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Design and Simulation of Optimized Microstrip Patch Antenna Using Metamaterial Media for Cellular Mobile Communication Systems

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Abstract

This study aims to introduce a new type of microstrip antenna with coupled feed by developing a CSSR structure in the ground plane. Over the past few years, the use of microstrip antennas has become popular due to their low-cost technology and easy fabrication. However, microstrip antennas have many operational limitations and there is potential room for improvement based on the presented structures. First, a square patch microstrip antenna was simulated and the results showed limited resonance and unacceptable gain. Further simulation was performed by embedding two metamaterial resonators in the ground plane. According to the simulation results, the placement coordinates of the resonators have a significant impact on the antenna resonance. Subsequently, some changes were made to the antenna feed and the results were fully described. Finally, by deploying four resonators on the ground plane and using an coupled feed, the resonance of the proposed antenna was in the range (7.5, 7.3). This quantity is defined in the C-band radar frequency domain, and the main use of such a band has become dominant by default in military radars. Resonances in the intervals (3.75, 3.6) and (9.8, 10) are defined in the 5G mid-band and X-band, respectively. Also, the miniaturization process in the dimensions of the antenna has been achieved compared to previous research and the antenna gain has been improved. The simulation results of the proposed antenna in HFSS and CST software are consistent with each other. As a result, the fabricated and tested antenna exhibits the represented frequency response.

Keywords: Optimized microstrip patch antenna, metamaterial media, cellular mobile communication systems, coupled feed

Introduction

Microstrip antennas or printed antennas are used to realize high gain, high directivity, and broadband along with microwave circuits in wireless communication systems and satisfy the challenges of new-generation communication. Standard microstrip antennas are lightweight, inexpensive, flat, low gain, narrow bandwidth, and can be easily integrated into electronic devices. By using various techniques, the limitations of microstrip antennas such as low gain and narrow bandwidth can be resolved. Recently, metamaterials equipped with artificial periodic structures with negative permittivity (ε_r) and negative permeability (μ) play an important role in enhancing the bandwidth and gain of integrated miniaturized microwave circuits.

Due to the multiple advantages, microstrip antennas are used in wireless systems such as mobile phones, rockets, and satellites. The simultaneous propagation of waves in media with negative ε and μ was discussed and analyzed by Veselago in [1] at the end of the 1960s. After thirty years, the first practical realization of the structure [2] emerged as left-handed media [1, 2]. Other terms for media equipped with negative ε and μ are prominent, such as negative-refractive media [3], backward media [4], double-negative media [5], and also Veselago structures [6].

The idea of microstrip patch antennas based on printed circuit technology was introduced not only for circuit components and transmission lines but also for the radiating elements of an electronic system. The radiating elements and feed lines are placed on a dielectric substance. Rectangular, circular, equilateral, and annular are common shapes for patches. Feeding is usually achieved by a coaxial probe or a microstrip line.

Numerous advantages such as low profile, conformability to a shaped surface, and ease of fabrication have led to the increasing applications of microstrip antennas in the wireless industry. Studies conducted in the last several decades have led to the development of dual-band and multiband patch antennas. The disadvantages of microstrip antennas include low efficiency, low power, poor polarization purity, unwanted feed radiation, and very narrow frequency bandwidth.

The electromagnetic properties of metamaterials are due to the electromagnetic properties of the constituent elements. Intermittency usually plays a secondary role in bulk metamaterials. Following Rothman [7], Pendry [8, 9], and Smith et al. [10], a standard approach was proposed to design artificial media with negative parameters at microwave frequencies. This approach uses wires and/or metal plates to achieve negative dielectric permittivity. To achieve negative magnetic permeability, a system of split ring resonators (SRRs) is also used. To implement left-handed media, i.e. SRRs, the constituent unit cells are used in combination with other elements. Also, the complementary split ring resonator (CSRR) is useful as a dual version of SRR to improve the performance of negative permittivity media. SRRs and CSRRs are small planar resonators printed on a low-loss dielectric fiber to realize planar arrays of resonators with interesting electromagnetic properties. According to the duality principle [11] and Babinet's principle [12], the behavior of SRR and CSRR planar arrays should be approximately dual.

As proposed by Pendry [13], the SRR consists of two concentric metal split rings printed on a microwave dielectric circuit board. According to the analysis, the SRR behaves as an LC resonator that can be excited by an external magnetic flux and exhibits a strong diamagnetism higher than its first resonance. SRRs also have cross-polarization effects (electromagnetic coupling) [14] such that excitation by a properly polarized time-varying external electric is possible. The cross-polarization effects in SRR should be taken into account [13] and generalized to CSRR. Therefore, this resonant element exhibits magnetic polarizability along its y-axis. Consequently, its main resonance can be excited by an external magnetic field applied in this direction [15].

In [16], a microstrip antenna with complementary split ring resonators (CSRRs) is introduced. The 100 x 100 mm antenna is miniaturized on 1.6 mm thick Rogers substance by etching the CSRR into the ground plane. The proposed antenna in this study is designed for use in the 915 MHz and 2.4 GHz bands. In [16], a rectangular microstrip patch antenna with a frequency of 2.4 GHz is designed on the substance equipped with $\varepsilon_r = 2.2$ and a thickness of 0.795 mm. The length and width of the antenna are 42.6 mm and 53 mm, respectively. The simulated patch antenna uses a coupled feed. Also, the resonators are arranged in an array around the ground plane. Also, the resonator gaps are formed from the top and bottom of the ring.

