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Design of an Efficient 2.45 GHz Antenna Array for RF Energy Harvesting

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Abstract A compact Mickey-shape 2 × 1 microstrip patch antenna array is presented in this work for use in radio frequency (RF) energy harvesting applications in the industry, science, and medicine (ISM) band of 2.45 GHz. High-frequency structural simulator (HFSS) software was used to construct and model the antenna, and a vector network analyzer was used to measure the antenna parameters. The proposed structure has an overall dimension of 12×8 cm^2 and spans a bandwidth of 2.42 GHz to 2.465 GHz. A 1.57 mm thick Rogers RT/Duroid substrate with a dielectric constant of 2.2 is used for modeling and manufacture. The modeling and experimental results show a very good performance in the operational band. Additionally, the results demonstrate enhanced antenna characteristics in terms of size, bandwidth, return loss, and efficiency. At 2.45 GHz, the suggested antenna has a high gain of 9.215 dBi. The findings demonstrate a strong agreement between measurements and models.

Keywords: Antenna array, Radiofrequency (RF), Energy harvesting, (ISM) band.

1 Introduction

Humans have relied mainly on electricity for the past 150 years to power factories, cars, light bulbs, and other devices. By 2018, there were more than 17 billion linked devices globally, including seven billion IoT devices, due to the quick development of IoT systems and technological breakthroughs [1]. With the expected growth of wireless devices, a demand for smaller form factors and more wireless sensor autonomy is arising [2]. Future wireless sensor nodes will need to have compact form factors and a long lifespan, which will not be possible with the battery technology that is now in use [3]. In order to ensure that a network will function for a predetermined amount of time, batteries usually have a limited operating duration and must be replenished or recharged. Environmental difficulties are caused by a number of battery-related challenges, including packing size, operating duration, and deposition [4]–[5]. However, replacing or recharging a battery might result in unwanted expenses and can be impractical or unavailable (for example, implanted devices within people or sensors embedded in buildings). Furthermore, because these small-power electronic devices require periodic battery replacement or recharge due to the location of the sensors in some deployments, replacing the batteries can be expensive and time-consuming. Moreover, improper disposal of spent piles might have a negative environmental impact. For wireless sensors positioned in difficult-to-reach places, the cable charging method is not feasible [6–10]. Many techniques for producing electricity from different ecological energy sources, such as wind, vibration, solar radiation, and electromagnetic (EM) waves, have been studied by researchers. Among these technologies, RF energy harvesting is unique in that it is sustainable and implantable, giving it an edge over vibration, solar, and wind energy collecting techniques [11–14]. Because wireless communication systems are always improving, there is a noticeable increase in the frequency of using radiofrequency (RF) sources in the environment. These sources suggest that using radio frequency (RF) energy to power low-power devices is becoming more feasible and realistic. Internet of Things (IoT) devices, wireless routers, and 5G communication base stations are some of these sources [15]. There has been a persuasive proposal lately to replace batteries with radiofrequency energy harvesting. Thus, one potential solution to the energy crisis could be to capture solar energy and use it to power low-power electronics. Nicola Tesla first proposed the concept of radiofrequency energy harvesting, or transforming ambient microwave energy into electrical energy, in the 1890s [16]. Wireless sensor

