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Experimental validation of a dual-band printed antenna array operating at 2.45/5.8 GHz with a high efficiency for wireless power transmission applications

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ABSTRACT

This paper presents a simple dual-band antenna element with a rectangular patch designed for the industrial, scientific, and medical bands at 2.45/5.8 GHz. The antenna achieves satisfactory simulated performance at both resonant frequencies, including a reflection coefficient below -10 dB, a voltage standing wave ratio (VSWR) not exceeding 1.2, radiation efficiencies of approximately 90% at 2.45 GHz and 95.55% at 5.8 GHz, and bandwidths of 125.80 MHz around 2.45 GHz and 308.60 MHz around 5.8 GHz. Building on this single-element design, an antenna array configuration comprising two elements etched on a Taconic TLY-5 substrate is developed. The two rectangular patches are connected via a T-junction to a 50 Ω excitation port. The proposed array's effectiveness is validated through simulations using three electromagnetic solvers and experimental measurements. The fabricated antenna array demonstrates improved performance, including a measured return loss of -16.78 dB at 2.45 GHz and -20.61 dB at 5.8 GHz, a VSWR not exceeding 1.5 (1.34 and 1.22 at 2.45 and 5.8 GHz, respectively), input impedance close to 50 Ω, high gain exceeding 8 dBi, bandwidths of 179.50 MHz at 2.45 GHz and 462.90 MHz at 5.8 GHz, and high radiation efficiencies of 96.54% at 2.45 GHz and 98.65% at 5.8 GHz. With only two patches, the proposed antenna array offers a compact, efficient, and practical solution for wireless power transmission applications, particularly for small wireless devices like rectenna systems, due to its simplicity, compact design, and excellent radiation efficiency.

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1. INTRODUCTION

Wireless power transmission (WPT) technology has attracted significant attention as a promising alternative to traditional wired systems, offering numerous advantages. These include eliminating poor connections and spark generation, reducing the complexity of wiring, and enhancing operational safety [1]. WPT is extensively utilized in various domains, including the medical field [2], industrial production [3], [4], transportation, and military. Recently, there has been growing interest in rectenna systems [5], which present an eco-friendly solution for generating electricity to power electronic devices. The rectenna (short for rectifying antenna) is a device that converts electromagnetic energy, typically in the form of radio waves or microwaves, into direct current (DC) electricity. This system enables devices to operate independently, without requiring a connection to a main power socket [6]. The antenna part of the rectenna captures the electromagnetic waves and converts them into an alternating current (AC) signal. The rectifier subsystem converts the AC signal into DC electricity, this is typically done using diodes that rectify the current. The rectenna consists of three primary components [7]–[9]: a receiving antenna, a rectifier circuit, and a load. A standard rectenna's block diagram in study [1].