Miniaturization of microstrip antennas has been achieved for a long time using various techniques. One common approach is to use a high-permittivity dielectric substance to reduce the guided wavelength and thus reduce the antenna dimensions [17]. However, the higher tendency of the radiated energy to return to the antenna leads to losses in the high-permittivity substances, which in turn reduces the impedance bandwidth. In order to overcome the narrow bandwidth of patch antennas on a high-permittivity substrate, several solutions using synthetic structures have been proposed [18–21]. In [22], a new design approach was proposed to realize compact antennas with improved impedance bandwidth using a ground plane loaded with complementary split ring resonators (CSRR). A microstrip patch antenna on a dielectric substance with CSRRs embedded in the ground plane was investigated and the resonant frequency, impedance bandwidth, and radiation characteristics were evaluated. The impedance bandwidth between the microstrip patch antenna on a high-permeability substance and the microstrip antenna without CSSR structure and with CSRR structure was compared. According to the results, a significant size reduction is possible for the microstrip antenna without bandwidth loss using the CSRR-based ground plane. The fabricated antenna achieved a 67% improvement in bandwidth compared to the conventional antenna. The present study aims to design and simulate an optimized microstrip patch antenna using metamaterial media for cellular mobile communication systems.

Proposed microstrip antenna

The initial idea of this research is inspired by [23]. The simulated 49.5×40 mm antenna is equipped with Rogers substance with $\varepsilon_r = 6.15$ and thickness of 1.6 mm. Four resonators are embedded in the ground plane with resonance at a frequency of 3.5 GHz.

The dimensions of the proposed antenna are 29×21, mounted on a substance made of FR-4 with a height of 1.6 mm and a dielectric constant of 4.3. Initially, the microstrip antenna was simulated and the results were extracted. Then, to improve the resonance and gain of the antenna, a metamaterial was used in the ground plane. Next, a resonator was embedded in the ground plane. Subsequently, the number of resonators was gradually increased and the antenna was simulated in HFSS and CST software. The results are explained in detail below.

1. Microstrip antenna simulation

The simulation of a microstrip antenna with dimensions of 29×21 mm on an FR-4 substance with a rectangular patch (with dimensions of 16×18 mm) and a feed line (with dimensions of 9×2 mm) is represented in Figure (1).

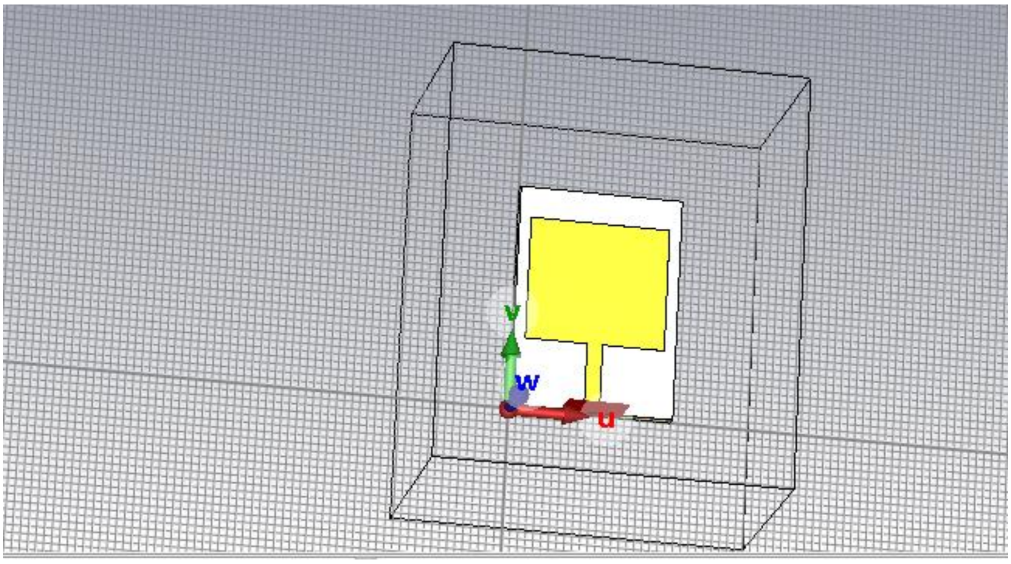

Figure 1: Microstrip antenna simulation

The s-parameters plot of the microstrip antenna is represented in Figure (2). The simulated microstrip antenna without coupled feed and metamaterial has limited resonance in two bands. In the following sections, the resonance of the proposed microstrip antenna is improved by using CSSR structure.

