**TELKOMNIKA**, Vol.17, No.5, October 2019, pp.2186~2193
ISSN: 1693-6930, accredited First Grade by Kemenristekdikti, Decree No: 21/E/KPT/2018
**DOI:** 10.12928/TELKOMNIKA.v17i5.11476 

# A new configuration of patch antenna array for rectenna array applications

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***Abstract***

*The performance and advantages of microstrip patch antennas made them a field of interest for wireless power transmission applications, especially for rectenna systems where the choice of the antenna is a crucial step. In this paper, a 5.8 GHz circularly polarized patch antenna has been designed and fabricated, then mounted by using 4 elements to achieve an antenna array to enhance the captured power to be converted by the rectifier circuit. The antenna array is well matched at 5.8 GHz in terms of reflection coefficient and has a directivity of 11 dB and a gain of 6 dB. Results have been confirmed by fabrication.*

***Keywords***: *antenna array, patch antenna, rectenna, wireless power transmission*



## 1. Introduction

Recent years have been characterized by a massive development of a wide range of portable electronic devices, not only in the consumer field, such as smartphones or tablets, but also in industrial applications, such as wireless sensor networks [1-3] or in medical applications [4]. The general trend is to move more and more towards miniaturization of devices in order to facilitate their portability and integration into the everyday environment. One of the most sensitive problems to be solved is the energy source of these devices. Nowadays, the development of power transmission system by microwave beams [5] is attracting new attention in many applications.

The wireless energy transfer [6] is a process that takes place in any system where electrical energy is transmitted from a power source to an electrical load, without involving wires. Wireless power transmission is ideal in cases where instantaneous or continuous energy transfer is needed, whereas wired connections are inconvenient, hazardous, or impossible. Figure 1 shows the overall synoptic diagram of a Wireless Power Transmission (WPT) system. This system is based on three operations: the conversion of electrical energy into microwaves, the transmission of these microwaves based on the property of an electromagnetic wave to be able to transport energy, and finally their conversion into electricity after reception which consists on rectifying (after filtering) the currents produced in an antenna by a high frequency diode, the result is a continuous voltage. The device used is called a Rectenna [7-11] (rectifier + antenna) which is a key element of the power transmission system.

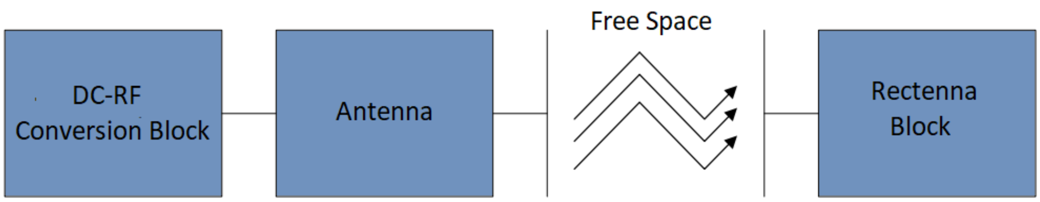



Figure 1. Wireless power transmission system

*Received October 16, 2018; Revised April 6, 2019; Accepted May 3, 2019*

Indeed, in the design process of a global wireless energy transport system, the last step, the Rectenna, is essential and must therefore be optimized in order to achieve optimal conversion efficiency. To this must be added technological and environmental constraints such as:

- Elementary rectenna networking strategy to limit the impact of the fragility of the rectifier diodes.
- Compliance with the international safety standard on electromagnetic radiation.
- Good environmental integration combined with a transparent property of the rectenna against solar radiation to make the reception surface useful.
- Ergonomic design of a manufacturable rectenna architecture (essential for the assembly of large rectenna structures).

The rectenna is typically constituted by the association of an antenna (or antenna array) with a rectifier [12] system (a Schottky diode [13]) and filtering elements. A typical rectenna block diagram is shown in Figure 2. The wireless energy can be collected by the antenna attached to rectifying diodes through filters and matching circuit (Load matching between antenna and circuit). The rectifying diodes convert the received wireless energy into DC power.

