



A Novel Design of a Microstrip Antenna Array for Wireless Power Transfer Applications

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Abstract

In this article, a new 1×4 microstrip antenna array operating at 2.45 GHz for wireless power transfer (WPT) applications is proposed. Besides the array configuration, and for maximum power transfer to the load, the performed design puts into contribution three other design techniques which are: defected ground structure, electromagnetic band gap and multilayer topology. The suggested antenna, printed on an FR-4 dielectric substrate, achieves significantly improved directivity and gain of 13.30 dBi and 10.90 dBi, respectively. Furthermore, an input reflection coefficient around -38 dB, a frequency bandwidth of about 180 MHz and a side lobe level (SLL) below -20 dB are obtained. It is also observed that the antenna gain is close to its maximum performance across the entire operating frequency band (2.36–2.54 GHz). A prototype of the performed design is fabricated and tested. Experimental results show a good agreement between simulated and measured input reflection coefficients. The achieved performances make the developed structure highly suitable for WPT systems.

Keywords Microstrip antenna array · Defected ground structure · Electromagnetic band gap · Multilayer technique · Wireless power transfer

1 Introduction

With the rapid progress in wireless communication technology, there is a constant demand for development of new wireless applications and devices. To feed these devices, traditional power supply cords are getting inappropriate as they limit mobility. Moreover, this solution is not feasible for powering wireless sensors located in inaccessible media. In this context, wireless power transfer (WPT) systems are gaining a considerable interest as they are indicated in various areas such as internet of things (IoTs) and wireless sensor networks (WSNs) devices as well as radio-frequency identification (RFID) [1–3]. A

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particular example of these applications concerns implanted medical devices' powering to enable communication with external equipments. WPT refers to transmission of electrical energy through electromagnetic field (EMF) without a physical link. It includes a power source connected to a transmitter which converts the power into a time-varying EMF radiated through an antenna device. On the other side, a receiver captures power and converts it into a current which is used to feed the load. Consequently, antennas used in WPT systems are required to have high gain to direct and deliver maximum power to the receiver. Usually, microstrip patch antennas (MPAs), which present several advantages such as low profile, conformable to planar and non-planar surfaces, simple and inexpensive to fabricate, achieve low gain. To overcome this limitation, antenna arrays were proposed. Although these structures can achieve considerable gain levels, they are usually not enough for WPT applications. Enhancements and modifications were introduced in antenna designs to refine the gain and the efficiency. Different techniques such as electromagnetic band gap (EBG) [4, 5], multilayer parasitic elements [6, 7], metamaterials [8, 9], and defected ground structure (DGS) [10–12] are commonly used for this purpose. Moreover, the feeding network is an important parameter that should be taken into consideration in antenna array designs. In this context, the parallel (or corporate feed) technique is usually used to feed the array elements.

Several designs of antenna arrays for WPT applications have been reported in the last decade [13–17]. In [13], a gain of 7.8 dBi along with a directivity of 10.8 dBi have been obtained with a 2×2 array, whereas a gain and a directivity of, respectively, 10.8 dBi and 14.5 dBi have been attained with a 2×4 structure. In [14], the effect of a multilayer structure height and the number of layers on an antenna gain has been investigated. It has been observed that the gain increases by steps of 1–2 dBi while increasing the number of layers and the antenna height up to a certain limit before starting to decrease. In [15], a 4×4 antenna array operating at 16 GHz using a flexible Kapton polyimide substrate for a far-field charging unit has been reported. In [16], a WPT system operating at 2.45 GHz and consisting of a transmitting and a receiving array of, respectively, 36 and 5 elements has been designed. In [17], a 4×4 phased array antenna operating in the ultra-wide frequency band [3.1–10.6 GHz] has been presented.

This work aims to develop a novel MPA array operating at 2.45 GHz frequency band with a gain and a directivity greater than 9 dBi and 12 dBi, respectively, and a side lobe level (SLL) lower than -20 dB. To take advantage from different design techniques for gain and directivity improvement, the performed design combines four techniques including array pattern, DGS, EBG as well as multilayer parasitic elements techniques. The developed antenna is printed on the low cost widely available FR-4 substrate material having a dielectric constant of 4.3, a thickness of 1.5 mm and a loss tangent of 0.02. The structure provides a directivity and a gain of 13.30 dBi and 10.90 dBi, respectively. These qualitative performances indicate that the proposed structure is well-suited for applications where WPT is required.

