Novel broadband circularly polarized pentagonal printed antenna design for wireless power transmission applications

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ABSTRACT

This paper provides a new conception for a microstrip patch antenna array that operates in a circularly polarized manner for wireless power transmission (WPT) at 2.45 GHz. The proposed conception combines four pentagonal patches and the defected ground structure (DGS) method. The antenna array with a dielectric constant of 4.4 and a tangential loss of 0.025 is printed on a FR4 where its thickness is about 1.58 mm. The developed design aims to optimize the antenna array performance. The main contribution, to the telecommunications and WPT fields, is to achieve a maximum energy transfer with low losses, while also ensuring adequate adaptation to the excitation port. To prove the effectiveness of this design, simulation results were obtained using computer simulation technology microwave studio (CST MWS) software and validated by another solver high-frequency structure simulator (HFSS). Simulation results are presented and compared with those obtained using existing conceptions in the literature. The proposed design has proven to be very effective in achieving the intended objectives, which makes this design very good for radiofrequency (RF) energy collection and its various applications to power a variety of devices without harming our planet.

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1. INTRODUCTION

Demand for electric power has been increasing more rapidly worldwide since the apparition of electricity. The demand for this energy is due to the urgent need for electrical energy to power various devices such as phones, micro-drones, helicopters, computers, and sensors. For this reason, researchers are motivated to look for new strategies that are more effective than traditional strategies. The utility of traditional strategies such as nuclear and fossil energy is undesirable due to environmental pollution and unsustainable resources. However, the usefulness of batteries is a poor choice because they are very difficult to implement in some inaccessible and dangerous areas [1], and their limited lifespan requires periodic disruptive replacement.

In recent years, thanks to researchers, an effective strategy has emerged. This strategy is known as wireless energy transmission (WPT) which is an interesting topic in the field of energy harvesting. The WPT is a powerful strategy to power all devices thanks to wireless technologies [2] that eliminate wires (i.e. cables), ease of integration with other devices, low manufacturing cost, non-pollution of the environment, and independence of the main socket [3]. The most attractive WPT system is the rectenna system which converts electromagnetic energy into direct current (DC) electricity. The main blocks of the rectenna systems [4] are a receive antenna, a radio frequency-direct current (RF-DC) rectifier circuit [5], and finally a resistive load.

The fundamental element of the rectenna system is a reception antenna that aims to increase the RF-DC rectifier system's efficiency by increasing the energy received at the input to the rectenna. There are different types of antennas: parabolic antenna, dipole antenna, horn antenna, helical antenna [6], microstrip patch antenna (MPA). The most used type of antenna is the MPA which is a better choice [7] for different WPT applications thanks to its low weight, small surface area, easy integration, low manufacturing cost, and low energy consumption [8]. The MPA is composed of three layers: the ground plane means the lower conductive surface; the patch means the upper conductive plate and the middle layer is the substrate means the dielectric material [9].

In the literature, studies concerning the design of MPAs as it has become the most important subject of wireless communications systems and rectenna systems [10], [11]. The purpose of these studies is to examine and analyze parameters that influence the functioning of the MPA, such as the patch's size, patch's shape, substrate's length, substrate's width, substrate's thickness, and substrate's dielectric constant to improve antenna's performance in terms of gain, bandwidth, reflection coefficient, directivity, and efficiency. Recently, researchers have focused on developing new designs of the MPA, including the shape of the radiator element [12] (such as a rectangle, a square, a triangle, a circle, a ring, or a heart [13]), the operating frequency [14], [15] (such as 2.4 GHz, and 5.8 GHz), the polarization (linear [16] or circular [17]), and miniaturization methods (defective ground structure (DGS) [18], defective microstrip structure (DMS) [19], and electromagnetic bandwidth structure (EBS) [20]). Some work in the literature where the operating frequency is about 2.45 GHz like [21]–[24], the bandwidth of this work is less than 68.80 MHz. In this context, this work was done to have a wide bandwidth around the resonant frequency of 2.45 GHz. In addition, this paper brings an improvement to the gain level and the overall surface of the proposed MPA.

