High gain 3×3 Circularly Polarized Antenna Array With V-Shaped Slots for Wireless Power Transmission

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Abstract: Wireless power transmission is an alternative energy solution to supply power to the electrical and electronics equipment without wired connection. In this paper we present an antenna array design which is the crucial part in a Rectenna (rectifier + antenna) system. The developed design consists of a new 3×3 antenna array having an operating frequency of 2.45 GHz with inclined slots at the center of each antenna element to improve the circular polarization and V-shaped slots to enhance the bandwidth around the operating frequency. The proposed design provides a high gain of 9.14dBi and overall size of 26.18×11.86 cm^2.Simulation and measurement results are in good agreement which make this antenna very suitable for WPT applications.

Keywords: WPT, Rectenna, Antenna array, Circular Polarization, V-shaped Slot.

1. Introduction

Over 100 years ago, the concept of Wireless Power Transmission (WPT) that was theorized, developed and demonstrated by Nikola Tesla in the early 1900s, have known a great advance and successful impact in many real life applications. Then it has been a topic of continued interests since the last several decades. Wireless power transmission is the transmission of electrical energy from a power source to an electrical load without wired connections. It is useful in cases where interconnecting wires are inconvenient, hazardous, or impossible.

In particular, a WPT system converts direct current (DC) power to microwaves, transmits that microwave radiation in the free space to a target. Once DC power is converted to microwaves and transmitted into space, a system that requires power needs to receive and convert microwaves back to useful DC power. The device used for this reception and conversion is called a rectenna (rectifying antenna), this term is derived from the fact that a rectenna is comprised of an antenna coupled with a rectifying circuit. The rectenna device was created by W.C. Brown in his groundbreaking work in WPT in the 1960s in Raytheon Technology Company in USA. He demonstrated its ability in 1964 by powering a helicopter from the solely through microwaves. Obviously, WPT could revolutionize our energy sector, our information and communication technology sector, our environment sector, and our medical sector. First, the proposed SPS (Solar Power Satellite) would bring clean energy from natural sunlight in space to power Earth without using the resources of our planet. This could fundamentally change the landscape of resource planning and energy renewable strategies. This idea was first proposed in 1968 and all of the experiments have only been carried out in terrestrial laboratories. The SPS satellites would be put in high earth orbit at geosynchronous location. This would allow them to receive light 99% of the year.

Hence the development of efficient rectennas has become a vital research topic [1]. In fact, a rectenna representing the key element for EM energy harvesting and wireless power transmission applications, thus device designed to collect the energy associated to a free propagating EM wave and to transform it into Direct Current (DC) energy. Recently, several rectenna devices have been proposed in the literature investigating several operating frequencies [2],[3]and [4]. Further Components of microwave power transmission have traditionally been focused at 2.45 GHz and recently moving up to 5.8 GHz, which has a smaller antenna aperture area than that of 2.45 GHz. Both frequencies have comparably low atmospheric loss, cheap components availability, and reported high conversion efficiency.

A block scheme of the basic architecture of a rectenna is illustrated in Figure 1. The Radio Frequency (RF)/microwave EM energy is collected by an antenna and converted into DC power by a rectifying circuit (the rectifier). In order to improve the rectenna RF-to-DC

conversion efficiency two blocks can be added respectively between the antenna and the rectifier, also between the rectifier and the load. In addition it's necessary to further reduce the transmission loss and to increase the input voltage of the rectifier circuit [5]. These blocks act as filtering and as matching sections, they should be optimized in order to simultaneously fulfill the following functions:

- to match the antenna and the load to the rectifier;
- to preserve the antenna from re-irradiating the high order harmonics generated by the rectifier (to this end the block between the antenna and the rectifier should be a pass-band filter);
- to preserve the load from any RF signals (to this end the block between the rectifier and the load should be a DC pass filter) [6].
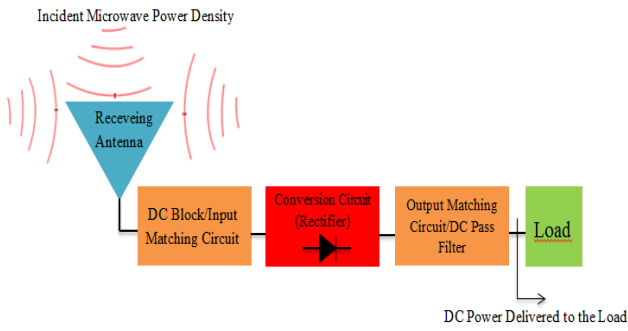