2 Antenna Array Structure and Design Procedure

The geometry and dimensions of the proposed antenna are shown in Fig. 1. It consists of a layer including four rectangular MPA (RMPA) elements, three power dividers, three DGS units, EBG cells, and a second layer loaded with parasitic elements.

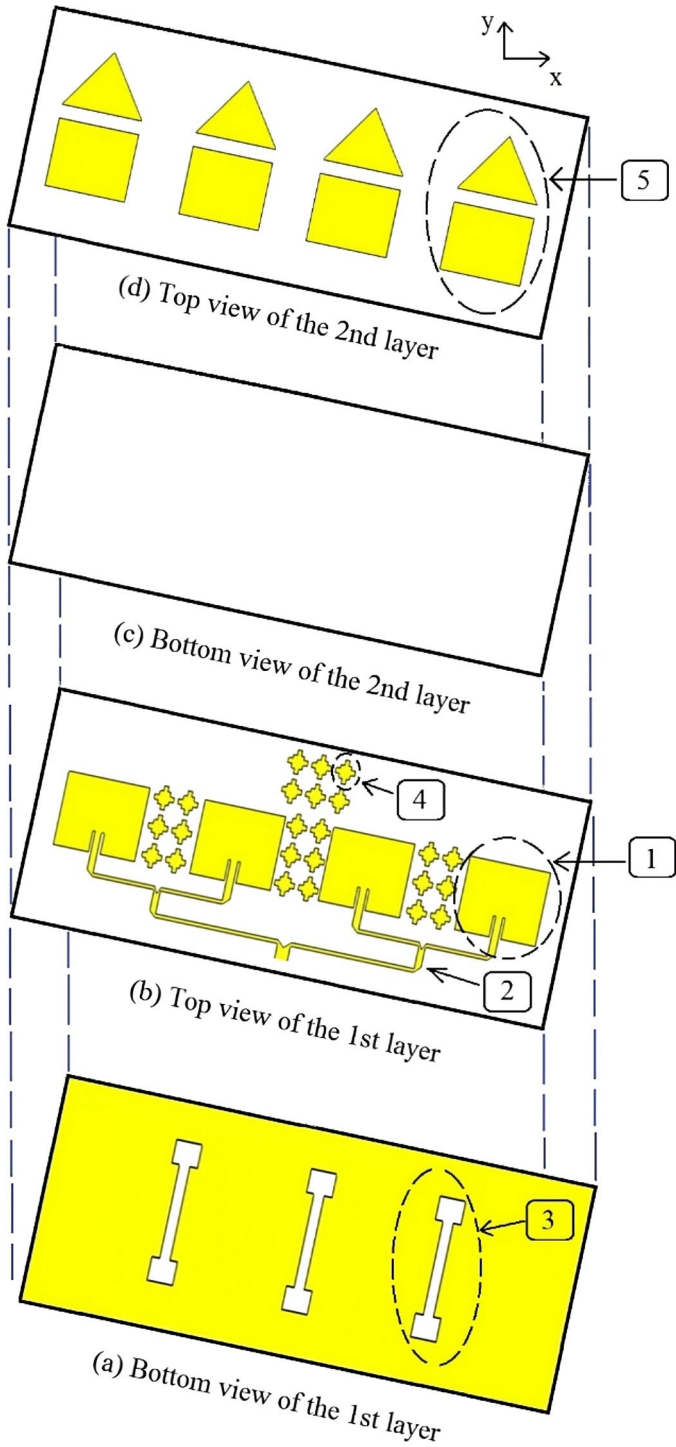
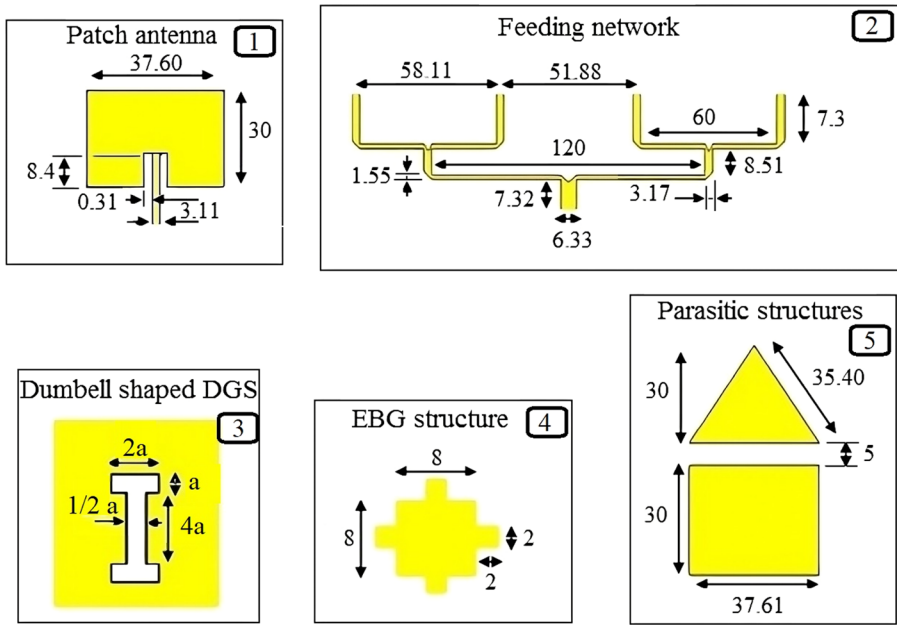