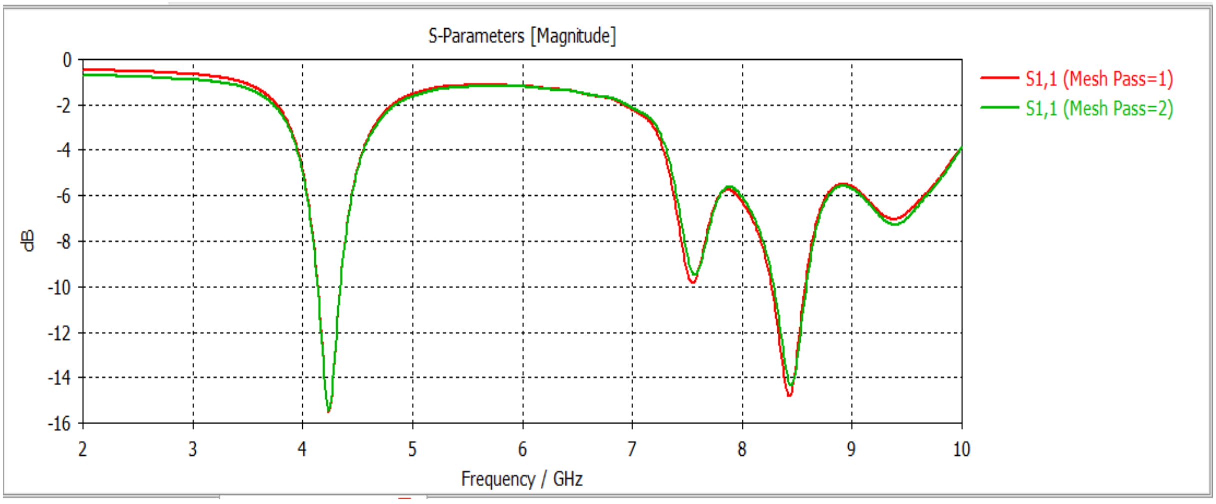

Figure 2: S-parameter plot of microstrip antenna without metamaterial and coupled feed

2. Using metamaterial and an coupled feed in the proposed microstrip patch antenna

To improve the resonant frequencies and gain of the proposed microstrip antenna, a coupled feed was embedded in the patch. Then, two resonators were embedded on the ground plane and their effect on the frequency response of the antenna was observed. The dimensions of the microstrip antenna and the dimensions of the resonators embedded on the ground plane are shown in Tables 1 and 2, respectively.

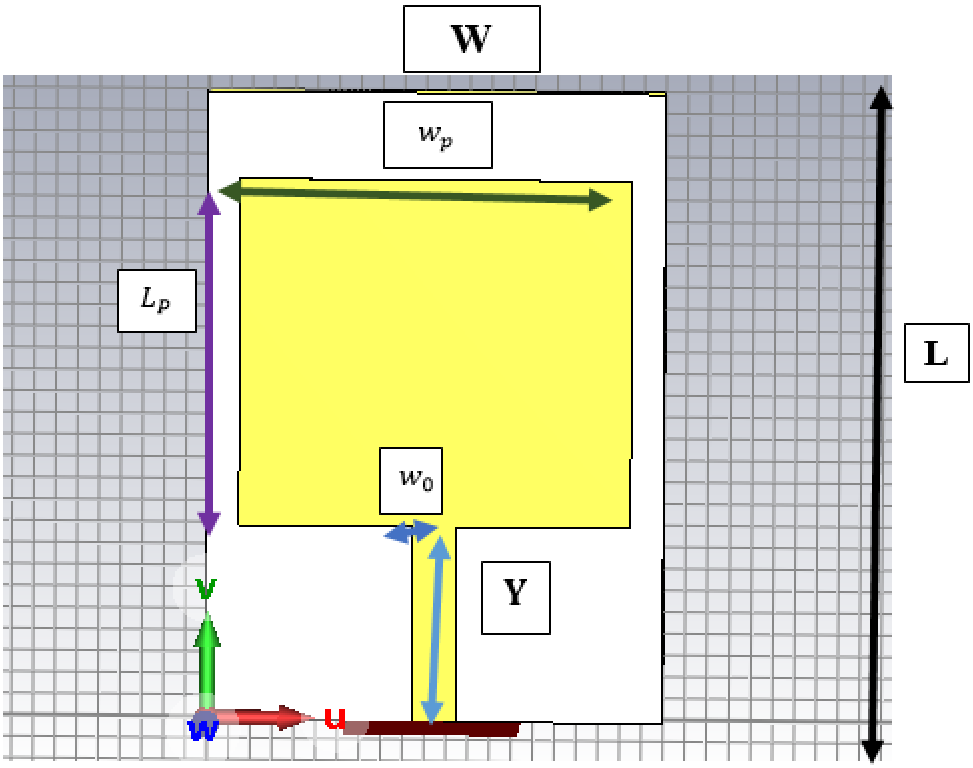

Figure 3: Simulated microstrip antenna

The dimensions and specifications of the microstrip antenna are represented in Table (1).

Table 1: Dimensions of the simulated microstrip antenna

Dimensions (mm)	Simulated antenna parameters
(w)	21
(L)	29
Thickness of the substance	1.6
(L_P)	16
(W_P)	18
Y_0	14
W_0	2

Two resonators embedded in the ground plane are represented in Figure (4).