The proposed conception in this work is a new broadband circularly polarized MPA with a pentagonal radiator using the method of miniaturization named the defected ground structure (DGS). The pentagonal shape radiator is advantageous because it achieves a phase quadrature while maintaining the same amplitude to achieve circular polarization (CP). The choice of CP is beneficial due to greater mobility, good penetration, and insensitivity to multipatch reflection. The choice of DGS is an advantageous method due to the extension of bandwidth and minimization of the overall surface of MPA. The array is developed to increase the antenna's performance by combining several radiating elements in a single substrate. The proposed MPA array is designed, simulated, optimized, and finally validated using two software computer simulation technology microwave studio (CST MWS) and high-frequency structure simulator (HFSS). This design has excellent performance in terms of a well-adapted input impedance corresponding to a power supply of circular polarization at 2.45 GHz in the industrial, scientific, and medical (ISM) band, return loss, pattern radiation, bandwidth, and gain. The main subject of this paper could be considered a good solution for various energy harvesting applications, especially WPT systems such as rectenna systems.

To better organize the paper, the document was divided into four parts. Section 2 is devoted to the presentation of the steps used for the microstrip patch antenna design. Section 3 is devoted to the simulation results of the proposed design of MPA, followed by a discussion of the results and a comparison showing that this design is more effective than other existing designs in the literature. The conclusion in the final section summarizes the main contributions of this paper.

2. METHOD

To design a microstrip patch antenna (MPA), the first step is to specify the essential parameters such as the operating frequency, and the specifications of the used material for the substrate (i.e., its relative permittivity, its thickness, and its tangential loss). The resonant frequency chosen is around 2.45 GHz in the ISM band. Choosing the substrate plays an important role in how MPA works. The substrate selected in this paper is defined by its characteristics mentioned in Table 1.

Table 1. Characteristics of substrate

Type of substrate	FR-4 expoy
Relative permittivity (ε_r)	4.4
Thickness (h)	1.58 mm
Tangential loss	0.025

The second step is devoted to the selection of the patch shape, its conductor type, and its dimensions by using the equations [25]. Among the forms of the patch that exist in the literature, the pentagonal shape which is a perfect conductor will be treated throughout this paper. The choice of the pentagonal shape of the patch is capable of operating with CP [26], [27] by performing a phase quadrature while maintaining the same amplitude. The CP is advantageous thanks to its greater mobility, its better penetration, and its insensitivity to multipatch reflection. According to (1) to (3) aim to determine the dimensions of the patch. These equations are given below. Where: W is the patch's width, ε_{reff} is the dielectric effective permittivity, h is the thickness of the substrate, λ is the wavelength, f_r is the resonance frequency, and C is the speed of light in a vacuum. Figure 1 illustrates the conventional dimensions of the pentagonal patch.

$$W = \frac{C}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (1)$$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \quad (2)$$

$$\lambda = \frac{C}{f_r\sqrt{\varepsilon_{reff}}} \quad (3)$$

The ground plane used is a perfect conductor type that will be defective by the DGS method. The DGS method is advantageous thanks to its large bandwidth and its capability to reduce the total surface of MPA. The MPA can be improved in a MPA array. Note that the array is a combination of several radiating elements in a single substrate. The main objective of the MPA array is to increase the MMPA's performance above all the gain and directivity. The last step is focused on the design of the proposed MPA structure, the simulation, and the optimization of all the dimensions such as the ground dimensions, substrate dimensions, and patch dimensions. The optimization of all dimensions is repeated until the simulation results meet the intended objectives. The patch antenna design flowchart and analysis method flowchart are shown in [9] to clarify the essential steps for designing the MPA. Figure 2 in *appendix* shows all the steps by beginning with one MPA and ending with a 1 × 4 MPA array. The 1 × 1 MPA is illustrated in Figure 2(a) and its ground plane is shown in Figure 2(b). The 1 × 2 MPA array design is depicted in Figure 2(c) and its ground plane is shown in Figure 2(d). The 1 × 4 MPA array design is depicted in Figure 2(e) and its ground plane is shown in Figure 2(f).