In this paper, the focus is on investigating the antenna part of the rectenna. The antennas are part of the broader concept of wireless energy transfer, used in applications ranging from charging electronic devices to powering drones and other remote systems. This focus shifts back to the antenna, emphasizing its role as a crucial component of the rectenna system. Acting as the interface between ambient electromagnetic energy and the rectifying circuit, the antenna's design plays a pivotal role in determining the performance and efficiency of the entire system. Antennas with high directivity and gain focus on the incoming energy enhance system performance. The key design parameters concerning the antenna are listed as follows. First, the frequency of operation aims for the antenna to resonate at the desired frequency for maximum energy capture. Secondly, the impedance matching aims to match the impedance of the antenna with the rectifying circuit to minimize power losses and ensure optimal operation with high performance. Finally, the appropriate selection of conductive materials and substrates aims to reduce losses and enhance energy transfer efficiency. Numerous antenna designs have been explored in the literature, incorporating various shapes for the radiating element, including square, hexagonal, pentagonal [10], and triangular configurations. These designs are developed to meet specific requirements, such as polarization type (linear [11] or circular [12]), operational modes (*e.g.*, single frequency at 2.45 or 5.8 GHz, dual-band [13], or multi-band [14]), and substrate material selection (*e.g.*, FR4-epoxy, Rogers RT/Duroid 5880, and Taconic TLY-5). While these designs offer distinct advantages, a significant challenge lies in optimizing antenna performance, particularly regarding impedance matching, gain, directivity, and radiation efficiency. Most antennas in the literature achieve a high peak gain and a high efficiency by using more patches such as the works in [2], [3], [10], [15]. Unfortunately, these antennas do have not a compact volume. Additionally, a major challenge remains in achieving dual-band operation, as many existing designs are optimized for a single mode, limiting their versatility and applicability in modern systems. These limitations highlight the necessity of an improved design that enhances both gain and efficiency while enabling reliable dual-band functionality. In response to these challenges, we introduce an efficient antenna design featuring a rectangular patch with an inset feed line and a truncated ground. This design operates in dual bands within the industrial, scientific, and medical (ISM) spectrum, specifically at 2.45 and 5.8 GHz. Expanding on this single antenna design, we also develop an antenna array configuration consisting of two patches to assess its performance against the single antenna. The performance of the antenna array is evaluated using three electromagnetic solvers: computer simulation technology microwave studio (CST MWS), high-frequency structure simulator (HFSS), and advanced design system (ADS). To verify the proposed antenna array's effectiveness, experimental tests are conducted. Measurements taken with a PNA-X network analyzer include reflection coefficient, voltage standing wave ratio (VSWR), and input impedance. Furthermore, the antenna is tested in an anechoic chamber to determine its gain and radiation pattern in both the azimuthal (horizontal) and elevation (vertical) planes. Finally, a comparative analysis is provided to demonstrate the superior performance of the proposed antenna array compared to existing designs in the literature.

The paper is organized into four sections. Section 1 provides a brief overview of the study antenna's context. Section 2 presents the proposed antenna design, detailing its specifications, followed by the design of the antenna array and its constructed prototype. Section 3 outlines the simulation and measurement results, accompanied by their interpretations. Section 4 concludes the paper by summarizing its key points and discussing potential directions for future research.

2. ANTENNA CONSTRUCTION STRUCTURE

The basic structure of a printed antenna consists of three layers: the ground plane, the substrate, and the radiating element (*i.e.*, the patch) [15]. The design process for creating this type of antenna follows the flowchart presented in [1]. According to the diagram, the selected substrate material is Taconic TLY-5 (its permittivity $\varepsilon_r = 2.2$, its thickness $h = 1.52$ mm, and its loss tangent equals 0.0009). The dimensions of the radiating element are calculated using (1) to (5) [16]. Equation (1) calculates the patch width, while (2) determines the effective dielectric permittivity. The patch length, as shown in (3), is adjusted by a distance, as indicated in (4), to account for fringing effects, with the wavelength defined by (5).

$$W = \frac{C}{2f_r}\left(\frac{2}{\varepsilon_r+1}\right)^{0.5} \quad (1)$$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1 + 12\frac{h}{W}\right]^{-0.5} \quad (2)$$

$$L = \frac{\lambda}{2} - \Delta L \quad (3)$$

$$\Delta L = 0.412h\left(\frac{\varepsilon_{reff}+0.3}{\varepsilon_{reff}-0.258}\right)\left(\frac{\frac{W}{h}+0.264}{\frac{W}{h}+0.8}\right) \quad (4)$$

$$\lambda = \frac{c}{f_r} \quad (5)$$

2.1. Single antenna design

This subsection presents the design of a single printed antenna, illustrating its evolution through various stages, including top and bottom views as shown in Figure 1. The top view of the initial antenna design is depicted in Figure 1(a), and its bottom view is shown in Figure 1(b). The design features a rectangular radiating element and a 50 Ω feed via port excitation. The dimensions of this antenna are provided in both Figure 1(a) and Figure 1(b). In the next stage, the patch in Figure 1(a) is modified by incorporating an inset feed line, as shown in Figure 1(c), with its corresponding dimensions. Its ground plane is truncated on both sides, as seen in Figure 1(d).