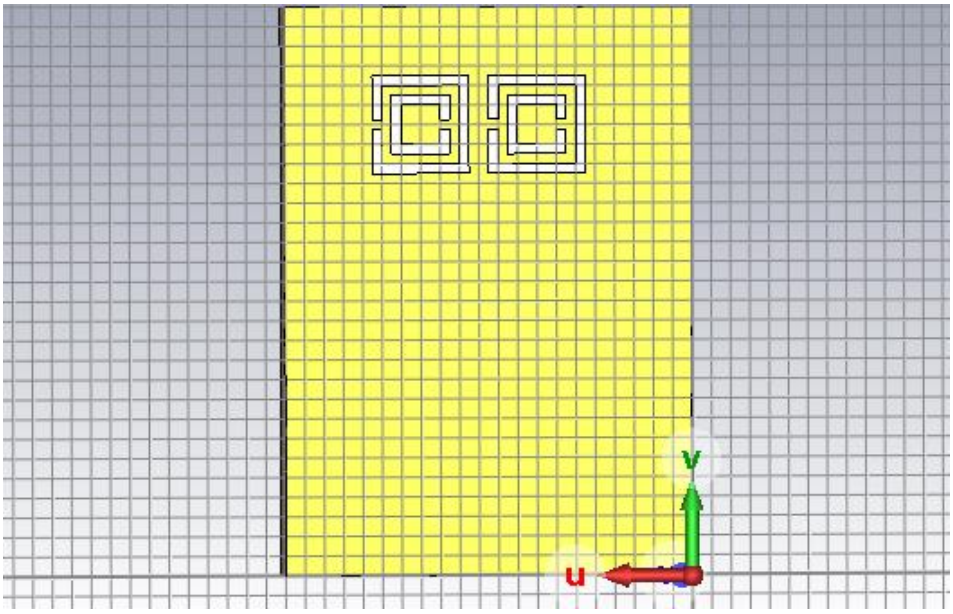

Figure 4: Ground plane and two resonators embedded in the ground plane

The resonator dimension parameters are represented in Figure (5).

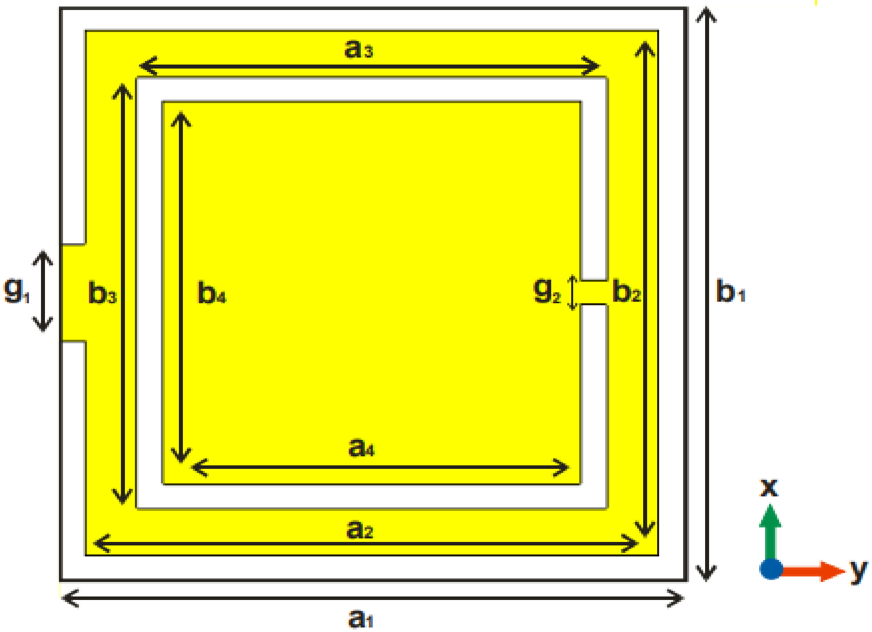

Figure 5: Resonator structure of the simulated antenna

To enhance the gain, CSRR resonators were embedded on the ground plane. The dimensions of the CSRR are represented in Table (2).

Table 2: Dimensions of the resonators (CSRR) in the simulated antenna

		Dimensions of resonators	
The first ring		The second ring	
a_1	5	a_3	3
a_2	4	a_4	2
b_1	5	b_3	3
b_2	4	b_4	2
g_1	0.5	g_2	0.5

The s-plot of the simulated antenna parameters equipped with two resonators in the ground plane is represented in Figure (6).

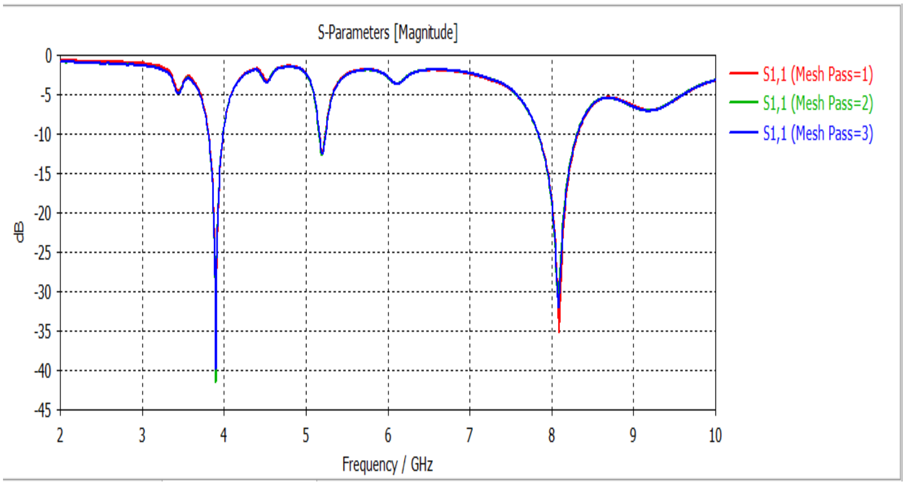

Figure 6: S-plot of simulated antenna parameters equipped with two resonators

To improve the resonant frequencies of the proposed antenna, four resonators were used in the next section.