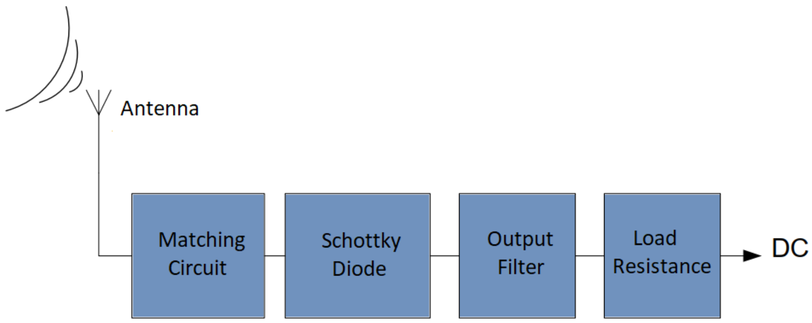



Figure 2. Block diagram of rectenna circuit

The receiving antenna will be the one that will allow us to collect microwave energy. There are no particular restrictions on the choice of antenna. It can be a dipole [14], a patch [15, 16], the technology used can be wired, plated or other. However, it is necessary to define in advance how to integrate the "rectification" module. For applications involving Wireless Power Transmission, the planar or Micro strip antennas [17, 18] are widely used. This type of antenna generally consists of a ground plane, one or more layers of dielectric substrates and one or more conductive radiating elements having different shapes: square, rectangular, triangular, circular, elliptical or other more complex shapes. Printed antennas are designed to meet the requirements of technological evolution, which is also leading to the miniaturization of electronic devices and telecommunications systems. With their small dimensions, their performance, their flexibility makes them particularly adaptable to mobile devices (satellite, aircraft, boat) and their suppleness which allows them to fit any shape of surface (flat or shaped), these antennas have proven their efficiency and tend to replace traditional antennas permanently. In addition, they are easy to fabricate, low cost, compact and they have the ability to integrate with microwave integrated circuits technology.

To optimize the power collected by the system, it is necessary to maximize the captured RF power. To do this, we can either increase the surface area of the antennas with the disadvantage of shifting the bandwidth to low frequencies, or keep the benefit of the same antennas by combining several in a network [19-23], which is the subject of extensive research. The technique proposed in this work is useful for collecting maximum power from antenna block to feed directly the rectification device. To this purpose, we have first designed a single element circularly polarized patch antenna at 5.8 GHz, printed on an FR4 substrate having dielectric constant $\varepsilon_r$=4.4, substrate thickness h = 1.6 mm and the loss tangent is 0.025. Then, we have mounted the antenna on a four elements array in order to improve the effective radiated power, the directivity, and the gain.

## 2. Single Element Antenna Design

A simple microstrip antenna consists of a very thin metal patch of dimensions L x W placed on a dielectric substrate fixed on a metallic ground plane as shown in Figure 3. The patch is actually a bit larger electrically than its physical dimensions due to the fringing fields and the difference between electrical and physical size is mainly dependent on the PC board thickness and dielectric constant of the substrate. The antenna can be considered as a resonant cavity transmission line with two open ends at a length λ/2 where the fields at the edges of the patch and the ground plan are exposed to the outside space and create the radiation. The finished dimensions of the radiating element (length and width) cause the field lines at the edges of the patch.

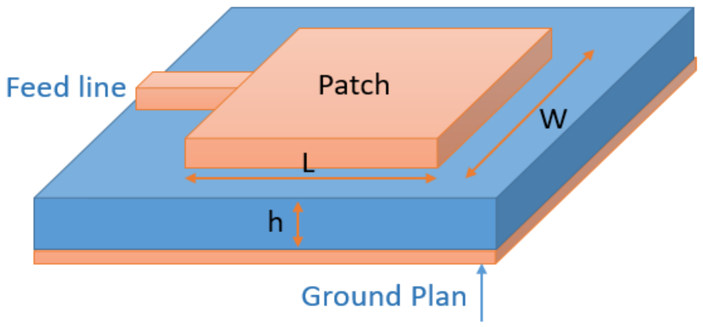



Figure 3. Rectangular micro strip antenna configuration

The antenna dimensions are calculated theorically as follow:

### 2.1. Calculation of Width (W)

For an effective radiator, practical width of the patch antenna that leads to good radiation efficiencies is given by [24]:

$$W = \frac{C_0}{2F_0}\sqrt{\frac{2}{1+\varepsilon_r}} \quad (1)$$

where $C_0$ is the free-space velocity of light i.e. $3\times10^{-8}$ m/s and $\varepsilon_r$ is the dielectric constant of material.

### 2.2. Calculation of Effective Dielectric Constant $\varepsilon_{reff}$

The value of effective dielectric constant is less than dielectric constant of the substrate, because of the fringing fields are not confined in dielectric substrate around the periphery of the patch only, but is also spread in the air. The value of this effective dielectric constant is given by [24]:

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

### 2.3. Calculation of Length (L)

The length of the patch determines the resonance frequency thus it is a critical factor for narrowband patch. Since it is not possible to accurately account the fringing field the results are not definite. Below is the equation to calculate the length of the patch [24]:

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

where ΔL is the length extension because of fringing field, which can be calculated as follow:

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

### 2.4. Feeding Mechanisms

A recurring problem in the design of printed antennas is the choice of excitation technique. Coaxial probe excitation is possible, but it is often preferable to use micro strip lines that allow several elements to be supplied at the same time, particularly in the case of antenna array. We will distinguish several types of power supplies whose main ones are: excitation by coaxial probe, by micro strip line, by proximity, and by coupling through a slot in the ground plane. The proximity feeding is done from two superposed substrates of different permittivities. The upper substrate will be chosen for low permittivity to promote radiation, while the lower substrate will be high permittivity to concentrate the electromagnetic field between the printed line and the ground plane. The aperture coupling method is considered as a solution to isolate the printed supply line from the radiating element by cutting a gap in the ground plane so that the line can be coupled to the radiating block.