Fig. 1. The Block diagram of the Rectenna

Recently many kinds of rectenna were reported, including linear [7],[8],[9] and [10] and circular polarization [11],[12],[13],[14] and [15] by using different configurations. The advantage of a circularly polarized (CP) rectenna over a linearly polarized one is that nearly constant DC output can be achieved where the receiver or the transmitter changes its direction. However most of the cited papers and others existing in the literature incorporate a single antenna or an antenna array with linear polarization, furthermore the researches focus to interconnect many rectennas in order to achieve high DC output (power and/or voltage), and as a result the size of the global system can be increased, which makes it difficult to be embedded in an electronic system. WPT involves a very wide range of research and development topics such as device technology, system architecture, antenna systems, material engineering, transmission safety, interference issue, application development, and market economy. This paper proposes a receiving antenna array design with circular polarization for rectenna system with high performances. The developed array has to be used in order to harvest a large amount of incoming power at 2.45GHz. The antenna here presented consists of a new 3×3 antenna array; the six elements are square patches antenna having inclined slots at the centers and a V-shaped slot at the corners of each patch, which are connected to a T-junction power divider in order to match the antenna input impedance to 50Ω.

2. Antenna Array Design Procedure

In rectenna application, it is necessary to design antennas with very high directive characteristics to meet the demands of long-distance links. Since the aim is to use the rectenna to transfer DC power through wireless links for a long distance, this can be only accomplished by increasing the electrical size of the antenna in order to enhance the rectenna conversion efficiency (Equation 1) by increasing the captured microwave power at the input of the rectifier.

$$\eta_{RF-DC} = \frac{P_{DC}}{P_{Received}} \times 100\% \qquad (1)$$

Where P_{DC} is the DC power produced at the load resistance R of the rectenna and $P_{received}$ is power received at the antenna, which can be calculated from the Friis transmission equation (Equation 2).

$$P_{Received} = \left(\frac{\lambda}{4\pi r}\right)^2 P_t G_t G_r \qquad (2)$$

Where G_r is the gain of the receiving antenna, λ is the operating wavelength, G_t and P_t are the gain and transmitted power of the transmitting antenna, and r is the propagation distance.

We present in this section the antenna array design which consisting of a 3×3 square patch antenna etched on FR4 substrate (ε_r= 4.4, thickness = 1.58 mm, tan δ = 0.025), in each antenna elements we have applied two methods, the first one is an inclined slot at the center to obtain the circular polarization, which is suitable for rectenna systems to preserve a constant DC voltage or power across the load where the transmitter or the receiver change it direction in the space. We have chosen this technique because it's more convenient to minimize the size of the antenna; the second one is a V-shaped slot at the corners of each antenna in order to increase the bandwidth around the operating frequency of 2.45GHz and also to improve the CP quality. Figure 2 presents the geometry shape of the developed antenna array.

As a first step in designing the 3×3 antenna array, we have started from the antenna (a) that is shown in the Figure 2(a) which is a square patch feeding by a microstrip line having a characteristic impedance of 100Ω and providing an operating frequency of 2.45GHz, in its corners we have introduced a V-shape slot in order to enhance the impedance bandwidth, also to improve the CP properties. The second step consists of increasing the number of elements to three patches (antenna (b) Figure 2(b)) in the goal to increase the antenna directivity and by preserving the operating frequency at 2.45GHz. To overcome the desired goal and improve the CP quality, the six elements are arranged in form of tree with a spacing angel between the elements of 90° (antenna (c) Figure 2(c)). This new optimized arrangement is selected in order to achieve minimum mutual coupling effect between the