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applications are supported by energy harvesting [17]– [18]. It is feasible to convey a few milliwatts over rather large distances via radiofrequency energy transmission [19]–[20]. Additionally, the supply of low-power sensor systems is made possible by RF energy harvesting from ambient sources that operate in several frequency bands [21]. The effectiveness and performance of the RF energy harvesting technique need to be studied in great detail [22]. Most people do not realize that there is plenty of energy all around us at all times. We are being bombarded with energy waves coming from cell phone towers, broadcast television signals, satellites orbiting Earth, as well as wireless radio (Wi-Fi) networks, routers, radio waves that are AM/FM, wireless LANs (WLANs), and even portable communications devices like mobile phones. All of them transmit signals, combinations of energy and information, constantly. A radio frequency (RF) energy harvester gathers RF signals and converts them into electricity. We have a great potential for RF energy harvesting devices since the environment contains a substantial quantity of radio frequency power in the form of electromagnetic (EM) waves. In theory, this unrestricted energy can be caught, transformed, and stored for later use. It can be utilized in several ultra-low-power, battery-free applications, such as Arduino boards, calculators, and wireless sensor networks. As a result, different ideas for RF energy scavenging have been generated for various applications, including portable devices, medical applications, and battery-charging systems. While RF energy harvesting devices have many advantages, they also have some challenges. One of the challenges of the system is that it depends on location. Distance is an essential limitation because the strength of radiation dissipates significantly with it. Although a great deal of systems transmit ambient radio frequency energy, the energy is incredibly low [23]. The rectenna, which is an antenna followed by a rectifying circuit, is the primary component of the RF energy harvesting system. Generally, the antenna converts the RF waves it receives from neighboring mobile phones, wireless LANs (WLANs), FM AM radio transmissions, and broadcast television signals into DC power. Antenna characteristics, including size, bandwidth, gain, and input impedance matching, impact the efficiency of the RF-DC conversion. To ensure optimal power transfer, impedance-matching circuits must be installed between the antenna and RF rectifier. Of all the components of the rectenna system, the antenna design is the most crucial. For usage in RF energy harvesting, There have been several suggested antenna designs lately. Microstrip patch antennas (MPAs) are becoming increasingly popular among other antennas for rectenna applications because of their ease of integration into feed networks, low production cost, and simplicity. Furthermore, selecting antenna patch forms and modes that correspond with impedance, polarization, signal pattern, and resonance frequency is simple. There are numerous design options available for creating compact multiband patch antennas that are suitable for RF energy harvesting [24]. In recent years, researchers have extensively studied the behavior of the rectenna's components, i.e., the RF rectifier and the receiving antenna. However, the little DC output power generated and the finite electromagnetic energy at a specific frequency limit the practical applications. Broadband, multiband, or array reflectors are showing promise as viable options to improve power-generating efficiency in order to get around this problem [25]. The literature has reported on a number of antenna designs to use two bands on the rectenna [26]–[27] and multi-bands [28]–[29]. Overall, the antenna gain in the previously published works remained modest, and the techniques used to raise the gain significantly increased the system’s complexity. Therefore, a fully integrated rectenna with a high gain, a simple design, a small size, and good efficiency is necessary. This paper presents an enhanced patch antenna array designed for RF energy harvesting devices that operate in the 2.45 GHz (ISM) frequency region. The goal of a two-element antenna array with a small Mickey-shaped patch antenna aims to improve the gain in order to enhance RF energy harvesting. The suggested antenna's performance is maximized by managing the current distribution across its surface to get the necessary gain and return loss across the targeted frequency range. There are three primary sections to this paper's structure. The antenna configuration is described in Section 2, along with a description and discussion of the unique shape antenna array design and the single patch element design. The measurement's outcomes of the prototype antenna array are covered in detail in Section 3. Finally, the paper ends with a conclusion.

2 Design and simulation of a new shaped microstrip patch antenna array

Any patch antenna's fundamental construction consists of the three components: ground, substrate, and patch. Ground and substrate play a crucial role in the functioning of the antenna and offer physical support to the patch, even though the patch alone is what makes it act as an antenna. In other cases, the ground might be the base on which the antenna is installed; in such cases, it might not be included in the design. A necessary component that influences the patch's radiation and bandwidth is the substrate. When building a patch antenna array, it is essential to set fundamental characteristics such the substrate material and resonance frequency (f).In order to gather energy, the 2.45 GHz ISM band is used. RT/duroid5880 substrate from Rogers is used in the suggested antenna design following comparative research. $\tan\delta = 0.0019$, an extremely low dissipation factor, and a substrate height of 1.57 mm describe the selected RT/duroid. Its dielectric constant, εr, is 2.2. Two circular patches printed on the top of the substrate and a full ground plane on the bottom of the geometry make up the suggested antenna design, which consists of a rectangular patch. A simple 50 Ω microstrip wire feeds the antenna. However, to improve impedance matching, the inset feed approach is used. The inset-fed patch antenna is suggested in this configuration because it gives improved polarization purity with the same realized gain and more closely adheres to the array design. After the design of the single patch antenna, a feeding network based on a T-junction has been utilized to form a two-element antenna array. The quarter wavelength technique matches the different impedances, as seen in Fig.1. The input power is equally split into two branches with the same phase.