Fig. 1 Geometry of the proposed 1 × 4 double-layered microstrip antenna array



(e) Details of each structure

Unit: mm

Fig. 1 (continued)

The design process, carried-out using the CST electromagnetic simulator, starts by considering a conventional inset fed RMPA operating at 2.45 GHz based on its advantages over other patch geometries [10]. However, though this single element structure achieves mono-band operation suitable for Wi-Fi applications, it exhibits poor gain and directivity, and, hence, it does not meet WPT requirements. Consequently, to enhance these fundamental parameters, an array configuration, first consisting of two elements, is designed.

To this end, it is required to design a parallel feeding network, known as a power divider, to split the power equally between the 1×2 array elements. This is performed by splitting the 50-Ohms feed line into two similar 100-Ohms feed lines. Although the two-element antenna array achieves a gain of 5.62 dBi and a directivity of 8.8 dBi, this does not meet requirements of WPT systems. To improve these parameters, the design is extended to a 1×4 antenna array configuration. The resulting structure achieves a gain and a directivity of, respectively, 7.8 dBi and 11.9 dBi which are still below the fixed objectives.

At this stage, the need for further improvement of the antenna performances while keeping the same size requires using other techniques. This has been performed by introducing successively DGS units, EBG cells, and, finally, a parasitic layer as detailed in the following subsections.

2.1 Using DGS Units

Defected ground structure (DGS) is a technique which consists on etching defects in the ground plane of a microstrip structure. Depending on their shape and location in an antenna

ground plane, the defects result in modifications of the structure performances [10–12]. In this work, this technique is used to enhance the frequency bandwidth and the isolation between the array elements. Three popular dumbbell DGS units, of the shape illustrated in Fig. 1e, are etched in the ground plane. The units are located at equal distance between projections of neighboring antenna array elements in the ground plane as shown in Fig. 1a. Another configuration consisting of five similar and equally spaced DGS units is also investigated. Table 1 illustrates the impact of the DGS unit width (a) on the antenna performances. It is noticed from this Table that the first configuration, based on three units of 5 mm width, extends the frequency bandwidth from 141.32 to 247.31 MHz, whereas the gain increases slightly by 0.06 dBi. It is also observed that using higher number of DGS units does not provide any improvement. Consequently, the configuration with three units is selected in the final design.

2.2 Using EBG Cells

An electromagnetic band-gap (EBG) structure consists of periodically distributed metallic cells placed around a microstrip antenna radiating patch [4, 5]. In this step, rather than using DGS units, the EBG cells, illustrated in Fig. 1e, which help reducing the mutual coupling between the array elements, are introduced. Several EBG shapes are reported in literature, however, a shape close to the one in [18] for planar array gain enhancement is considered in this work. Figure 2 shows different arrangements of EBG cells around the patches and Table 2 summarizes the respective antennas characteristics. It is observed from this Table that structure 1, with 24 cells arranged around the radiating elements, yields enhanced characteristics with a gain and a directivity of 8.22 dBi and 12.10 dBi, respectively. The objective of a directivity greater than 12 dBi being satisfied, remains the gain which is still lower than 9 dBi. Consequently, neither the DGS nor the EBG technique achieves simultaneously the required performances. For this reason, the two techniques are used together in the next step.