array elements in the radiation pattern and to avoid grating lobes; furthermore it can occupy a reduced area.
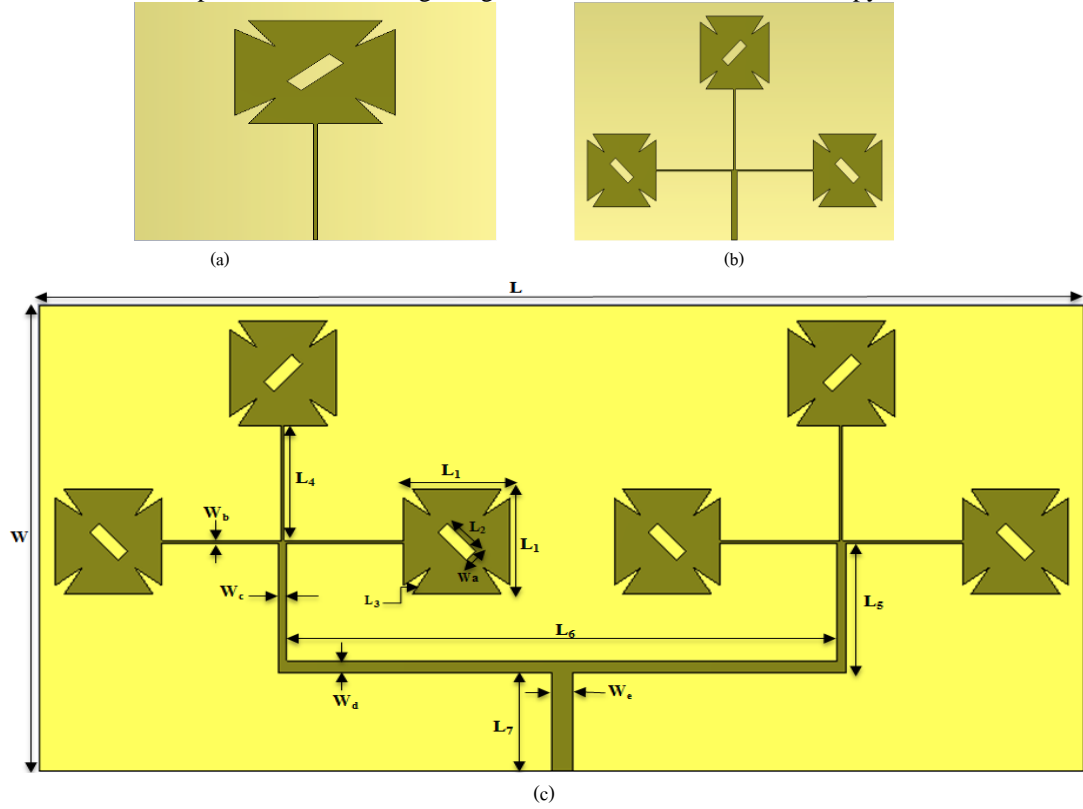

(a)

(b)

(c)

Fig. 2. Geometry Shape of the proposed 3×3 antenna array: (a) simple square antenna with V-Shape and CP, (b) antenna array of three square antenna elements, (c) 3×3 antenna array with CP

We firstly optimized the dimensions of the antenna (a) and after the antenna (b) and at last the global array to have a resonance frequency at 2.45 GHz. Optimizations were performed by means of the full-wave simulator CST Microwave Studio [16]. Table. 1 below shows the various optimized parameters of the proposed antenna array. Also the characteristic impedances of the microstrip lines have used for feeding various elements of the array are given in Table 2. Then the antenna is fabricated and the photograph of the prototype can be seen in Figure 3. An experimental measurement also has been made to validate the expected simulation results.

Table 1. Physical Dimensions of the 3X3 CP Antenna Array.

Parameters	Value (mm)	Parameters	Value (mm)
W	118.6	L_1	26.52
W_a	3.3	L_2	10
W_b	0.704	L_3	8
W_c	2.123	L_4	29.29
W_d	3.044	L_5	33.04
We	5.12	L_6	137.87
L	261.8	L_7	33.04

Table 2. Microstrip Line Impedances.