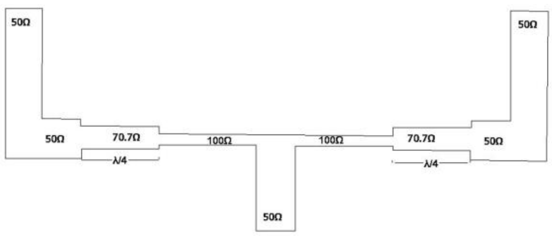


Fig. 1 Feeding network of the proposed antenna array.

2.1 Single-element antenna design

The Mickey-shaped antenna design, which uses an inset feed approach, is shown in Fig. 2. The pattern consists of a rectangular patch loaded with two circular stubs with four horizontal narrow slits. . In order to decrease the antenna's size and improve impedance matching in the targeted frequency range, slits and circular stubs are added.

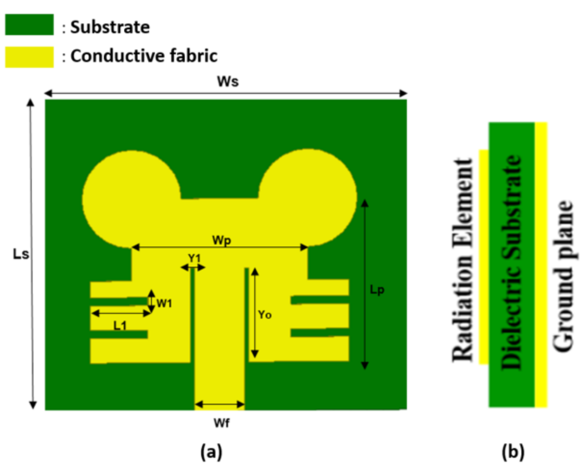


Fig. 2 Geometrical design of a single antenna. (a) Top view of the antenna. (b) Side view of the antenna.

ANSYS HFSS was utilized to get the ideal geometrical parameters, which are presented in Table 1. The transmission line model equations [30]–[31] are employed to calculate the microstrip antenna patch's geometrical dimensions depending on its operating frequency. Furthermore, the single antenna structure was simulated using the HFSS Optimization was applied to the antenna's configuration, especially on the dimensions (L_1) and (R), to get the best possible performance of the antenna.The results of several sweeps in (L_1) are displayed in Fig. 4(a), where the S11 of the proposed antenna suggests resonance at 2.4 GHz with a bandwidth of 2.3 to 2.49 GHz for $|S11| \leqslant -10\ dB$. Figure 3 illustrates the recommended antenna configurations, beginning with the preliminary design stages and ending with the finished construction.

Table 1 Optimized dimensions of single antenna element

Parameters	value(mm)
W_s	56
L_s	47
W_p	21.26
L_p	20
W_f	6
W_1	1
L_1	7
Y_1	0.5
Y_o	11.5