2.3 Using Both DGS Units and EBG Cells

This stage combines both DGS and EBG techniques, considered separately in the previous steps. The investigation of the resulting structure, illustrated in Fig. 3, has led to the antenna characteristics summarized in Table 3. As compared to the configuration

Table 1 Antenna array performances with DGS units

Number of DGS units	Three (03)			Five (05)		
	4	5	6	4	5	6
Width a (mm)						
S_{11} (dB)	-26.60	-30.69	-24.3	-26.60	-30.55	-24.20
VSWR	1.29	1.13	1.31	1.19	1.15	1.23
Gain (dBi)	7.94	7.98	7.90	7.94	7.98	7.85
Directivity (dBi)	11.80	11.80	11.60	11.80	11.80	11.60
SLL (dB)	-15.20	-15.80	-15.20	-15.30	-15.80	-14.80
BW (MHz)	192.92	247.31	185.70	195.90	246.50	185.90
Efficiency (%)	41.60	42.80	41.80	41.60	42.80	41.80

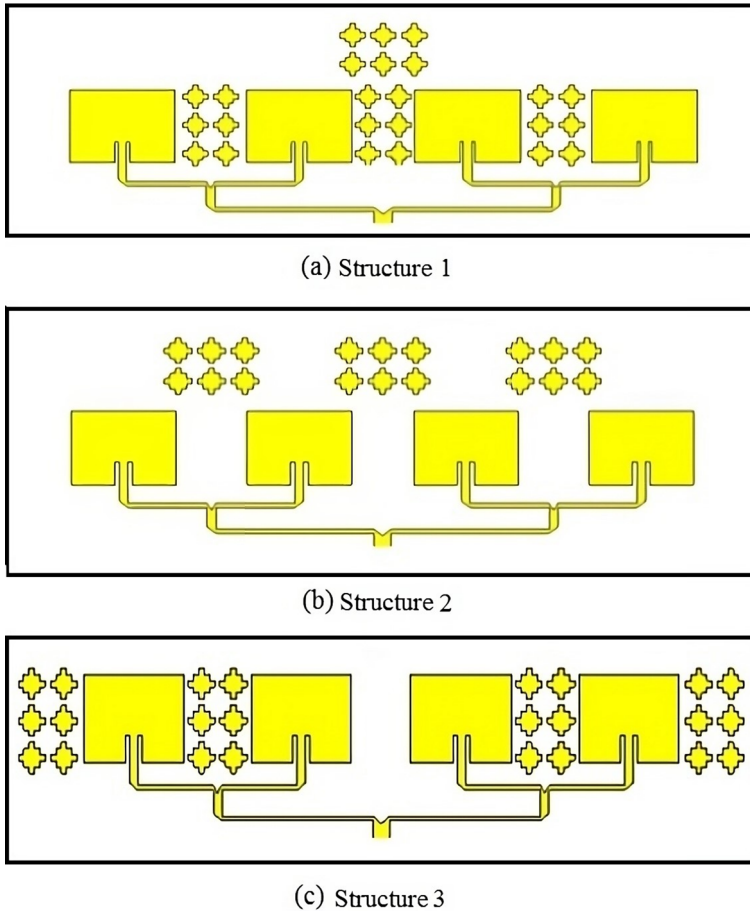


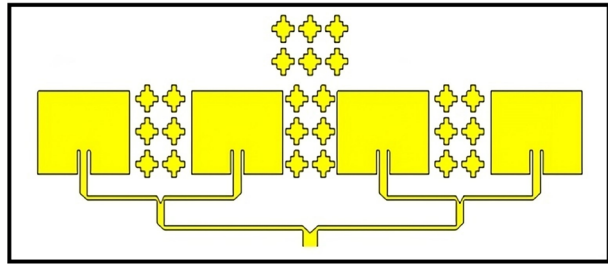
Fig. 2 EBG cells arrangements around the antenna array