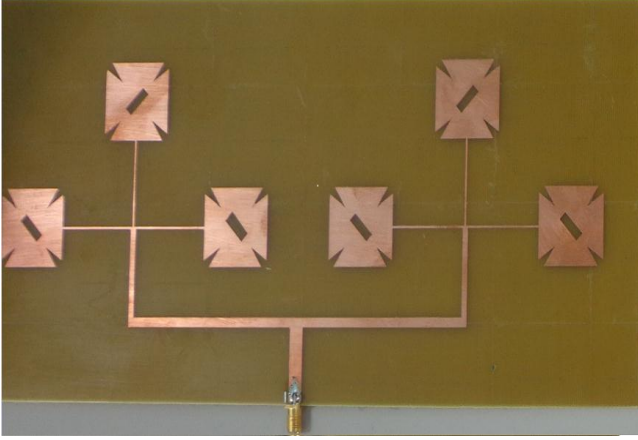| Microstrip Line Impedance	Z_b	Z_c	Z_d	Z_e
Value(Ω)	100	61.237	50	35.35

Fig. 3. Fabricated prototype of the 3×3 CP antenna array

3. Results and Discussion

This section mainly presents the major simulation and experimental results of the designed CP antenna array. Figure 4 presents the simulated return loss of the antennas (a), (b) and (c), also Figure 5 shows the radiation pattern of the two first antennas. From the graphs it's clear the three structures provide a good reflexion coefficient at the operating frequency of 2.45GHz. In addition the directivity of the antenna (b) is increased from 6.21dBi to 7.95dBi.
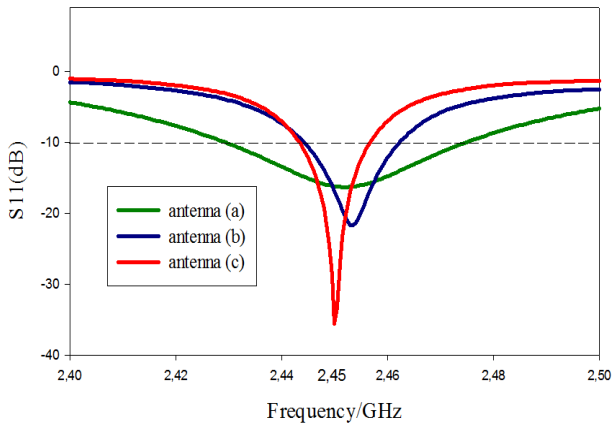
Fig. 4. The simulated return loss of the three antenna structures
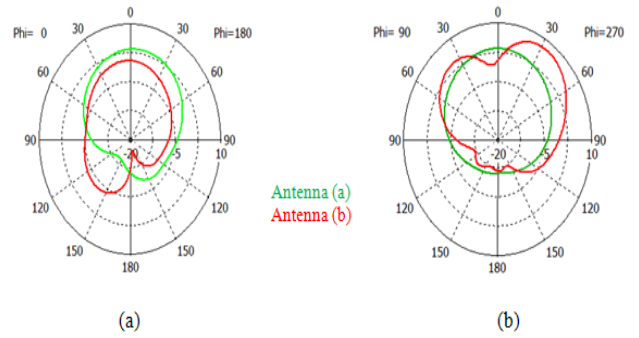

Fig. 5. 2D simulated radiation patterns ((a): E-plane (φ=0°), (b): H-plane (φ=90°)) of the antenna (a) and (b)