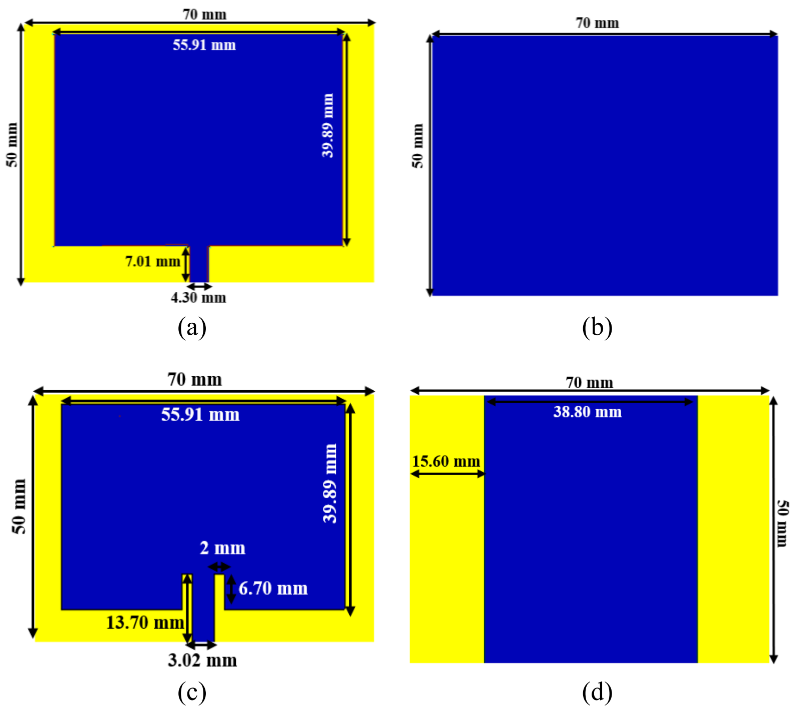

Figure 1. Proposed single antenna evolution steps: (a) initial top view, (b) initial bottom view, (c) modified top view with inset feed, and (d) modified bottom view with truncated ground

2.2. Antenna array design and its constructed prototype

Building on the design of the single antenna, see Figure 1(c) and Figure 1(d), a printed antenna array is proposed, consisting of two identical patches linked by a T-junction power divider. The top view of the antenna array is shown in Figure 2(a), while its bottom view is depicted in Figure 2(b), with the dimensions of all layers (*i.e.*, ground, substrate, and patches) provided. This antenna array is fabricated using printed circuit board (PCB) technology through laser etching. The prototype's top view is shown in Figure 2(c), and its bottom view is displayed in Figure 2(d). The prototype is connected to a PNA-X network analyzer for measuring its electrical characteristics, as shown in Figure 2(e). Additionally, the prototype is tested in an anechoic chamber, as seen in Figure 2(f), to measure its gain and radiation pattern in both the azimuthal (horizontal) and elevation (vertical) planes.