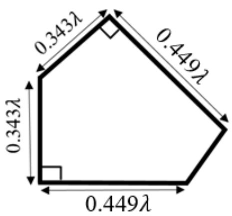

Figure 1. The conventional pentagonal shape of the patch

3. RESULTS AND DISCUSSION

The major characteristics of the MPA are simulated using the CST MWS software. These numerical results are followed by their comprehensive discussions to show the power of the proposed design in this present paper. The effectiveness of the developed design in this work is validated by another solver named HFSS. Figure 3 illustrates the variation of the simulated reflection coefficient according to frequency. For Figure 3(a) at 2.45 GHz, the return loss is about -33.54 [dB] with CST MWS and -18.36 [dB] with HFSS. For Figure 3(b) at 2.45 GHz, the return loss is about -38.13 [dB] with CST MWS and -19.71 [dB] with HFSS. For Figure 3(c) at 2.45 GHz, the return loss is about -33.60 [dB] with CST MWS and -21.25 [dB] with HFSS. It is the numerical method used by each solver that accounts for the difference between the results obtained by the two software packages. These numerical results show that the developed MPAs work well at 2.45 GHz. Adequate matching to the excitation port of 50 ohms is required.

Figure 4 presents the robustness of the 1 × 4 antenna patch array developed in the present work in terms of bandwidth, voltage standing wave ratio (VSWR), and axial ratio. At the operating frequency, the bandwidth in Figure 4(a) is about 265.47 MHz with both solvers. From Figure 4(b), VSWR is about 1.04 with CST MWS and with 1.19 HFSS. The axial ratio in Figure 4(c) is about 1.92 [dB] with CST MWS and 0.29 [dB] with HFSS. These results demonstrate the robustness of the developed array in this paper: this 1×4 antenna patch array developed operates in a wideband which makes this array multifunctional, it operates with adequate adaptation and a small quantity of return loss, and it operates with a CP with bandwidth about 227 MHz. Figure 4(d) presents the curve of the input impedance according to frequency for the 1×4 antenna patch array. From Figure 4(d), the real part of the input impedance at 2.45 GHz is approximately 50 ohms. The value of the imaginary part is about 0 ohms. The value of the input impedance is equal to $50 + j0\ \Omega$. So, this proposed antenna is well suited to the excitation port value of $50\ \Omega$.

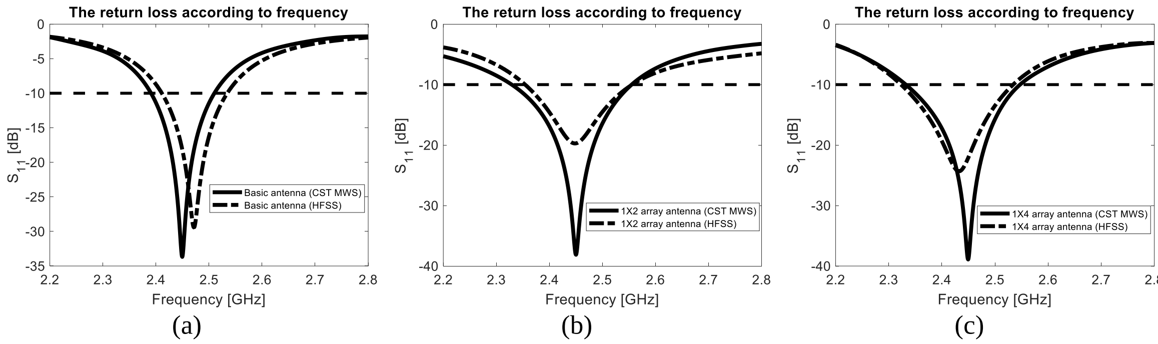

Figure 3. Return loss VS. frequency: (a) basic antenna patch, (b) 1×2 antenna patch array, and (c) 1×4 antenna patch array