Table 2 Antenna array performances with EBG cells

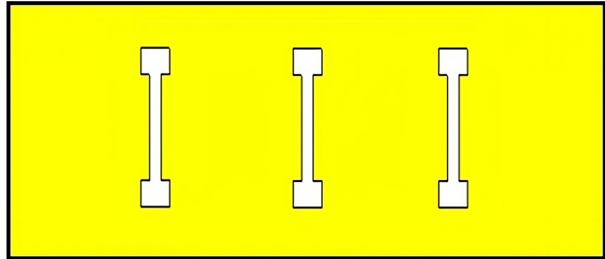
Structures	Structure 1	Structure 2	Structure 3
S_{11} (dB)	-28.28	-24.54	-27.90
VSWR	1.08	1.12	1.08
Gain (dBi)	8.22	8.14	8.16
Directivity (dBi)	12.10	12.10	12.10
SLL (dB)	-15.20	-14.40	-14.90
BW (MHz)	137.50	143.63	115.98
Efficiency (%)	40.70	40.10	40.20

based on the relatively more performant EBG technique, it is noticed from this Table that combining the two techniques provides a slight improvement of the gain, from 8.22 to 8.32 dBi, and an enhancement of the SLL from -15.20 to -15.60 dB. Again, as

Fig. 3 Antenna array with DGS units and EBG cells



(a) Top view



(b) Bottom view

Table 3 Antenna array performances with DGS units and EBG cells

S_{11} (dB)	BW (MHz)	VSWR	Gain (dBi)	Directivity (dBi)	SLL (dB)	Efficiency (%)
-27.32	183.49	1.08	8.32	12.10	-15.6	41.30

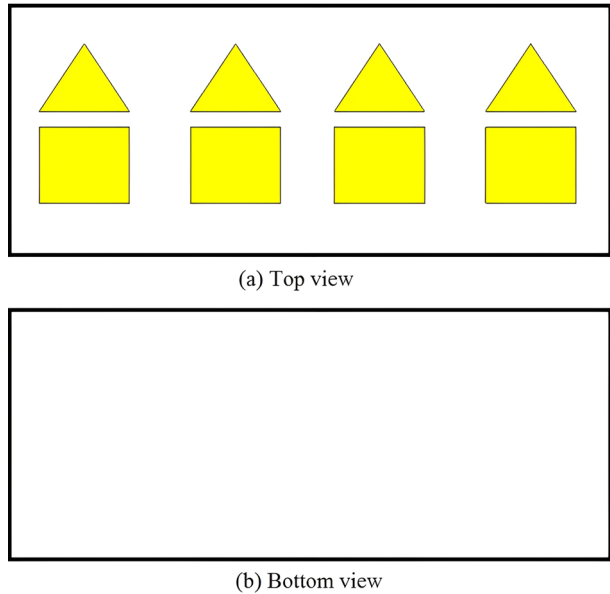
the fixed objectives are not satisfied yet using DGS and EBG techniques, the multilayer parasitic elements technique is put into contribution in the next design step.

2.4 Using Multilayer Parasitic Elements

Multilayer structure microstrip antenna consists on using two or more patch-loaded substrate layers to enhance the antenna performances. Adding layers with parasitic elements to a microstrip antenna helps improving the structure gain and directivity [7, 19]. The parasitic layer is fixed on the top of the antenna and separated from it by an air-gap. Several layers can be used, but the space issue and the fabrication complexity should be taken into consideration. This technique is introduced in this work to further improve the performances achieved by the DGS and EBG techniques. To this end, a layer containing rectangular parasitic elements is added to the antenna array [20]. Additional triangular parasitic elements are also added as illustrated in the layout of Fig. 4.

Varying the height of the air-gap layer modifies the whole structure thickness. This affects the gain without modifying the substrate layer thickness. Accordingly, the air-gap height is varied gradually while observing the impact on the antenna gain. In doing so, it has been noticed that a height below 5 mm results in a gain lower than the one obtained

Fig. 4 Geometry of the parasitic layer



with a single layer. However, as the air-gap height is increased starting from 5 mm the antenna gain increases up to some height beyond which the gain decreases. The analysis has shown that using one parasitic layer with an air-gap height of 6.4 mm yield better results than the fixed objectives as detailed in the next section.

