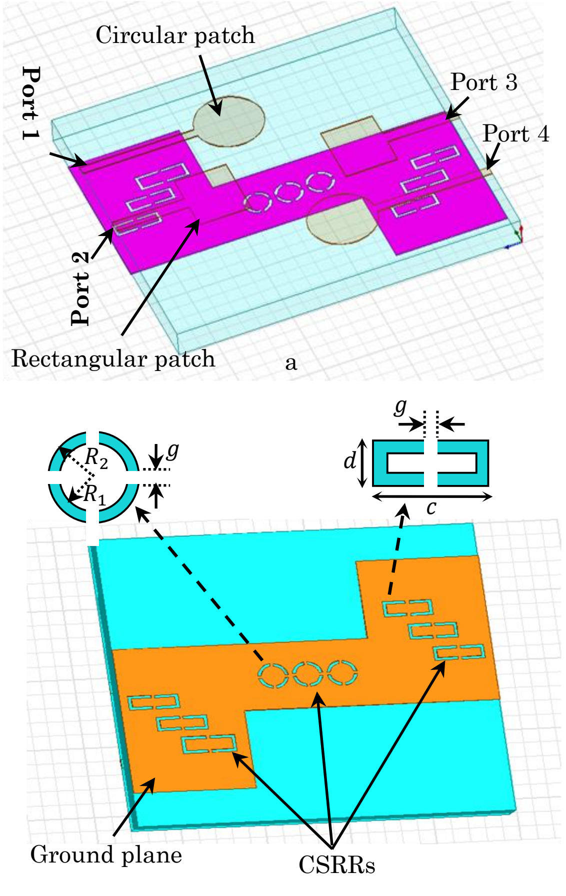
The dimensions of our proposed antenna are chosen for a resonance of the antenna in the 3.3-4.2 GHz band. For the working frequency estimated at 3.61 GHz (the center of the considered range), the dimensions of the patches (rectangular and circular) and the dimensions of the ground planes are summarized in Table 1. For these dimensions, the designed MIMO antenna has a length of 101.56 mm and a width of 84.04 mm.

**Table 1** – Dimensions of the proposed MIMO antenna

| Parameter | Value (mm) |
|---|---|
| $W$ | 24 |
| $L_{eff}$ | 19.3 |
| $a$ | 09.52 |
| $L_1$ | 36.5 |
| $L_2$ | 22.5 |
| Δ | 1 |
| $\theta$ | 2 |
| $S_1$ | 6 |
| $S_2$ | 29 |
| $w_1$ | 0.8 |
| $w_2$ | 0.6 |
| $e$ | 17.96 |

### 2.3 Configuration with CSRRs

For the second configuration, we keep the same MIMO antenna proposed previously (shapes and sizes of the patches). On the lower plane of the substrate, we connect 4 ground planes and then etch 9 complementary resonators (CSRRs) on the copper: three rectangular CSRRs (with two gaps) to decouple ports 1 and 2, three other resonators (of the same shape and size) to decouple ports 3 and 4; for decoupling of ports 2 and 3, we use three CSRRs of a circular shape (with four gaps). The global MIMO antenna is shown in Fig. 2.



b

**Fig. 2** – Proposed MIMO antenna with CSRRs: (a) perspective view, (b) bottom view

The spacing between rectangular CSRRs is 4 mm and between circular CSRRs it is 1 mm. The dimensions of rectangular and circular CSRRs are given in Table 2.

**Table 2** – Dimensions of various CSRRs

| Parameter | $c$ | $d$ | $R_1$ | $R_2$ | $g$ |
|---|---|---|---|---|---|
| Value (mm) | 7 | 4 | 2 | 2.5 | 0.5 |