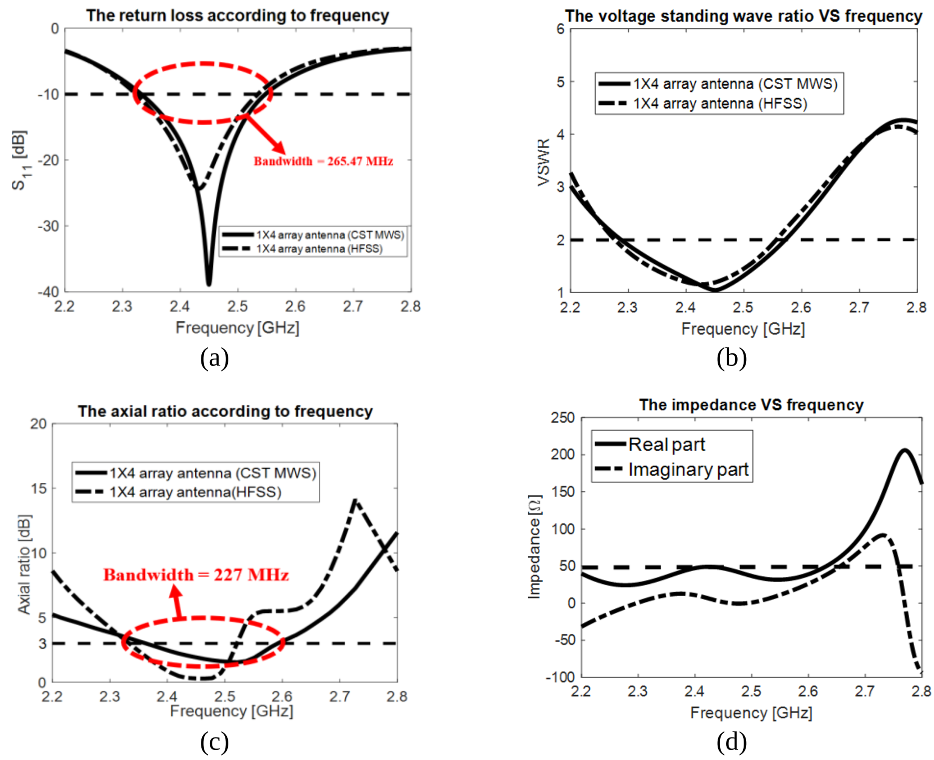

Figure 4. Simulated results of the 1×4 antenna patch array: (a) return loss VS. frequency, (b) VSWR VS. frequency, (c) axial ratio VS. frequency, and (d) input impedance

Figure 5 shows the better performance of this antenna array in terms of efficiency by showing the variation of the various powers (power accepted, power radiated, and power reflected). Figure 5(a) shows the total efficiency variation according to frequency. At the operating frequency of 2.45 GHz, the total efficiency value is about 94.83%. This value of efficiency guarantees that the developed array works well by transferring the maximum energy. Figure 5(b) illustrates the simulated powers according to the frequency obtained by the CST MWS of the 1×4 MPA array. From Figure 5(b) at 2.45 GHz, the accepted power is about 0.4998 [W], the radiated power is about 0.4742 [W], and the reflected power is about 2.18×10^{-4} [W]. These results show that this proposed array transfers the maximum amount of energy with the minimum amount of losses in both the metal and the dielectric.

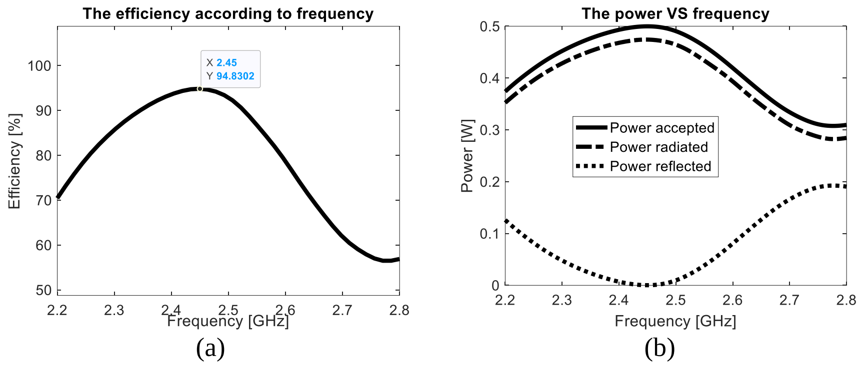

Figure 5. 1×4 antenna patch array simulated results (a) efficiency VS. frequency and (b) power VS. frequency

Figure 6 depicts the radiation pattern at 2.45 GHz in three-dimensional (3D) and two-dimensional (2D). Figure 6(a) depicts the three-dimensional radiation pattern at 2.45 GHz of the 1×4 MPA array. From Figure 6(a), the gain is approximately 7.94 [dBi] and the directivity is approximately 8.17 [dBi]. Figure 6(b) shows the two-dimensional polar radiation pattern including the E-plane and the H-plane at 2.45 GHz of the 1×4 MPA array.