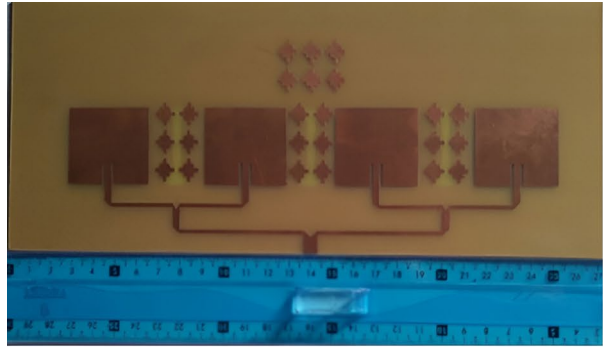
3 Fabrication and Measurements

A prototype of the proposed 1×4 double-layered antenna array with an overall dimension of $223 \times 69.83 \times 9.4 \text{ mm}^3$ is fabricated and tested. A photograph of the fabricated structure is shown in Fig. 5. Figure 6 illustrates a comparison between the measured and the simulated input reflection coefficients. The two graphs show quite similar profiles indicating a good agreement between simulated and measured results. The acceptable shift is attributed to various factors associated to tolerances in physical parameters, mainly the substrate layer, accuracies in the fabrication process affecting the geometrical dimensions, soldering imperfections as well as the experimental conditions.

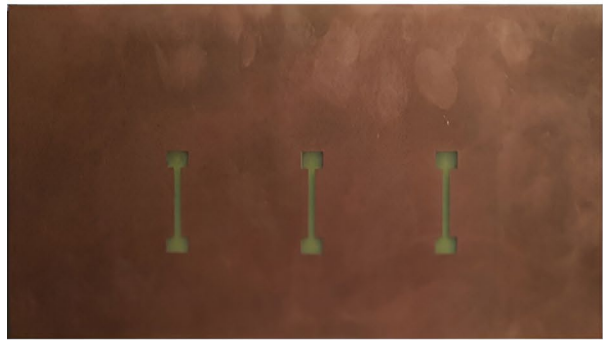
The antenna operating frequency bandwidth ($|S_{11}| \leq -10 \text{ dB}$) is slightly greater than 180 MHz and its return loss is nearly 38 dB.

The 2-D far-field radiation patterns at the resonant frequency in E- and H- planes are depicted in Figs. 7 and 8, respectively. It is observed that the main lobes of the co- and the cross-polar components in the E-plane show levels of 10.9 dB and -9.54 dB , respectively. In the H-plane, these parameters are 10.6 dB for the co-polar and -85.4 dB for the cross-polar component. The contrasts between the co- and the cross-polar components, greater than 20 dB, indicate good polarization purity in both principal planes. Figure 9 shows the antenna array 3-D radiation pattern at the resonant frequency with a maximum directivity

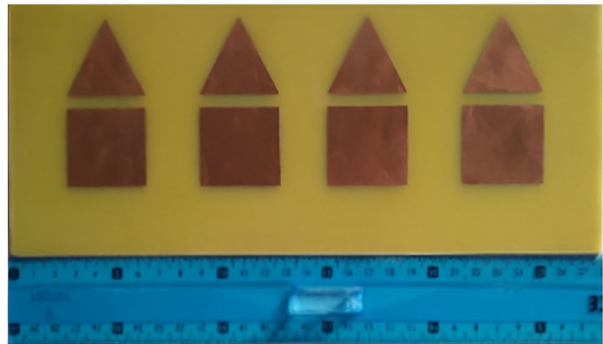
Fig. 5 Photographs of the fabricated double-layered antenna array prototype



(a) Top view of the 1st layer



(b) Bottom view of the 1st layer



(c) Top view of the 2nd layer



(d) Side view of the proposed antenna array

of 13.30 dBi in the maximum direction of propagation, and side lobes lower than -8.00 dBi denoting a performant SLL of less than -20 dB.