Microstrip antenna simulation

A microstrip antenna with dimensions of 29×21 and substance of FR-4 and thickness of 1.6 is simulated in Figure (7). Increasing the number of resonators (as shown in Figure (8)) has led to improvement of the resonance and gain of the antenna. This procedure has been simulated in HFSS and CST software and the results obtained are consistent with each other.

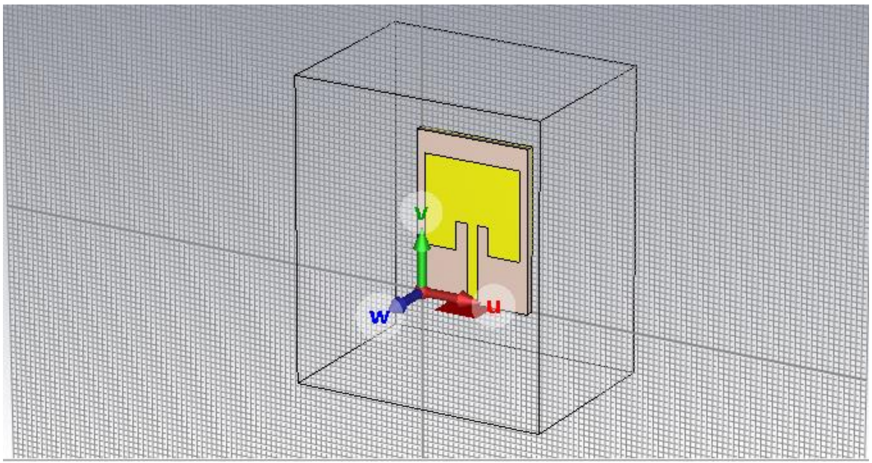

Figure 7: Simulated microstrip antenna

In Figure (8), four resonators are embedded in the ground plane with the coordinates of the resonators' placement changed. In the first resonator, the coordinates of the outer rectangle of the outer ring of the resonator are u→5.5 to 10.5 and v→14.5 to 19.5. Also, the coordinates of the inner rectangle of the outer ring of the resonator are u→6 to 10 and v→15 to 19. In the second resonator, the coordinates of the outer rectangle of the outer ring of the resonator are u→5.5 to 10.5 and v→20.5 to 25.5, and the coordinates of the inner rectangle of the outer ring of the resonator are u→6 to 10 and v→21 to 25.

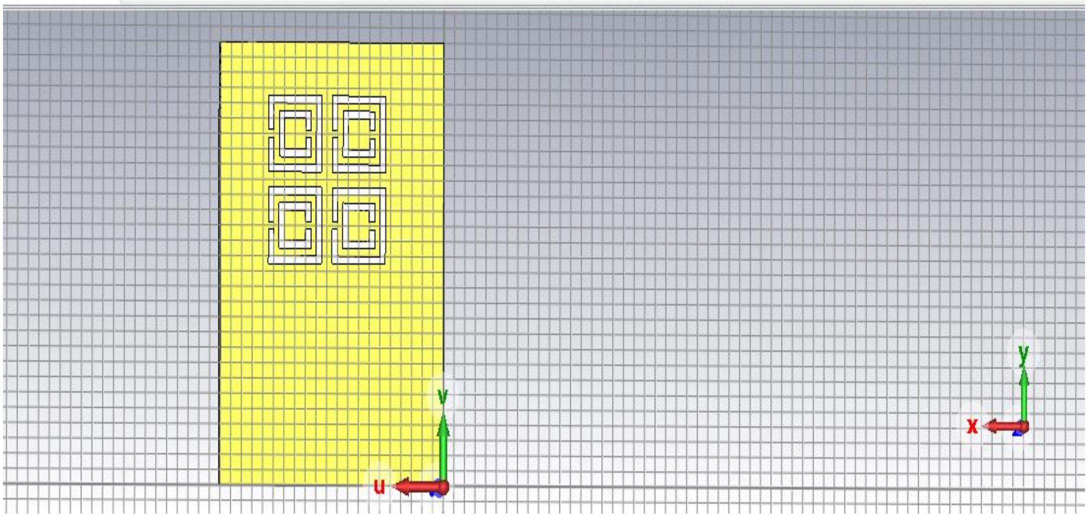

Figure 8: Ground plane of the simulated antenna

The s_{11} plots of the simulated antenna in CST software are represented in Figure (9).