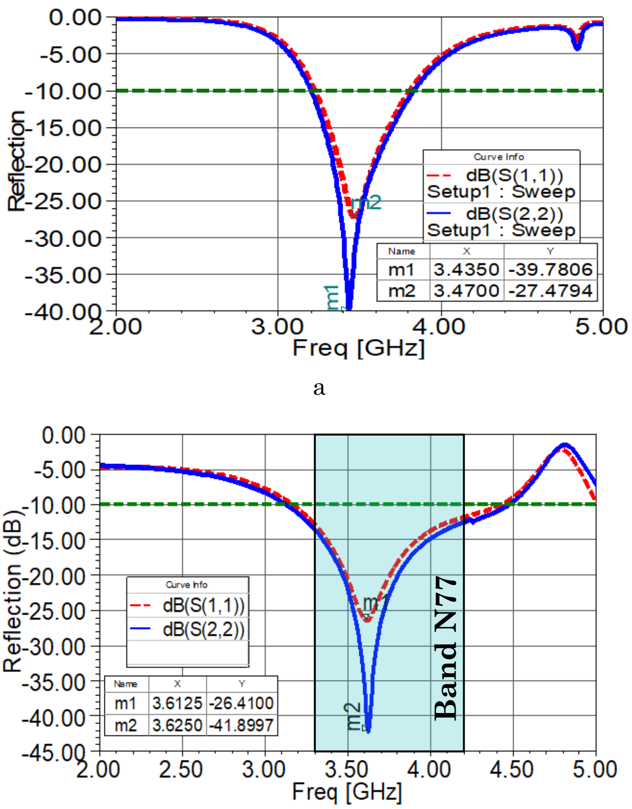
## 3. RESULTS AND ANALYSIS

### 3.1 Reflection and Coupling

To show the influence of CSRRs on the reflection of four ports ($S_{11} = S_{44}$ and $S_{22} = S_{33}$) of our MIMO antenna, we present this reflection for two proposed configurations. Fig. 3a represents the reflection of the antenna for the first configuration (without CSRRs). We observe a reflection of – 27.47 dB at the 3.47 GHz resonance for ports 1 and 4, and a reflection of – 39.78 dB at the 3.43 GHz resonance for ports 2 and 3 with a band-width of 630 MHz.

For the second configuration (with CSRRs), we observe a reflection of – 26.41 dB for ports 1 and 4 and a reflection of – 41.89 dB for ports 2 and 3 at frequencies of 3.61 GHz and 3.62 GHz, respectively. For the global antenna with CSRRs, the bandwidth is 1360 MHz.

Fig. 4 shows the coupling between adjacent ports. In the minimum band, we observe a high isolation which is attained for every two ports (< – 28 dB) that justifies the role of CSRRs for the reduction of the mutual coupling between the ports of the proposed antenna.



b

**Fig. 3** – Reflection coefficient for ports 1 and 2: (a) without CSRRs, (b) with CSRRs

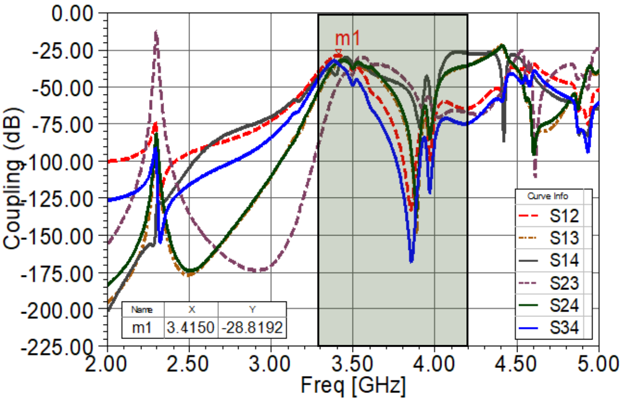


**Fig. 4** – Simulated coupling between each adjacent port (with CSRRs)

### 3.2 Proposed MIMO Antenna Performances

For the MIMO antenna performances, we represent the gain and radiations pattern. Fig. 5 represents the gain of the MIMO antenna for the two ports 1 and 4 of the global network. In the band of interest, the maximum gain is 15.79 dB which satisfies the functional requirements and makes the proposed antenna applicable for 5G systems.

As shown in Fig. 6, radiation patterns are presented in the *E*- ($\varnothing = 90°$) and *H*- ($\theta = 90°$) planes for all ports at 3.61 and 3.62 GHz. In Fig. 6a, when both ports 1 and 4 are excited, we note that the MIMO elements provide a nearly omni-directional *E*-plane pattern and a bi-directional *H*-plane pattern. In Fig. 6b, when both ports 2 and 3 are excited, we note that the MIMO elements provide an omni-directional *E*-plane pattern and a bi-directional *H*-plane pattern.