Furthermore, Fig. 10, which illustrates the maximum gain versus frequency, indicates that the antenna gain is greater than 10 dBi over the frequency interval extending

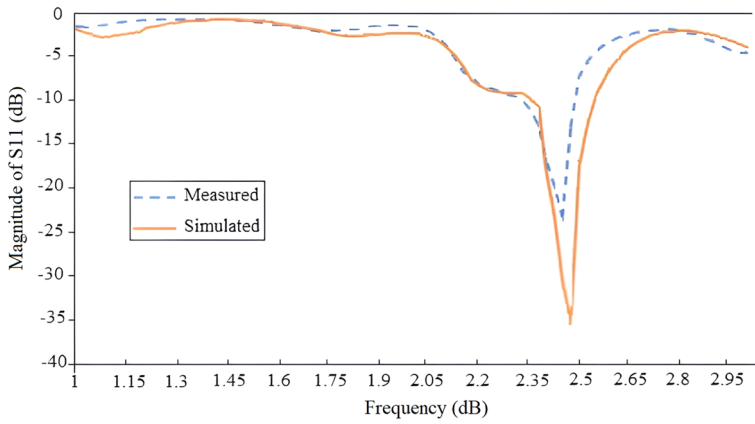


Fig. 6 Simulated and measured input reflection coefficients of the proposed antenna

Fig. 7 E-plane radiation pattern at 2.45 GHz. **a** Co-polarization and **b** cross polarization

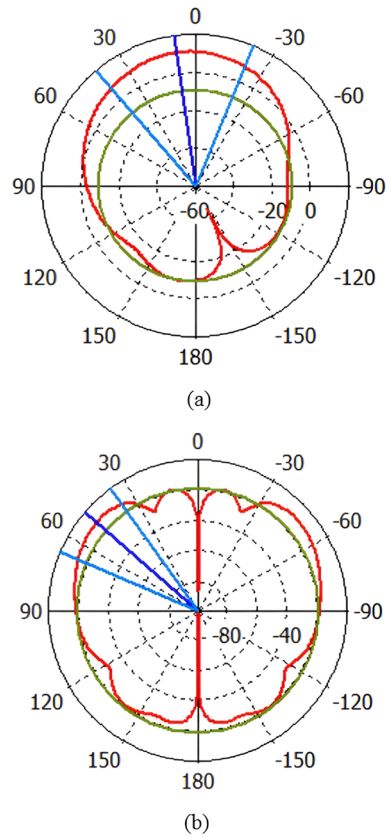


Fig. 8 H-plane radiation pattern at 2.45 GHz. **a** Co-polarization and **b** cross polarization

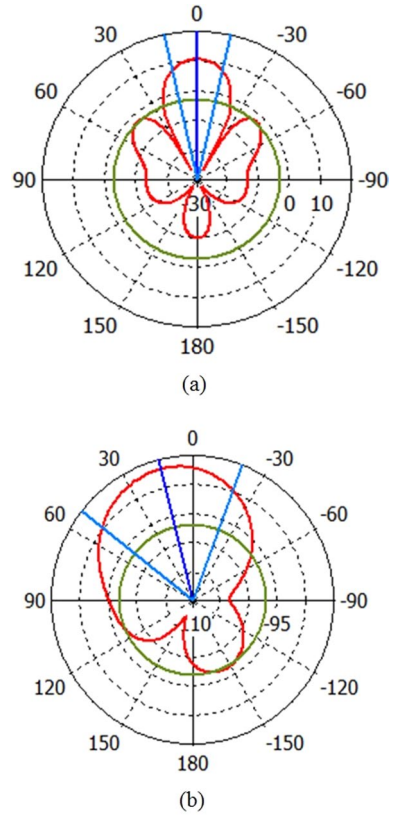
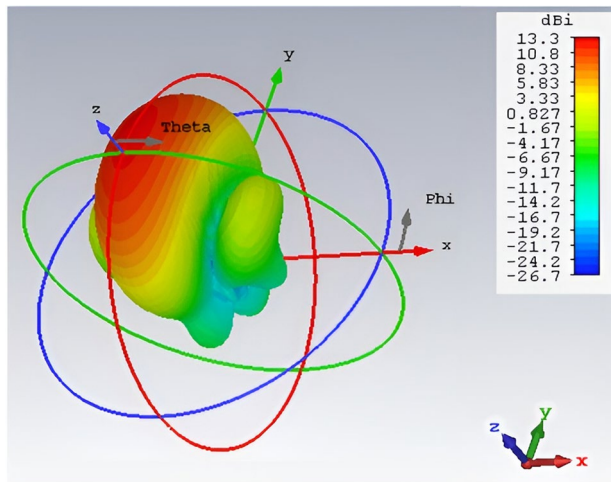