The performances of the CP antenna array, such as return loss, the voltage standing wave ratio(VSWR) also the axial ratio and the directivity of the developed array are evaluated. It can be noticed that this performances are greatly affected by the slots size (length and width), and distance between the various patches also by the feeding lines chosen to match all elements at the resonant frequency. Figures 6 and **7** shows the effect of length and width of the inclined slot denoted by L_S and W_S respectively on the CP antenna array's return loss ($|S11|$) (dB) and axial ratio.
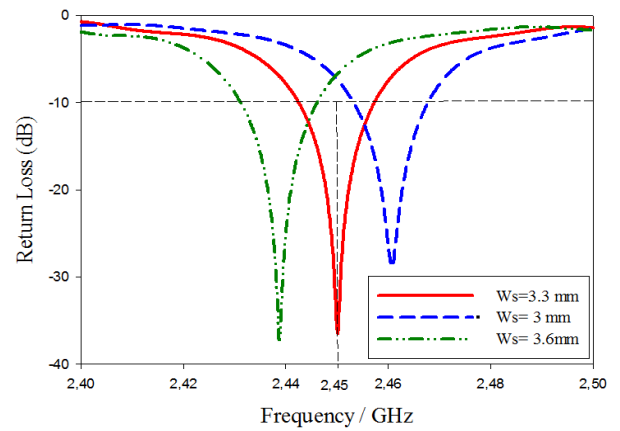
(a)
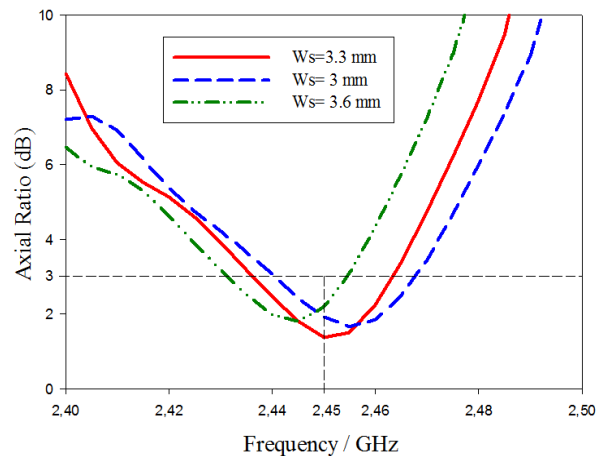
(b)

Fig. 6. Simulated results of the proposed CP antenna array as a function of slot's width (Ws) (a): return loss and (b): axial ratio
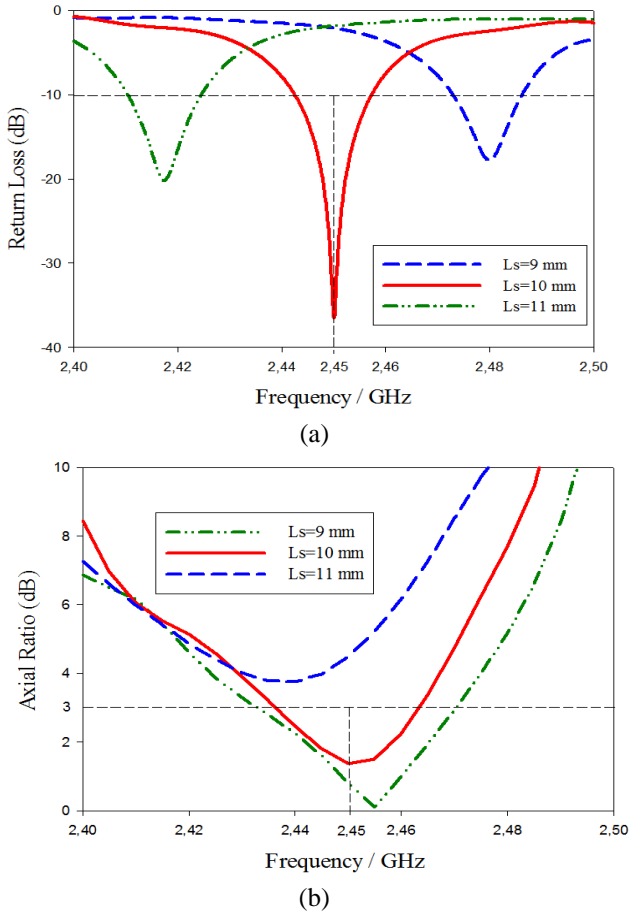

(a)

(b)

Fig.7. Simulated results of the proposed CP antenna array as a function of slot's Length (Ls) (a): return loss and (b): axial ratio