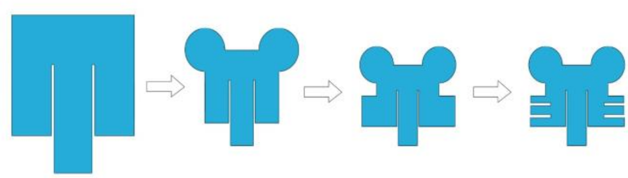
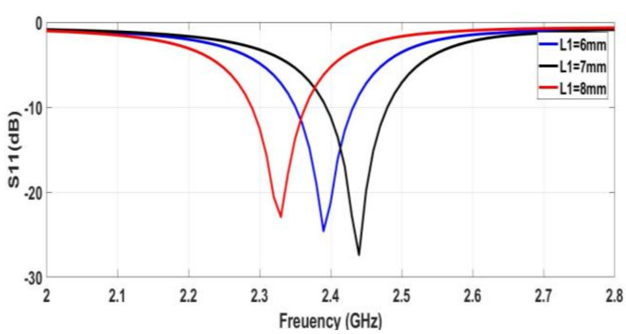
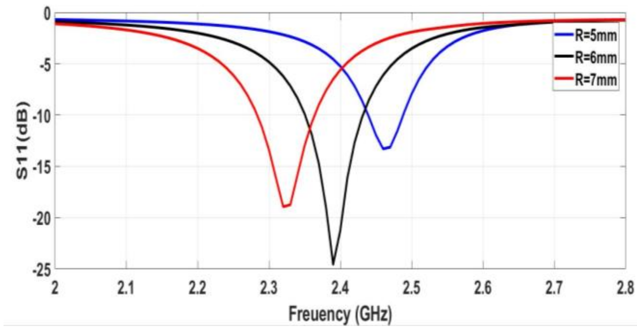


Fig. 3 The proposed design configuration steps.

The antenna design begins with a simple rectangular radiating patch, and then we try to reduce the patch size with many phases. As shown in Fig.3, we configured four antennas with similar patch shapes but varying lengths, decreasing in size progressively. The first configuration features a patch size of 40.47×48.37mm. This is followed by configuration with a patch size of 32.5×30mm. The third configuration has a reduced patch size of 25.47×20mm. Finally, the most compact design is the last one, which has a patch size of 21.262×20 mm. Among these, it achieves the smallest form factor and demonstrates the best performance results, highlighting the efficiency of compact antenna designs in our study. First, when the size was reduced, it affected its resonant frequency, so we gradually added two circular stubs following it by two small rectangles on both sides of the patch to bring back the desired frequency band and enhance the s11 matching. Lastly, the four rectangular slits were added to the rectangular radiator to further reduce the antenna's size. The fins attached to the patch are crucial for aligning the antenna with the intended frequency. The size of the fins has been adjusted to introduce deeper resonances at various frequencies, such as 2.45 GHz. Due to the often concentrated current distributions at 2.40 GHz, the antenna's reflection coefficient is further increased with two slits. A large frequency bandwidth is included in the third slot design, and deep resonance at 2.4 GHz is offered in the fourth iteration with an extra slot. By adjusting the slot length (L_1) and examining the |S11| parameters, as illustrated in Fig. 4(a), the antenna's overall intended performance is investigated. When "L_1" increases from 6 to 8 mm, the resonance frequency decreases. Additionally, the proposed antenna design provided the necessary frequency spectrum for a 7 mm "L_1" length. In order to learn more about the antenna, several "R" values—that is, the circle's radius—between 5 and 7 mm are considered. Compared to gain, "R" has a greater effect on the resonating frequency and bandwidth. As the value of 'R' rises, the resonant frequency decreases significantly; the proposed antenna design provided the necessary frequency spectrum for 'R' of 6 mm. The remarkable performance analysis of ’R’ is illustrated in Figure 4(b). Fig. 4(C) shows that the antenna has a strong gain and superior matching performance at the operating frequency when (R) =6mm, revealing a maximum gain of 2.123 dB, comparing it with different optimistic values. Fig. 4(d) depicts the antenna’s efficiency, revealing a maximum efficiency of 96%.



(a)



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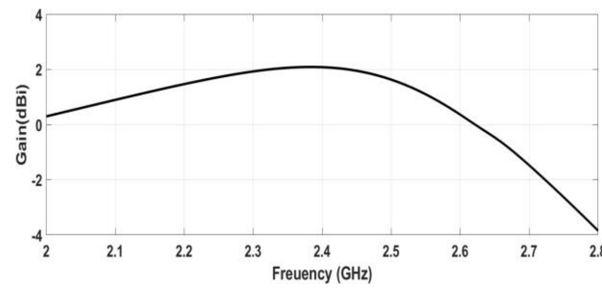