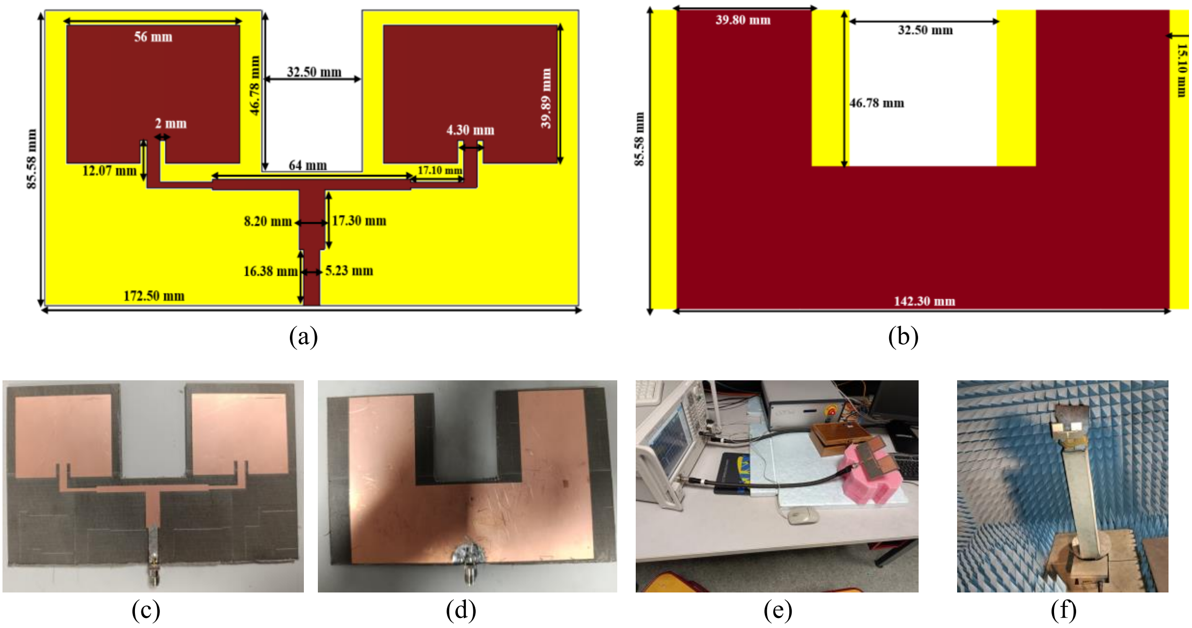

Figure 2. Proposed antenna array and its prototype: (a) front view of the proposed antenna, (b) back view of the proposed antenna, (c) top view of the fabricated antenna, (d) bottom view of the fabricated antenna, (e) fabricated antenna connecting with the PNA-X network analyzer, and (f) fabricate antenna tested in an anechoic chamber

3. SIMULATED AND MEASUREMENTS RESULTS

The simulated results for the single antenna as depicted in Figure 1(c) for its top view and Figure 1(d) for its bottom view, including the reflection coefficient (S_{11}) and VSWR versus frequency, are shown in Figure 3. A parametric study on the ground width of this single antenna design is performed and analyzed, as seen in Figure 3(a). The optimal ground width is found to be 38.80 mm (in the red color) as shown in Figure 3(a), as it yields the best resonance at both resonant frequencies: 2.45 GHz (lower frequency) and 5.8 GHz (upper frequency), which correspond to industrial, scientific, and medical (ISM) band. Figure 3(b) presents the variation in the reflection coefficient obtained using computer simulation technology Microwave Studio (CST MWS) and high-frequency structure simulator (HFSS) solvers, based on this optimal ground width of the single antenna which equals 38.80 mm. As shown in Figure 3(b), both solvers confirm that the proposed antenna operates effectively at the two resonant frequencies of 2.45 GHz and 5.8 GHz with a $S_{11} \ll -10$ dB . The variation of VSWR, calculated using CST MWS and based on this optimal ground width of the single antenna, is shown in Figure 3(c) and verified by the HFSS solver. From Figure 3(c), the VSWR does not exceed 1.5 at both operating frequencies using both solvers. The proposed single antenna demonstrates excellent performance at both operating frequencies in terms of a good level of adaptation at the port and a maximum transfer of energy with low losses.