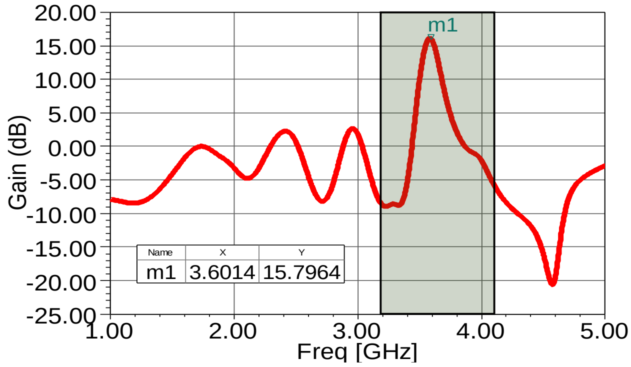


**Fig. 5** – Gain of the MIMO antenna (for ports1 and 4)

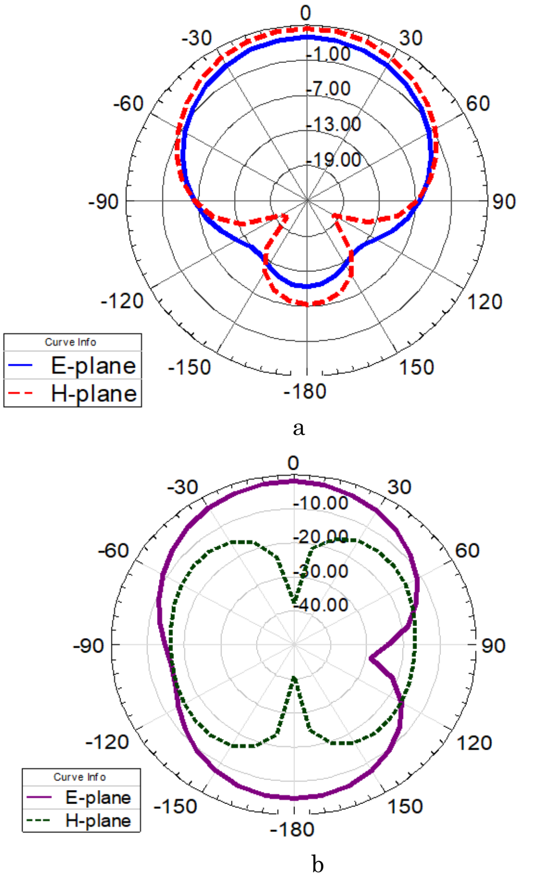


**Fig. 6** – Radiation patterns: (a) ports 1 and 4 excited at 3.61 GHz, (b) ports 2 and 3 excited at 3.62 GHz

To verify the performance and capability of the proposed MIMO antenna, the envelope correlation coefficient (ECC) was analyzed. The ECC is given by the following expression [15]:

$$ECC = \frac{\left|S_{11}^{*}S_{12} + S_{21}^{*}S_{22}\right|^{2}}{\left(1-\left|S_{11}\right|^{2}-\left|S_{21}\right|^{2}\right)\left(1-\left|S_{22}\right|^{2}-\left|S_{12}\right|^{2}\right)} . \tag{6}$$

Ideally, the ECC should be zero, but a value less than 0.5 is practically admissible. The ECC of the proposed antenna, shown in Fig. 7, is less than 0.07 between the antenna elements. This characteristic is obtained by reducing the mutual coupling between the radiating elements, which justifies the influence of CSRRs on the performance of our antenna. Fig. 8 represents the surface current distribution on the radiating elements at the 3.61 GHz antenna resonance.

The surface current density distribution of the proposed MIMO antenna at 3.61 GHz is shown in Fig. 8. It is visible from this figure that the surface current is significantly suppressed by introducing CSRRs on the ground plane. Weak current concentrations appeared on the four patches, which justifies isolation levels obtained by the reduction of the mutual coupling to improve the performance of our MIMO antenna.