Table 2 summarizes some of the results found in the literature for antenna patch networks working at an operating frequency of 2.45 GHz. Table 2 helps us to make a comparison between the developed design in this paper and other works in the literature. Based on Table 2, the proposed conception of the 1×4 MPA array is more performant than the other cited work [21]–[24]. Thanks to its utility of four elements, its smallest surface, its greater gain, and its largest bandwidth. As a result, the proposed network design is more efficient. So it can be used in all applications that depend on WPT such as wireless sensor networks, aerospace applications, automotive applications to recharge electric vehicle batteries, machines in medicine, wireless mobile chargers, and rectenna systems [28] in the field of energy engineering.

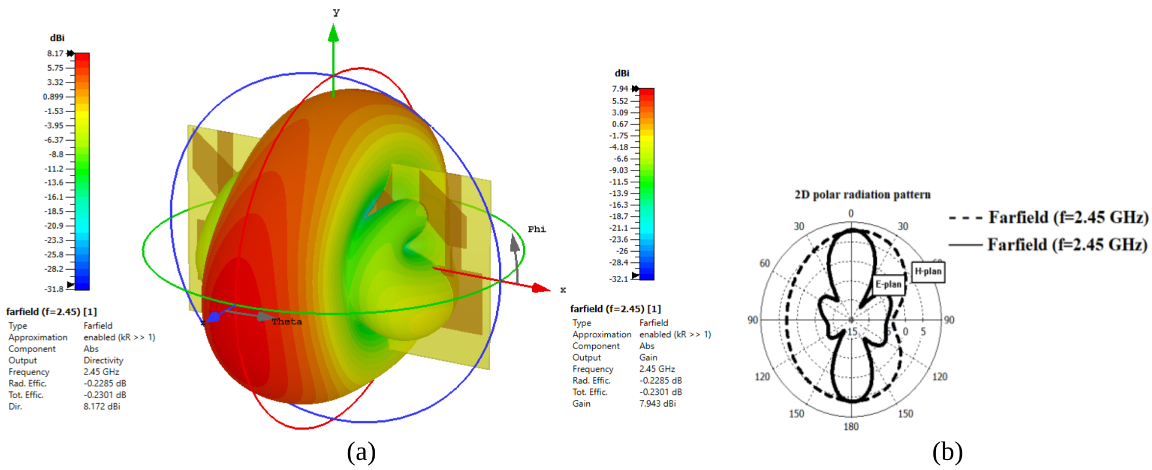

Figure 6. Simulated results of the 1 × 4 MPA array (a) 3D radiation pattern at 2.45 GHz and (b) 2D polar radiation pattern at 2.45 GHz

Table 2. Results comparison

Reference	Antenna patch type	Resonant frequency [GHz]	Surface [mm²]	Gain [dBi]	Bandwidth [MHz]
Tabakh *et al.* [21]	1 × 2 antenna patch array	2.45	75 × 95	4.73	68.80
Abu *et al.* [22]	No cited	2.45	225 × 225	7.5	62
Sennouni *et al.* [23]	2 × 3 antenna patch array	2.45	261.8 × 118.6	No cited	15
Zbitou *et al.* [24]	2 × 2 antenna patch array	2.45	150 × 180	6.8	No cited
Proposed 1 × 4 antenna patch array (in this paper)	1 × 4 antenna patch array	2.45	190.77 × 113.49	7.94	265.47

4. CONCLUSION

In conclusion, this work presents a new wideband microstrip patch antenna array design that works in a circularly polarized way for WPT at 2.45 GHz in the ISM band. This conception has been designed and simulated with great success. This 1×4 microstrip antenna patch network design organizes four identical pentagonal elements connected to a T-junction power divider to match the antenna input impedance to 50 ohms of power port. The miniaturization method used is the defected ground structure method. The ground was defective in the lower two corners, in the upper two corners, and in the middle at the top. The simulation results, using CST MWS software, confirm the excellent performance. The results are successfully validated by another HFSS solver. The performance of this design extracted from the software includes a reflection coefficient of -33.59 [dB], VSWR of 1.04, an axial ratio of 1.92 [dB], a bandwidth of 265.47 MHz, gain of 7.94 [dBi], and directivity of 8.17 [dBi]. This design is advantageous thanks to its flexibility, its easy integration with radiofrequency applications implemented using microstrip technology, its high bandwidth, its small surface area is about 190.77×113.49 [mm^2], its low weight, its multifunctionality, and its greater mobility. The results obtained give a clear vision that this design is a viable solution in the fields of telecommunications and renewable energy (especially WPT) in the ISM band. In future research, the manufacture of the new proposed design to test its prototype to compare the results obtained with those of simulation using the CST MWS and HFSS. In addition, the integration of this proposed MPA network with a rectifier circuit to make an overall design of the rectenna system.