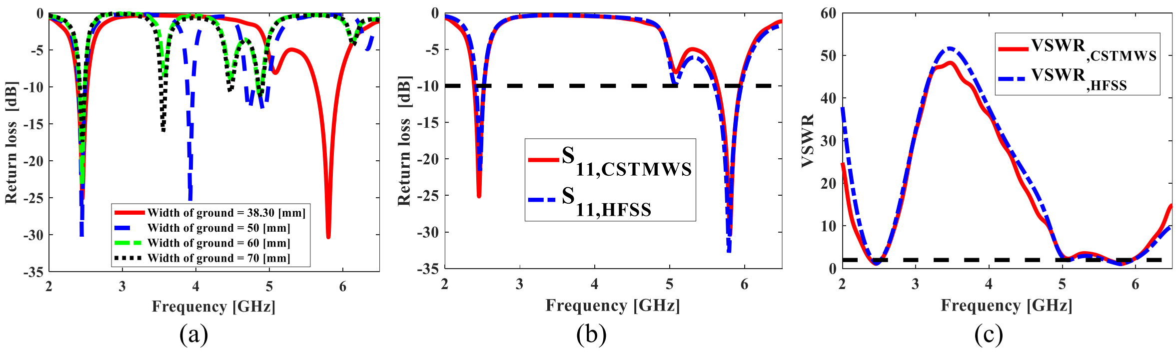

Figure 3. Simulated results of single antenna: (a) parametric study, (b) return loss, and (c) VSWR

The obtained results from the proposed antenna array are shown in Figure 4. Figure 4(a) shows the obtained return loss for the proposed antenna array via various solvers (CST MWS, HFSS, and ADS) and the measured one according to frequency. The proposed antenna array operates at two resonant frequencies which are 2.45 and 5.8 GHz in ISM band. From Figure 4(a), the proposed antenna array is well-adapted because its return loss value is less than -10 dB ($S_{11} \ll -10$ dB) in both operating frequencies. Figure 4(b) represents the curve of VSWR using two solvers: CST MWS and HFSS and the measured VSWR. Based on Figure 4(b), this proposed antenna array has a VSWR value closer to 1 which proves this antenna array transfers the maximum energy with low losses. Figure 4(c) shows the real part of the input impedance of the proposed antenna array.

The gain, directivity, and radiation efficiency of both the single antenna and the array are shown in Figures 5(a), 5(b), and 5(c), respectively. The numerical results for gain, directivity, and efficiency demonstrate that the antenna array achieves superior performance compared to the single antenna. This improvement aligns with the primary objective of designing the antenna array, which is to enhance gain, directivity, and efficiency.

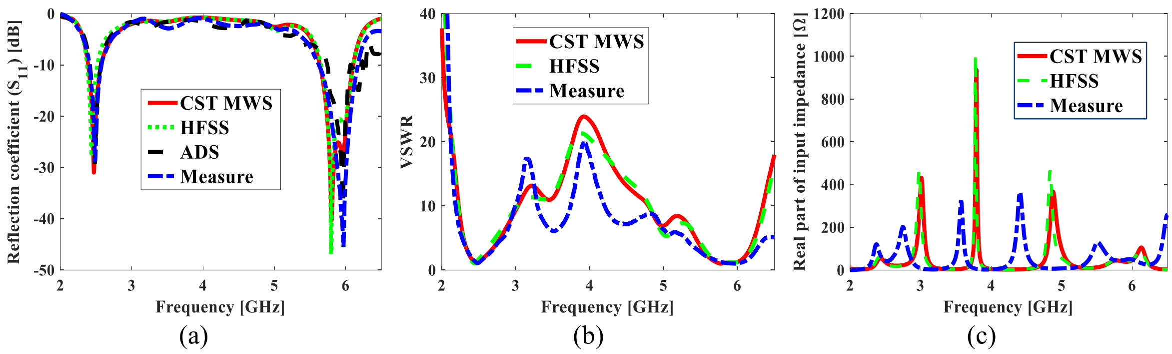

Figure 4. Simulated results of proposed antenna array (return loss, VSWR, and input impedance): (a) return loss, (b) VSWR, and (c) input impedance