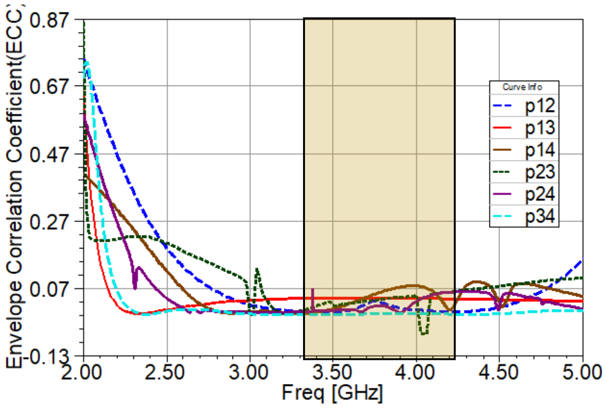


**Fig. 7** – The ECC of the suggested MIMO antenna for adjacent ports

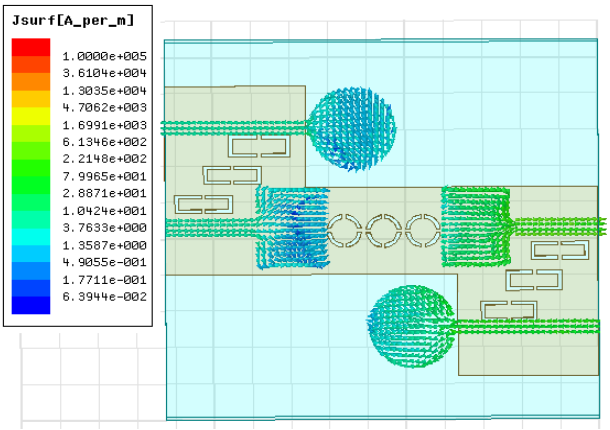


**Fig. 8** – Surface current distribution on the radiating elements at a frequency of 3.61 GHz

## 4. CONCLUSIONS

To sum up, a 4-port MIMO antenna covering the 3.3-4.2 GHz band has been designed in this work for 5G applications. The proposed antenna consists of four radiating elements of different shapes (rectangular and circular) and different dimensions. The main objective of this study is to reduce the mutual coupling between the patches. For this reason, we have introduced complementary rectangular and circular metamaterial resonators into the design. The obtained results show good performance with a gain of 15.79 dB, a bandwidth of more than 1360 MHz, and an envelope correlation coefficient of less than 0.07, making our antenna a potential candidate for sub-6 GHz 5G applications.

## ACKNOWLEDGEMENTS

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# Покращена 4-портова MIMO антена на основі зменшення електромагнітного взаємного зв'язку з використанням CSRRs з метаматеріалу для додатків Sub-6 ГГц 5G

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У роботі представлена антена з багатьма входами та багатьма виходами (MIMO). Пропонована антена утворена чотирма (04) випромінювальними патч-елементами різних розмірів і форм (прямокутна і кругла). Ці елементи збуджуються чотирма портами живлення, кожен порт паралельний трьом іншим суміжним портам. Усі елементи вигравірувані на верхній поверхні діелектричної підкладки FR4_Epoxy з електричними розмірами $1,26\lambda_0 \times 1,05\lambda_0 \times 0,019\lambda_0$ ($\lambda_0$ розраховується при робочій частоті 3,75 ГГц). Щоб покращити продуктивність нашої MIMO антени, дев'ять (09) комплементарних резонаторів з метаматеріалу (CSRRs) компактних розмірів надруковані на заземленій поверхні загальної структури. Ці симетричні прямокутні та круглі CSRRs діють як ізолятор між випромінюючими елементами, що сприяє зменшенню взаємного зв'язку між цими суміжними елементами. Отримані результати показують, що запропонована антена працює в діапазоні sub-6 ГГц 5G на частоті 3,61 ГГц (3,3-4,2 ГГц) з високою ізоляцією портів (менше 28 дБ). Крім того, антена, навантажена CSRRs, демонструє хорошу продуктивність MIMO з коефіцієнтом кореляції обвідної (ECC) менше 0,07, смугою пропускання понад 1360 МГц, незначним взаємним зв'язком і посиленням 15,79 дБ. Запропонована MIMO антена, яка працює в діапазоні sub-6 ГГц, підходить для додатків 5G.

**Ключові слова:** Коефіцієнт кореляції обвідної (ECC), CSRRs, Метаматеріал, MIMO антена, Sub-6 ГГц.