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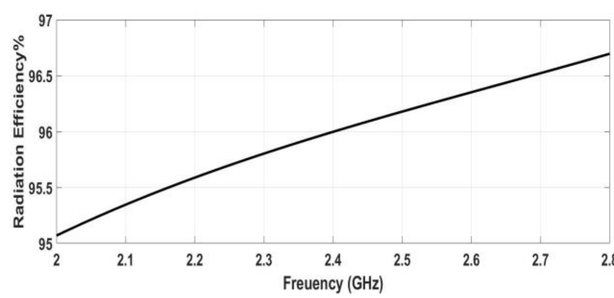


(d)

Fig.4 Performance parameters of single antenna. (a) S-parameter effects due to change in L_1. (b) S-parameter effects due to change in R. (c) Gain. (d) Efficiency.

2.2 Two-element antenna array design

The same single-element patches were used in the second phase of the design to create a two-element array, which increased the antenna's bandwidth, gain, and efficiency. The arrangement of the array and its feeding network is shown in Fig. 5. The array is excited using a T-junction to provide a two-element array antenna. The microstrip line feed with transformer λ/4 matches the impedances seen in Fig. 1. The simulation's impedance matching is done using standard transmission line formulae.

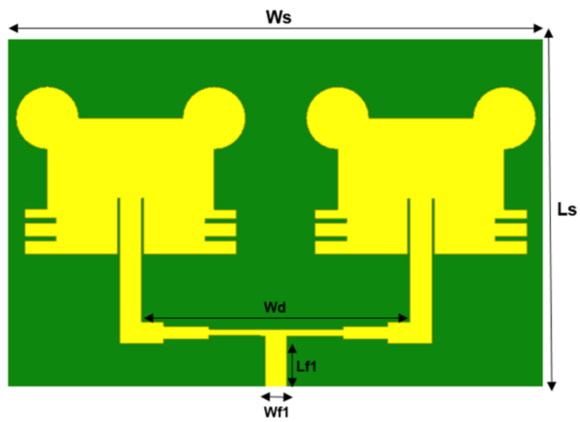
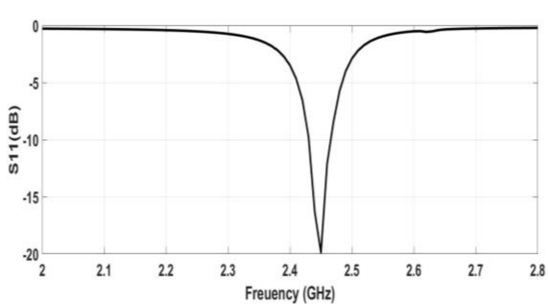


Fig. 5 Configuration of the proposed 2×1 antenna array.

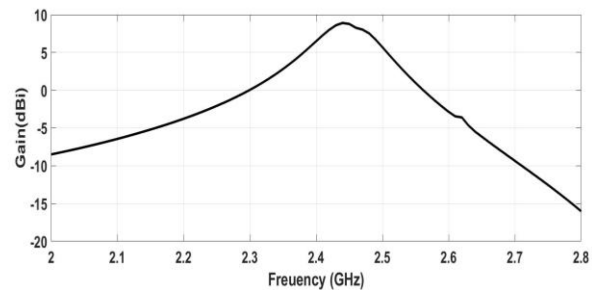
Table 2 lists the geometrical parameters that have been optimized. We analyze the two-element array antenna modeling findings with respect to S11, realized gain, and efficiency. When compared to the single-element antenna, the two-element antenna resonates around the 2.45 GHz frequency range with superior impedance matching and enhanced bandwidth, as shown by its reflection coefficient in Fig. 6(a). The two-element antenna array's gain, 3D radiation pattern, and radiation efficiency are displayed in Figures 6(b), 6(c), and 6(d), respectively. As seen in Figure 6, a two-element array offers much higher radiation efficiency and gain than a single element.