Therefore the optimum values of the inclined slot size was got at Ws=3.3mm and Ls=10mm which can provides a good matching input impedance with a good return loss of -36.54dB at the operating frequency of 2.45GHz. Moreover to achieve CP propriety, the axial ratio has to be kept below 3dB, eventually the optimum values of the inclined slot size give a better axial ratio with a minimum of 1.36dB at operation frequency of 2.45GHz. In addition

a comparison between the measured return loss and the simulated one is presented in Figure 8 It is quite clear that there is a good agreement between the measured and the simulated return loss of the proposed antenna array, which has been achieved from 2.442GHz to 2.457GHz with an impedance bandwidth of 15MHz. Then the measured return loss has been achieved from 2.42GHz to 2.452GHz with an impedance bandwidth of 32MHz. This is a 113.3% improvement over the simulation bandwidth prediction. Although there was bandwidth improvement the resonant frequency is slightly shifted and matching at the center frequency suffered, it has a return loss of -13.94 dB at 2.44 GHz. Also Figure 9 depicts the simulated VSWR of the presented CP antenna array. It can reach a minimum of 1.02 at operating frequency of 2.45GHz, and having a bandwidth of 16 MHz which is from 2.441GHz to 2.457 GHz.
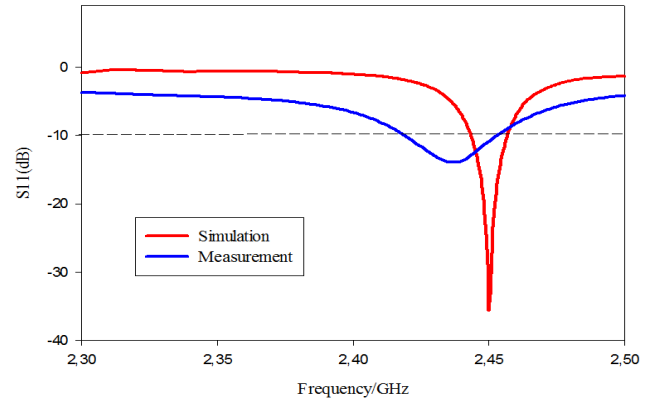

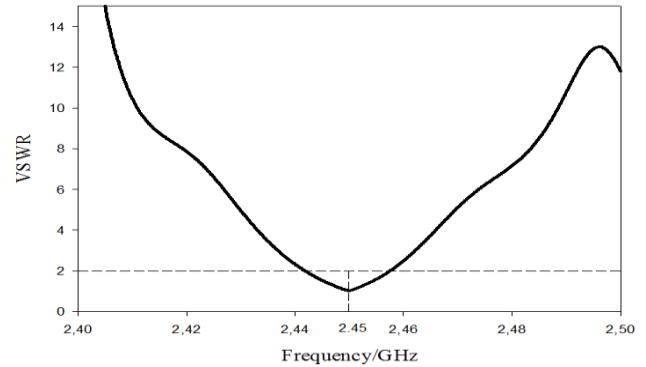Fig. 8. Simulated and Measured return loss of the proposed CP antenna array

Fig. 9. Simulated VSWR of the proposed CP antenna array

Table 3. Summary of Simulation and Measurement Results of the proposed antenna array

Parameter	Simulation	Measurement
Return loss (dB)	-37.48dB @2.45 GHz	-13.94dB@ 2.44 GHz
Bandwidth (MHz)	15	32
Fractional Bandwidth (%)	0.53	1.33
VSWR	1.02	═
Axial Ratio	1.36	═

In Figure 10, the simulated variation of the antenna input impedance versus frequency of the 3×3 CP antenna array can be seen. At the operating frequency of 2.45 GHz, the

average value of the resistance (real part) is 50 Ohms and the average value of the reactance (imaginary part) is 0-Ohms which gives the adequate input impedance matching

at the desired resonant frequency. Then Figure 11 depicts power available at the antenna port is 0.5 Watt, hence the radiated power can reach a maximum value of about 0.49 Watt, however the reflected one has a minimum value of approximately 0 Watt at 2.445 GHz, which means that the previous developed antenna array has the required potential to be used in a rectenna system with a minimum power loss.
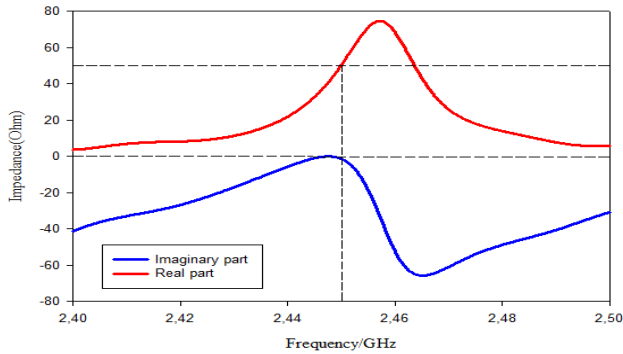