APPENDIX

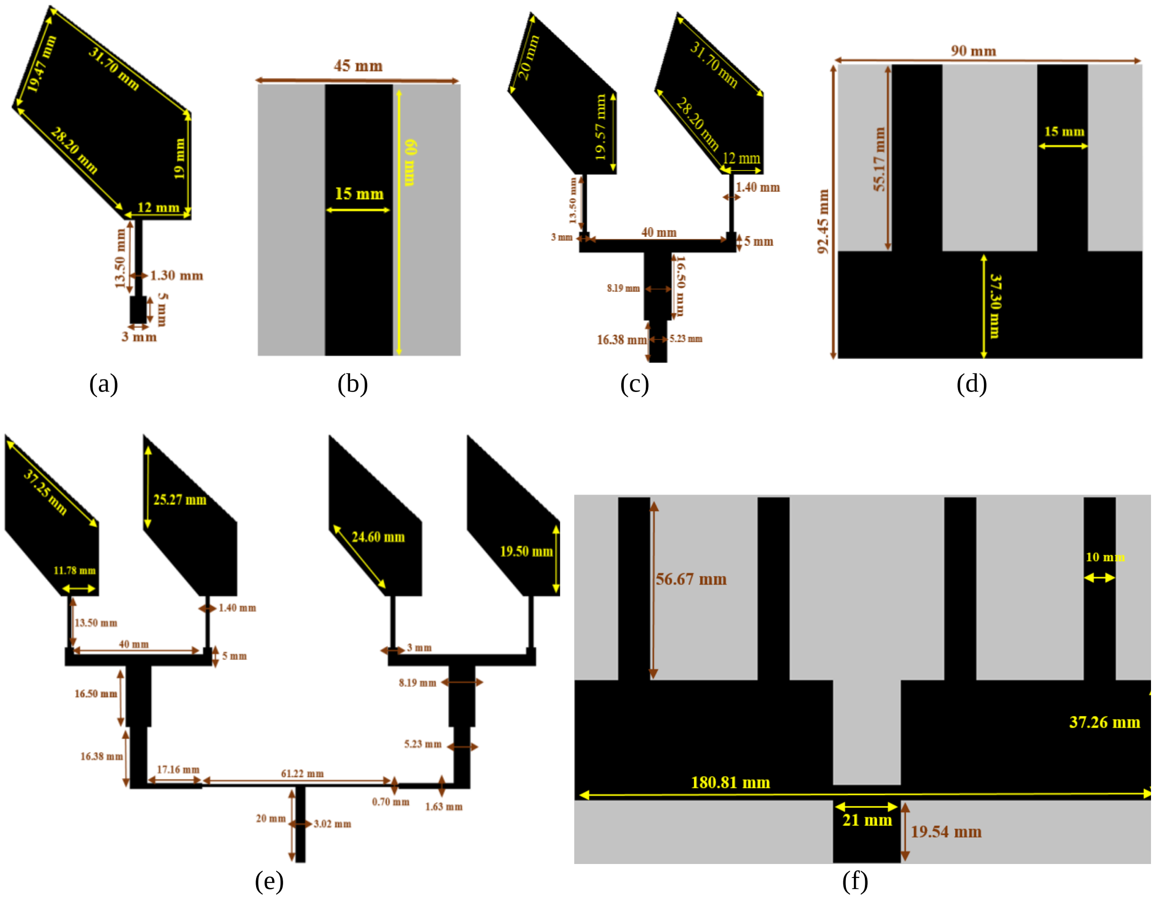

Figure 2. Broadband circularly polarized pentagonal microstrip patch antenna design based on DGS and its optimized dimensions: (a) top view of MPA, (b) bottom view of MPA, (c) top view of 1×2 MPA array, (d) bottom view of 1×2 MPA array, (e) top view of 1×4 MPA array, and (f) bottom view of 1×4 MPA array

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