Table 2 Optimized dimensions of two-element antenna array

Parameters	value(mm)
W_s	120
L_s	80
L_{f1}	12
W_{f1}	4.83
W_d	60
R	6



(a)



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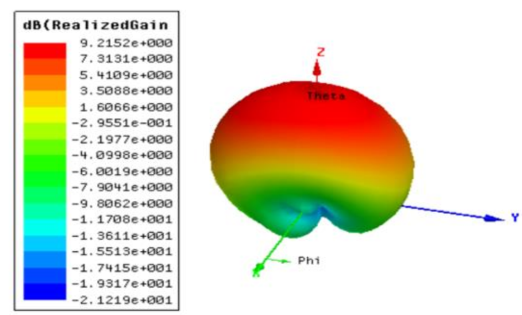

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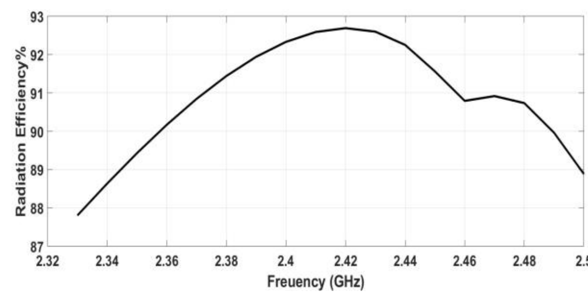
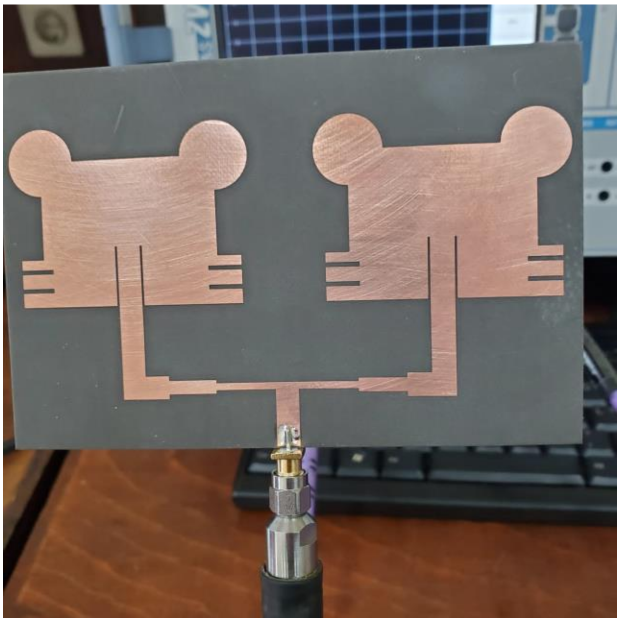


(d)

Fig. 6 Two-element antenna array results. (a) Reflection coefficient. (b) Gain. (c) 3D radiation pattern. (d) Radiation efficiency.

3 EXPERIMENTAL INVESTIGATIONS

The suggested antenna design has been calculated, modeled, and then measured. The produced mickey-shape microstrip antenna array in Figure 7(a) illustrates the practicality and ease of use of the design, which was built based on simulation-derived parameters. The substrate material, RT/duroid 5880, is printed with the antenna. On the bottom of the antenna is a ground plane that has the same dimensions as the substrate. Ansoft's high-frequency structural simulator (HFSS) is used to simulate the antenna, and photolithography is used to fabricate it. As seen in Figs. 7(b) and 7(c), respectively, the antenna measurements were carried out indoors using a vector network analyzer model Rohde&Schwarz no. ZVB20 within an anechoic chamber. The findings of the measured and simulated proto-type's reflection coefficient demonstrate the efficacy of the suggested design. For the purpose of measuring and connecting coaxial cables, a 50Ω SMA connector was attached to the antenna's input port.