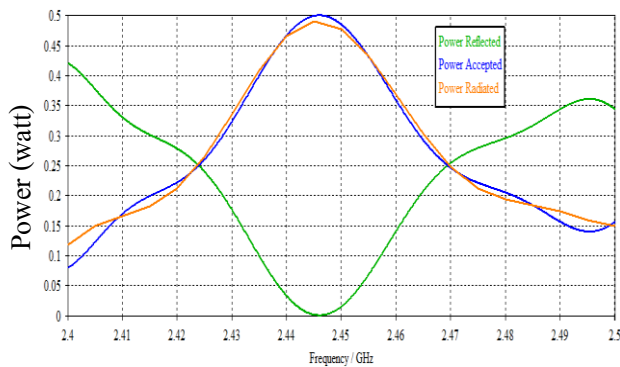Fig. 10. Simulated antenna impedance (Ohm) vs. frequency of the proposed CP antenna array

Fig. 11. Simulated powers at antenna port (Watt) vs. frequency of the proposed CP antenna array

Therefore the radiation efficiency of the proposed antenna array is evaluated for a good prediction of the proposed design to harvest high microwave power densities. Figure 12 presents the simulated radiation efficiency versus frequency of the developed CP 3X3 antenna array. From the graph it's clear that the antenna radiation efficiency has a peak efficiency of 98% at 2.445GHz.
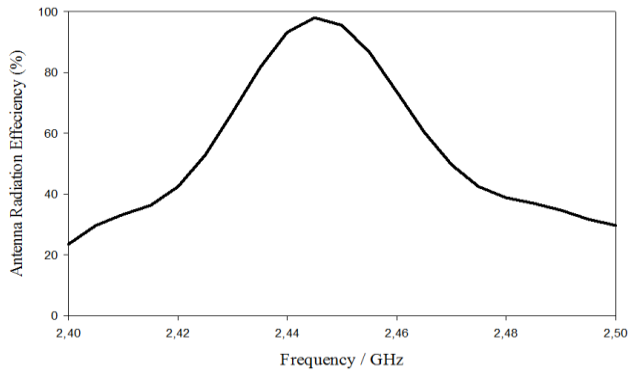

Fig. 12. Simulated Antenna Radiation Efficiency vs. frequency of the proposed CP antenna array

the simulated input power versus frequency. The input Current distribution determines how the current flows on the patches of the antenna array. Figure 13 demonstrates these results at operating frequency of 2.45GHz. From Figure 13, one can observe that a uniform high strength of current radiates along the transmission line and the boundary of the patches of the array. However, the boundary of the V-shape and the inclined slot was also support a significant radiating area.
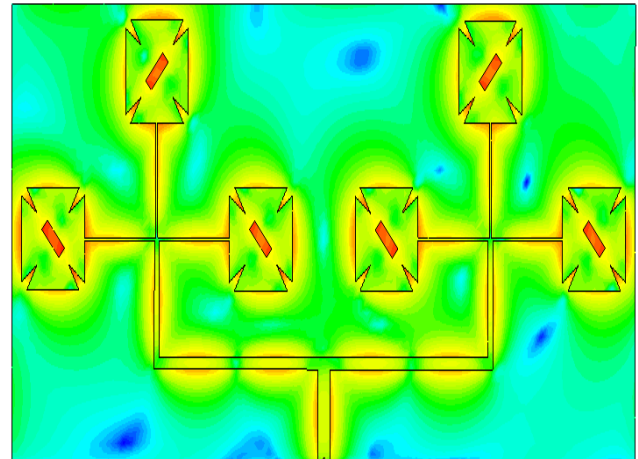