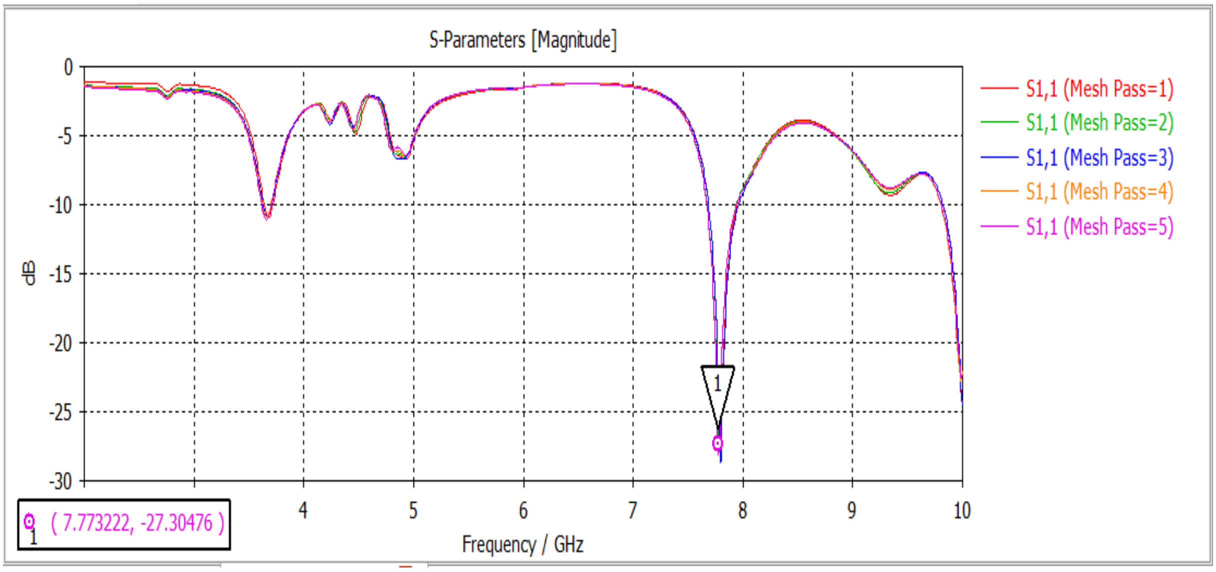

Figure 9: Simulated s_{11} plot in CST software

The s_{11} plots of the antenna simulated in HFSS software are represented in Figure (10).

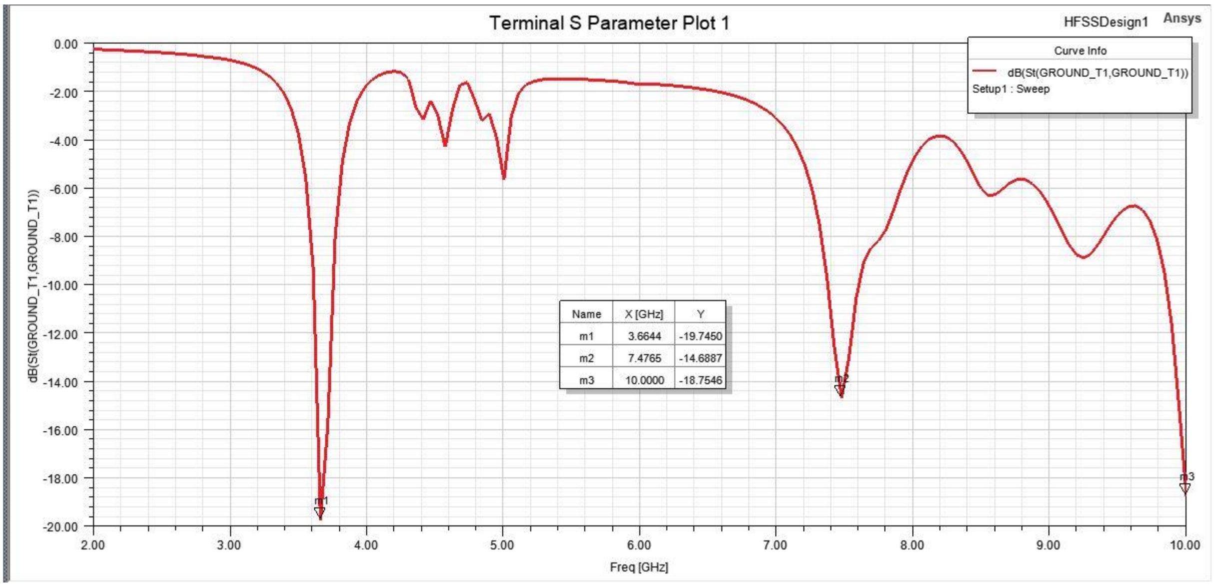

Figure 10: s_{11} plot of the simulated antenna in HFSS software

The resonance of the proposed antenna varies in the range (7.5, 7.3). This quantity is defined in the frequency domain of C-band radar, which is the main application of this band in military radars. Resonances in the intervals (3.75, 3.6) and (9.8, 10) are defined in the 5G mid-band and X-band, respectively.

Figure (11) shows the gain plot of the simulated antenna at a frequency of 3.6 GHz.

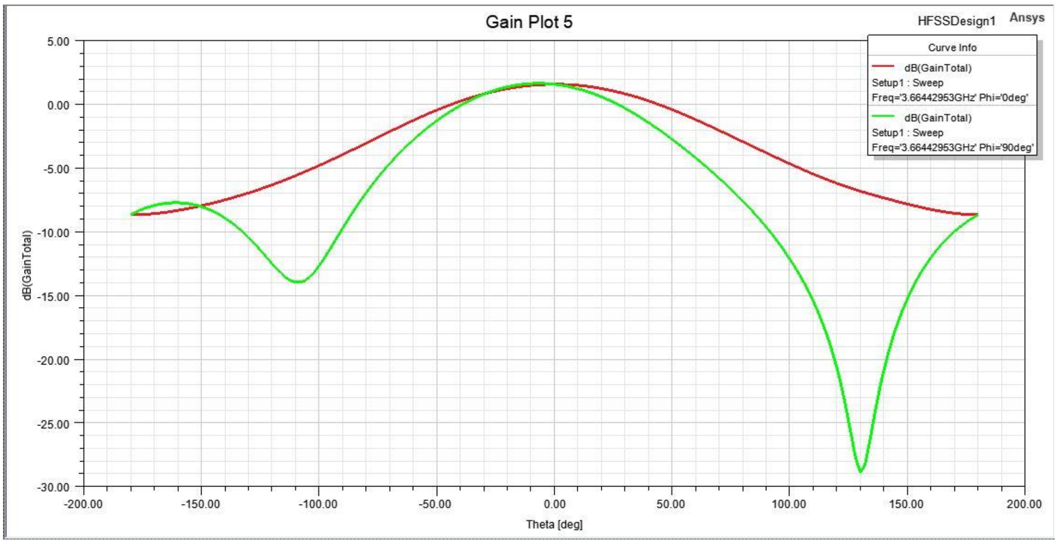

Figure 11: Simulated antenna gain plot at 3.6 GHz.