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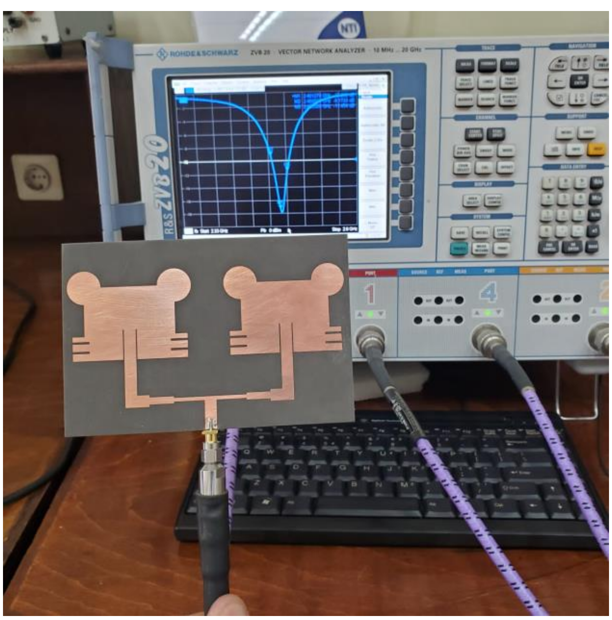

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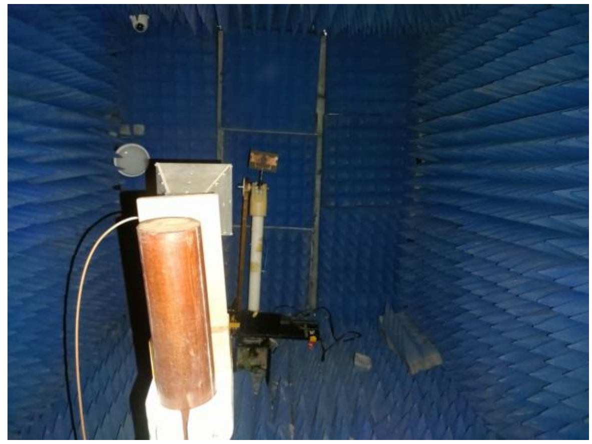

(c)

Fig. 7 (a) Photograph of the fabricated antenna. (b) Antenna measurement using vector network analyzer. (c) Antenna inside anechoic chamber for radiation pattern measurement.

Figure 8(a) shows the results of the modeling and measurements of the suggested antenna's reflection coefficient. It can be shown that the simulated bandwidth of the antenna is 2.42 to 2.465 GHz, whereas the measurement bandwidth is 2.46 to 2.49GHz. It is evident that there is a strong correlation between the simulation and measurement outcomes. But there is a little difference between the measured and calculated reflection coefficients (S11), which might be the result of manufacturing and measurement tolerances. The soldering faults (SMA) connection efficiency, substrate dielectric constant, manufacturing tolerances, etc., are the reasons for the discrepancy between the measured and simulated results. The simulation results show that the proposed structure resonates at 2.45 GHz with a reflection coefficient of about 20 dB and a gain of 9.215 dBi. However, the measured data confirm that the proposed antenna resonates at 2.48 GHz, having a significant reflection coefficient of 19.3 dB. The suggested array antenna's simulated and observed radiation patterns in the E- and H-planes at 2.45 GHz are contrasted in Figures 8(b) and 8(c). It implies that the recommended design is the best choice for wireless local area network (WLAN) frequency spectrum applications including radiofrequency energy harvesting. The array structure is well-fitted, as indicated by the measured value of S11 that was attained. Therefore, the suggested array is appropriate for the desired 2.45 GHz RF energy harvesting applications, as confirmed by both simulated and measured data. Table 3 compares the RF energy harvesting strategies for various antenna systems in terms of size, antenna gain, frequency ranges covered, substrate type, and antenna design topologies. As shown in Table 3, this work has demonstrated outstanding performance