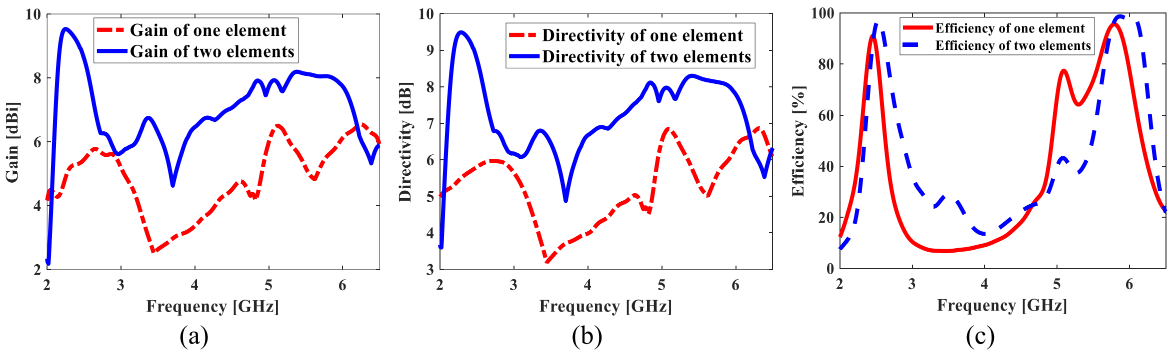

Figure 5. Simulated results (gain, directivity, and efficiency): (a) gain, (b) directivity, and (c) efficiency

Figure 6(a) represents the measured gain at 2.45 GHz when the proposed antenna array is tested in an anechoic chamber, as shown in Figure 2(f), the measured gain at 2.45 GHz is equal to 8.10 dBi. The measured radiation pattern in the vertical plane at 2.45 GHz at 0°, 45°, and 90° is shown in Figure 6(b). In addition, Figure 6(c) illustrates the measured radiation pattern in the horizontal plane at 2.45 GHz for the same angles.

Figure 7 shows the equivalent circuit model of the proposed antenna array. Figure 7(a) shows the essential components which are the resistance denoted R, inductance denoted L, and capacitance denoted C which will be adjusted using the genetic algorithm until the return loss is less than − 10 [dB] for both resonant frequencies (2.45 and 5.80 GHz). Figure 7(b) shows the return loss obtained by ADS. The reflection coefficient equals − 24.755 [dB], and − 20.037 [dB] at 2.45 and 5.8 GHz respectively. So, the equivalent circuit model of the proposed antenna array is well-matched at both resonant frequencies.