The simulated antenna gain plot at 10 GHz is represented in Figure (12).

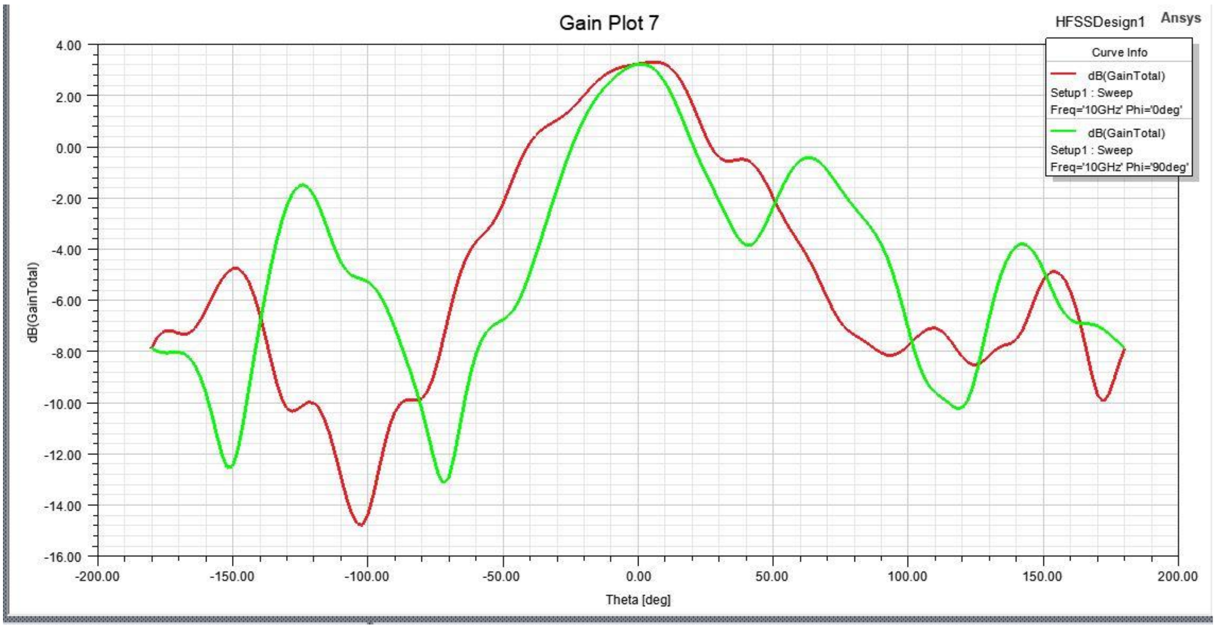

Figure 12: Simulated antenna gain plot at 10 GHz

Results

A miniaturized microstrip patch antenna is presented in [24]. As a complementary, a planar metal structure is obtained by replacing the metal parts of the main structure with slots and gaps with metal plates. As shown in Figure (13), its main and complementary split ring resonators should be dual. As a result, these two structures have almost the same resonant frequency [25]. Therefore, the quasi-static formulas for the SRR design proposed in [26] can be applied to CSRR. Here, the operating frequency of CSRR is set to 6.7 GHz.

The antenna size is reduced by using a CSRR structure on the ground plane. A microstrip antenna based on a CSSR structure radiating in the WIMAX and WLAN bands was presented in [27]. By using a CSSR structure on the ground plane, the antenna radiated in three bands (Figures 13).

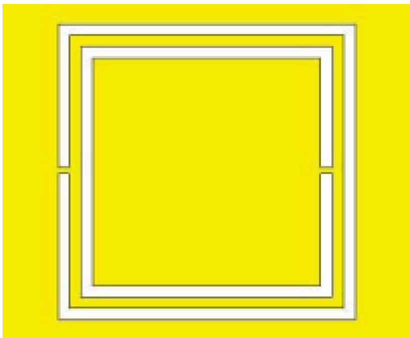

Figure 13: Antenna back view

The dimensions of the proposed microstrip antenna are 1.6×45×45 mm. By embedding a resonator in the ground plane, the multiband antenna radiates in the WLAN and WiMAX bands. The dimensions of the rectangular patch microstrip antenna are reduced and the antenna bandwidth is improved. The final product can be used in wireless systems.

The design of a complementary split ring resonator (CSRR) metamaterial on a ground plane structure to reduce the dimensions of a wearable antenna is presented in [28]. This antenna is designed for operation on the C-band frequency as a candidate for the 5G network. The proposed antenna is based on a triangular patch with a frequency of 3.5 GHz as one of the frequency bands of the 5G network. It can also be used as a wearable antenna at the 5G frequency in wireless systems. The material used is FR4-Epoxy with a thickness of 1.6 mm and dimensions of 34×34.4 mm. In this study, a CSSR structure was added to the ground plane in the form of four 4×4 cell arrays to achieve better performance and smaller dimensions, as shown in Figure (14).