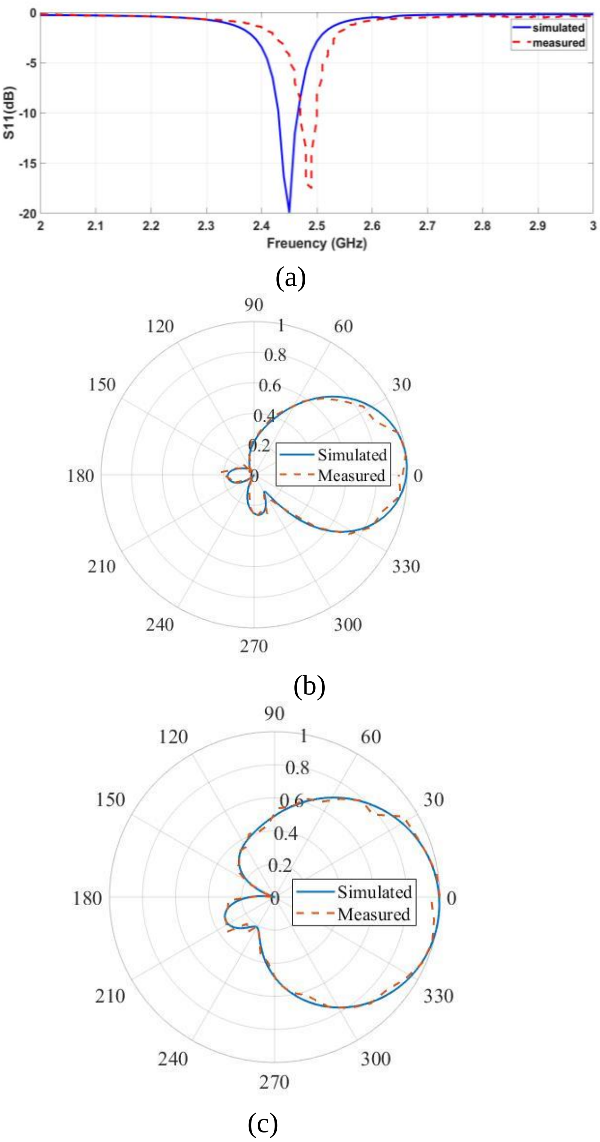

Fig.8 (a) The proposed antenna's simulated and measured reflection coefficient. (b) The antenna's simulated and measured radiation patterns in the E-plane. (c) The antenna's simulated and measured radiation patterns in the H-plane.

compared to previously reported work. It is worth emphasizing that this is the first antenna with a reduced size, giving a deep resonance at 2.45 GHz with the highest gain. Furthermore, the demonstrated work shows comparably high gain antenna and good efficiency among selected work. In addition, the demonstrated antenna has a low design complexity compared with other work. In the comparison table, all the antenna radiation patterns are directional, indicating that they concentrate the radiated energy in specific directions rather than uniformly in all directions. This focused emission enhances the antenna's performance by increasing its gain and improving signal strength in the targeted areas, making them highly effective for applications requiring precise signal coverage, such as in point-to-point communication links, radar systems, and certain broadcasting scenarios.

TABLE 3 Comparison of this work with relevant work.

Ref.	Freq. (GHZ)	Substrate	Size (λg)	Gain(dBi)
[32]	2.45	FR4	1.9722×2.9278×0.05	6
[33]	2.45	FR4	3.569×1.508×0.025	7.75
[34]	2.45	Cordura textile	1.692×1.692×0.0507	3.57
[35]	2.45	Optically transparent plexiglas	3.009×1.186×0.0354	1.94
[36]	2.45	FR4	1.79×1.455×0.012	1.94
This work	2.45	Roger5880	1.357×0.904×0.0177	9.215

4 Conclusion

In this work, a new, high-gain microstrip array antenna is proposed, designed, fabricated, and tested for RF energy harvesting applications operating at 2.45 GHz. The results of the simulation indicate that the antenna characteristics were enhanced by the design stages. In applications involving RF power harvesting, the antenna prototype meets the radiating criteria. A high gain of 9.215 dBi is obtained with the antenna with VSWR less than two and efficiency of 92%, respectively. The findings show that the recommended antenna suits RF energy harvesting and portable applications. The proposed antenna's low cost, minimal feed network loss, and strong performance make it a promising option for a range of Portable devices and systems for collecting radiofrequency energy. To sum up, The antenna achieves an excellent radiation pattern and a high gain over the working frequency range. There is consistency between the simulation and measurement findings when the antenna is fabricated and measured experimentally.

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