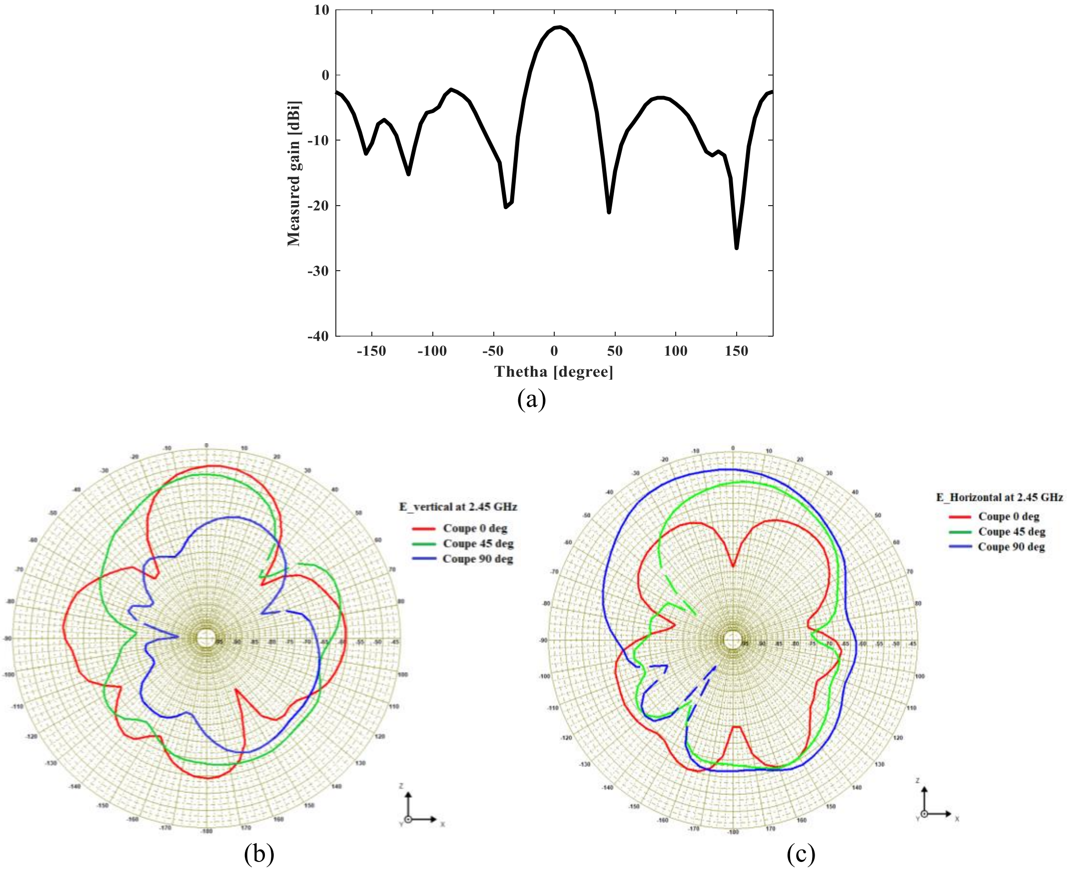

Figure 6. Measured results at 2.45 GHz (gain, and radiation pattern) (a) gain, (b) E vertical at 2.45 GHz, and (c) E horizontal at 2.45 GHz

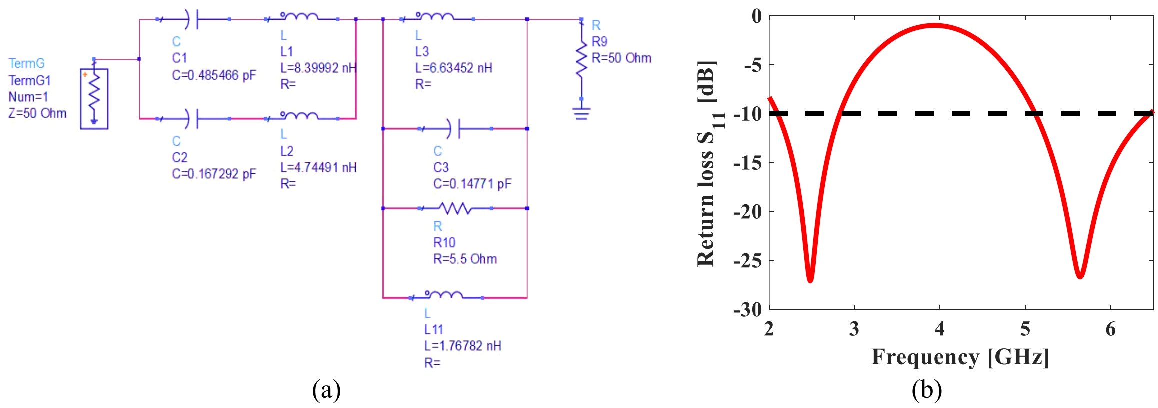

Figure 7. Measured results at 2.45 GHz (gain, and radiation pattern) (a) equivalent circuit and (b) return loss

Table 1 summarizes the numerical results obtained from CST MWS for both the single antenna and the developed antenna array. These results highlight the primary goal of the antenna array: to improve performance metrics such as gain, directivity, radiation efficiency, and bandwidth, while preserving the advantages of the single antenna, including excellent return loss and VSWR characteristics. To further validate the proposed antenna array's effectiveness, Table 2 presents results obtained from various electromagnetic solvers alongside measured data. Additionally, Table 3 offers a comparative analysis of the proposed antenna design against existing designs, demonstrating its effectiveness in terms of the number of patches, return loss, gain, and efficiency. Our proposed antenna array will be used in all applications that rely on WPT in a variety of areas, such as wireless sensor networks [17], automotive applications for charging electric vehicle batteries [18], brain-machine interface systems in medicine, and wireless mobile chargers.