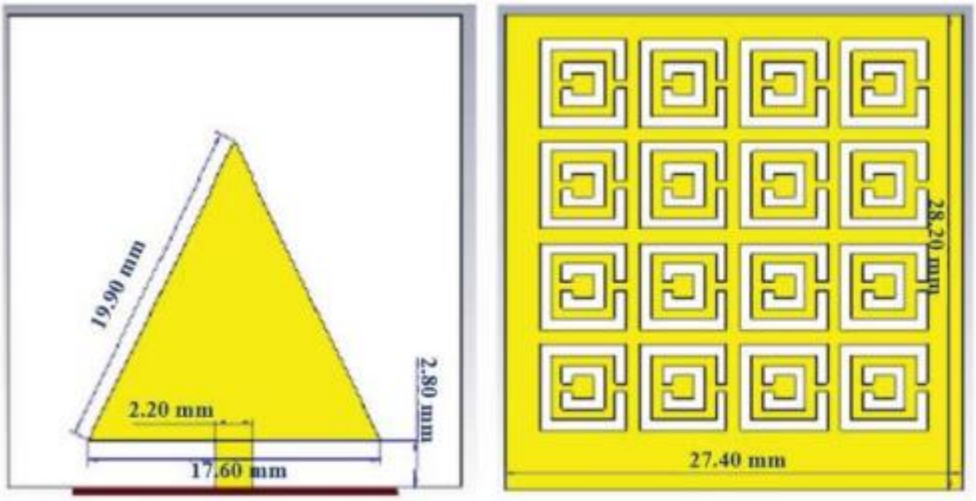

Figure 14: Triangular patch antenna with a CSSR structure on the ground plane

The simulated CSRR antenna on the ground plane has a significant effect on reducing the dimensions of the triangular patch antenna. Therefore, the final design can be used as a small, compact, and high-performance wearable antenna. The frequency response plot of the simulated antenna is represented in Figure (15).

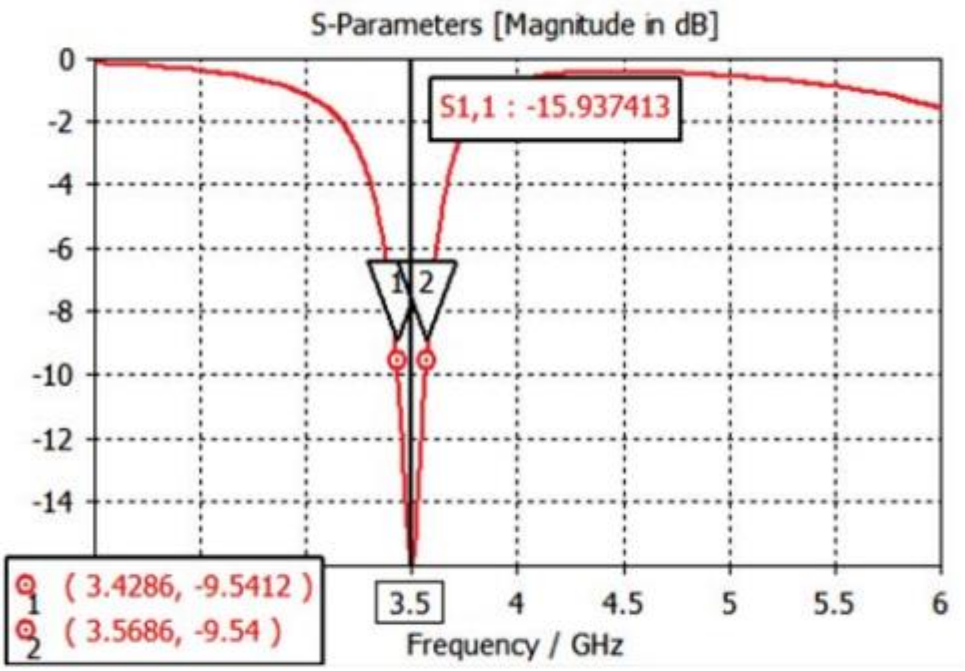

Figure 15: S-plot of the simulated antenna parameter in [28]

Table 3: Comparison of the proposed antenna parameters with references

Resonant frequency	Antenna dimensions	References
WLAN and WIMAX	45×45	[27]
(3.42, 3.56)	34.4×34	[28]
The resonance of the proposed antenna was in the range (7.5, 7.3). This quantity is defined in the C-band radar frequency domain. Resonances in the intervals (3.75, 3.6) and (9.8, 10) are defined in the 5G mid-band and X-band, respectively.	21×29	Proposed antenna

Conclusion

The dimensions of the simulated antenna in this study have been minimized. Placing the resonators in the ground plane has led to an improvement in the antenna gain. Also, the simulation results of the proposed design in HFSS and CST software are consistent. Also, the final antenna design has resonance in the 5G mid-band. The resonance of the simulated antenna at high frequencies can also be used in the radar domain. Considering the results of the feed structures in the patch to improve the gain and resonance frequency, using microstrip antennas with metamaterial media embedded inside the horn antennas is suggested to increase the directivity.

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