Fig. 13. Simulated surface currents at 2.45 GHz of the antenna array prototype

Then the purpose of this work is to develop an antenna array for a rectenna system with a high directional pattern and gain. To overcome this goal an antenna array is designed with six square elements with equal spacing and uniform excitation. Hence the radiation pattern is taken into account to predict the capabilities of the developed array to harvest microwave power. Array radiation gain patterns were taken in an anechoic chamber for gain and directivity verification, Figure 14 shows the simulated and measured radiation pattern for the developed CP antenna array in E-plan and H-plan at operating frequency of 2.45GHz. The above graphs shows a good agreement between measured and simulated results, that the antenna provides a directional behavior with a half power beam width of 94° and 29.8° for E-plane and H-plane respectively, with enhanced directivity of about 9.14dBi is achieved. Further the pattern is almost symmetric in both E-plane and H-plane and side lobes are small as shown in Figure 14. As expected from the calculated results, the array emits no radiation behind the ground plane.
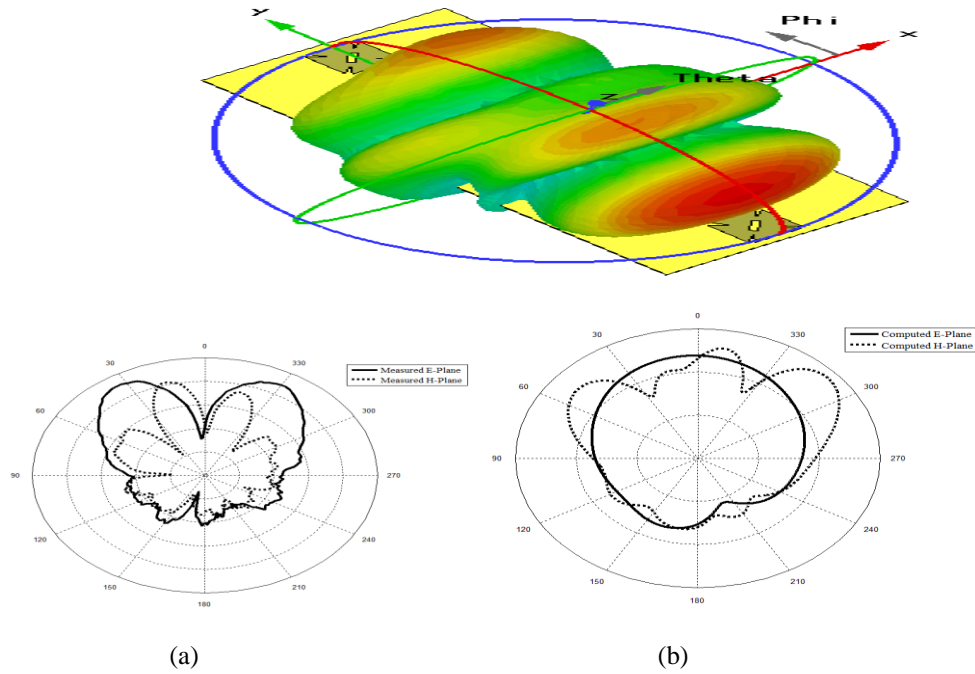
Figure 14. Three and Two-dimensional radiation pattern in E-plane and H-plane of the CP antenna array @ 2.45 GHz, (a) measured results, (b) simulated results.

Table 4. Overview of antenna array at 2.45 GHz described in the literature for Rectenna system.

Ref	Antenna type	Antenna gain
[7]	LP 4 element patch array	7dBi
[17]	CP multilayers 4 circular patch array	10.8dBi
[18]	CP 4 element patch array with reflector	6.56dB
This work	CP 6 element patch array	9.14dBi

Consequently it's clear from the above results have been presented and discussed that the proposed design has the required performances and the potential to be investigated for a rectenna system to scavenge RF microwave power at free ISM frequency band of 2.45GHz.

4. Conclusion

In this paper, a novel antenna array design at 2.45GHz has been presented; simulated, fabricated and tested. The proposed design incorporate a new circularly polarized 3X3 antenna array with high gain to enhance microwave power at the input of a RF-to-DC rectifier which in order to enhance the RF-to-DC conversion efficiency by properly choosing the dimensions and the arrangement of the array elements also the techniques of feeding various paths. The proposed design exhibits a total gain of 9.14dBi and a radiation efficiency of 98% with minimum power loss at the operating frequency .These features make the developed rectenna very suitable for wireless powered sensors and actuators.

laboratory for various measurements of the proposed antenna.

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