Table 1. Numerical obtained results by CST MWS for single antenna and antenna array

Parameter	At 2.45 GHz		At 5.8 GHz	
	Single antenna	Antenna array	Single antenna	Antenna array
Coefficient reflection [dB]	-24.37	-21.61	-30.07	-38.86
VSWR	1.12	1.18	1.06	1.02
Gain [dBi]	5.34	8.91	5.77	8.05
Directivity [dB]	5.74	9.03	5.77	8.11
Efficiency [%]	90	96.54	95.55	98.65
Bandwidth [MHz]	125.80	179.50	308.60	462.90

Table 2. Comparison among measured and simulated values for various solvers (antenna array)

Parameter	CST MWS		HFSS		ADS		Measure	
	At 2.45 GHz	At 5.80 GHz	At 2.45 GHz	At 5.80 GHz	At 2.45 GHz	At 5.80 GHz	At 2.45 GHz	At 5.80 GHz
Return loss [dB]	-21.61	-38.86	-23.36	-46.35	-17.73	-16.31	-16.78	-20.61
VSWR	1.18	1.02	1.145	1.01	1.3166	1.3722	1.34	1.22
Input impedance [Ω]	53.119	44.5535	47.4135	49.5838	55.85	57.37	56.8441	43.4806

Table 3. Comparison of the proposed antenna design with existing antenna designs

Reference	Operating frequency [GHz]	Antenna type	Return loss [dB]	Peak gain [dBi]	Total efficiency [%]
[19]]	2.4; 5.2	1 × 2	-20.6; -16	1.6; 3.95	80; 67
[20]	1.8; 2.1; 2.45; 2.6	1 × 2	-13.08; -16.67; -11.48; -12.51	3.28; 3.84; 4.47; 4.74	85; 89; 84; 84
[21]	1.8	2 × 2	-25	9.2	-
[22]	2.4	7 elements	< -50	15.8	94
[23]	2.4	2 × 4	-26.2	17.5	-
[24]	2.4	1 × 1; 1 × 2 ; 2 × 2 ; 2 × 3; 2 × 4	-17.33; -19.29; -12.26; -26.86; - 42.33	5.28; 7.20; 11.0; 10.4; 10.3	-
[25]	2.45	3 elements	-32.886	11.24	89.41
[26]	2.45; 5.8	-	< -20; < -30	7.8; 6.8	90;80
[27]	2.4; 5.8	-	-	4; 6.81	-
In this paper	2.45; 5.8	2 elements	CST MWS: -21.61; -38.86 Or measure: -16.78; -20.61	CST MWS: 8.91; 8.05	CST MWS: 96.54; 98.65

4. CONCLUSION

A dual-band printed antenna array operating at 2.45/5.80 GHz within the industrial, scientific, and medical (ISM) band has been designed, analyzed, simulated, fabricated, and measured. The antenna array is implemented on a Taconic TLY-5 substrate with a thickness of 1.52 mm, a dielectric constant of 2.2, and a loss tangent of 0.0009. It is fed by a 50 Ω microstrip line and consists of two identical rectangular radiators. To achieve a compact design, the ground plane and substrate are truncated. The design was simulated using CST MWS, HFSS, and ADS to validate its performance across multiple electromagnetic solvers. The fabricated prototype was tested using a PNA-X network analyzer, showing good agreement with simulation results. The antenna demonstrated superior performance, including a measured return loss of -16.78 dB at 2.45 GHz and -20.61 dB at 5.80 GHz, a VSWR below 1.5 (1.34 at 2.45 GHz and 1.22 at 5.80 GHz), input impedance close to 50 Ω, a high gain exceeding 8 dBi, bandwidths of 179.50 MHz at 2.45 GHz and 462.90 MHz at 5.80 GHz, and high radiation efficiencies of 96.54% at 2.45 GHz and 98.65% at 5.80 GHz. This antenna array is highly suitable for energy harvesting and wireless power transmission applications.

Future work will focus on the measurement of radiation patterns, gain, and radiation efficiency at both operating frequencies. Additionally, a rectifying circuit will be developed and integrated with the antenna to create a system capable of powering devices such as smartphones, drones, sensors, and electric vehicles.

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