Fig. 9 3D radiation pattern



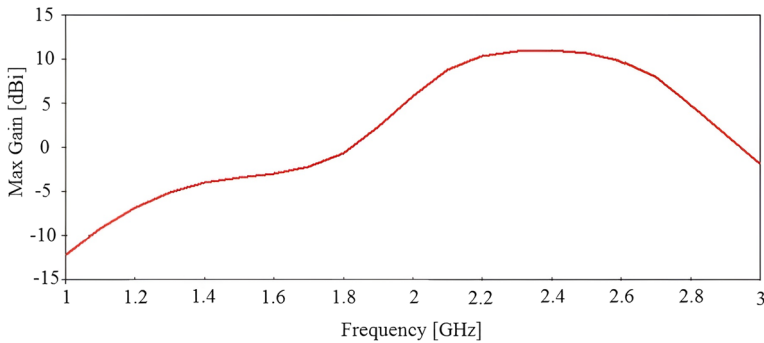


Fig. 10 Maximum gain versus frequency

from 2.2 to 2.6 GHz with a peak level of 10.90 dBi at the resonance. It is also observed that the gain is close to its maximum performance across the entire operating frequency band, which extends from 2.36 to 2.54 GHz. This feature keeps maximum power transfer to the receiver despite any operating frequency variation within the frequency bandwidth.

Another parameter characterizing WPT systems is the maximum power transfer that can be handled by the antenna. This power capacity, P_{max} , is evaluated by [14]:

$$P_{max} = \left(\frac{E_{br}}{E_0} \right)^2 P_{in} \quad (1)$$

where P_{in} is the input power set to 1 Watt, E_0 is the maximum electric field intensity, and E_{br} is the vacuum breakdown threshold (6.4 MV/m in S band [21]). The maximum electric field intensity is estimated to 8663 V/m resulting in a significant power transfer capacity of around 0.574 MW.

Finally, Table 4 summarizes the proposed antenna performances whereas Table 5 illustrates a comparison with recently reported designs. This table indicates that the developed structure exhibits interesting features in terms of frequency bandwidth, SLL, -3 dB beamwidth, directivity and gain. These attractive performances indicate that the developed antenna is well-suited for WPT systems, and used in the large variety of applications where wireless power transfer is required.

Table 4 Antenna array performances with DGS units, EBG cells and a parasitic layer

S_{11} (dB)	BW (MHz)	VSWR	Gain (dBi)	Directivity (dBi)	SLL (dB)	Efficiency (%)
-37.94	180.53	1.03	10.90	13.30	-20.30	57.54

Table 5 Comparison with other published designs

References	Proposed work	[13]	[14]	[15]	[16]	[17]
Application	WPT					
Material	FR-4	FR-4	Aluminum PTFE spacers	Flexible Kapton polyimide	FR-4	FR-4
Number of elements	4	4	16	16	36	16
Operating frequency (GHz)	2.45	2.45	2.45	16	2.45	3.1–10.6
Frequency band (MHz)	180.53	76.50	400	240	175	Multiband: 420, 690, 1670
S_{11} (dB)	-37.94	-24.20	-30.00	-28.22	-28	-
Beamwidth (°)	24.7	-	-	29.4	-	-
Directivity (dBi)	13.30	10.80	-	-	-	-
Gain (dBi)	10.90	7.80	13.00	16.38	-	12.2
SLL (dB)	-20.30	-21.90	-20.00	-	-	-
Polarization purity	Good	-	-	Good	-	-
Efficiency (%)	57.54	50.11	75–90	36.67	-	-

4 Conclusion

In this work, a new antenna array for WPT applications operating at 2.45 GHz is developed. The performed design is based on different techniques including array configuration, DGS units, EBG cells as well as a multilayer topology. The suggested antenna achieves a maximum gain of 10.90 dBi, a directivity of 13.30 dBi, and a peak-to-side lobe level suppression of -20.30 dB. Furthermore, the structure exhibits an operating frequency bandwidth around 180 MHz and a return loss of nearly -38 dB. The designed antenna array is prototyped and tested and a good agreement is observed between simulated and measured return losses. The obtained performances confirm that the proposed structure is a promising candidate for WPT systems.

Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Mokrane DEHMAS, Mouloud CHALLAL, Ali AROUS and Hamza HAIF. The first draft of the manuscript was written by Mouloud CHALLAL and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest All authors declare that they have no conflict of interest.

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