This solution, which requires three levels of metallization, is attractive because it allows active components to be integrated into the printed line without damaging the antenna's radiation given the presence of the ground plane between the two. Unfortunately, parasitic rear radiation can occur, especially if you work at a frequency close to the resonance of the coupling slot. Finally, the technique used in this paper is to feed the patch antenna by micro strip line, the advantage of feeding by micro strip line on the same plane is the simplicity of implementation and easiness of fabrication. Only one substrate is used here, and we can match the impedance by using several technics.

### 2.5. Antenna Design

The electromagnetic behaviour of an antenna is complex and there are many approximation formulas in the literature that allow to approach a behaviour in a frequency band. Optimization is essential, it can be done either by measurement alone (but this requires quite expensive equipment) or by using an electromagnetic simulator to reduce the measurement steps. However, these softwares are time-consuming to compute since they use the digitized Maxwell equations. Nowadays several simulation tools have emerged, each has its advantages and limitations, but overall they all allow the design and simulation of antennas and radiating structures, the calculation of RF properties such as reflection coefficients, efficiencies, near and far field values, gains etc. Among these softwares, Advanced Design System (ADS) [25] was chosen during the work of simulation of this structure. Through its Momentum tool, it allows to perform an electromagnetic simulation based on the finite element grid of the patch and presents the gain and directivity values as well as the two and three-dimensional radiation pattern. In addition, it features a very advanced and intuitive interface for design and visualization of results. Figure 4 shows the geometry of the proposed patch antenna which operate at 5.8 GHz.

The reflection coefficient commonly referred to as S11 describes the ratio between the reflected wave and the incident wave at the antenna input. The study of the reflection coefficient is very rich in information because it provides us with information on the antenna's behavior in terms of bandwidth and level of adaptation, which are two essential characteristics of good or bad functioning. The bandwidth can be defined according to several criteria: with reference to the reflection coefficient ($|S11| \leq -10$ dB) or almost equivalent to the Stationary Wave Ratio ($SWR \leq 2$), or in relation to the efficiency (Eff ≥ 80% for example). Of course, the chosen reference level can change from one application to another. While within the antenna scientific community it is generally considered that an antenna is well matched when $|S11| \leq -10$ dB, in practice this requirement is often reduced when considering antennas for radiocommunication terminals (where a criterion of $|S11| \leq -5$ dB is common). In our case, the antenna performance in terms of impedance matching is depicted in Figure 5. It’s clear from the graph that the antenna is well matched at 5.8 GHz.

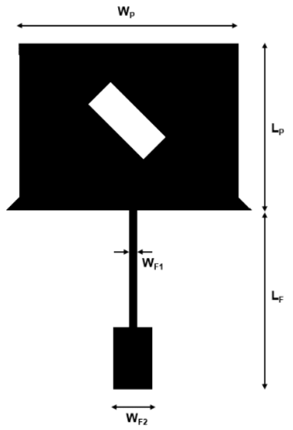



Figure 4. The proposed patch antenna

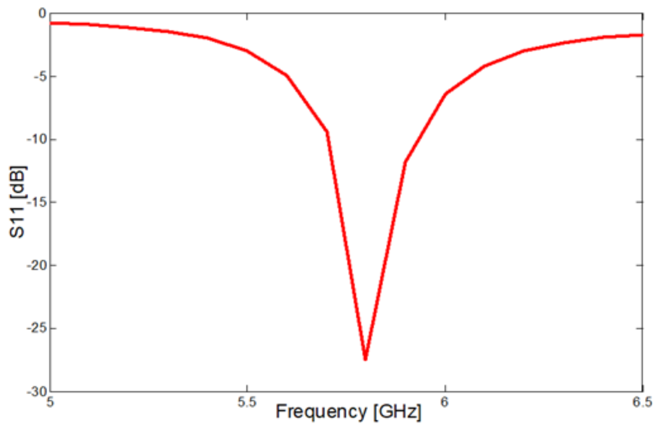



Figure 5. Simulated reflection coefficient versus frequency

## 3. Antenna Array Design

In rectenna application, it is necessary to design antennas with high directive characteristics to meet the demands of long-distance links. Hence, one element antenna could not respond to this requirement. To overcome this problem, antenna arrays are suggested in order to benefit from the advantage of superimposing the radiation of each element in the same direction to increase the overall gain and directivity of the antenna.

Several constraints can influence the design of antenna arrays. Mutual coupling, input impedance matching of the supply line and distance between the elements are the most important factors to consider when designing. The spacing between the network elements directly affect the radiation pattern and gain. If the elements are too close to each other, a coupling phenomenon reduces the gain value and when they are too far away, that affect the principal lobe and therefore reduce the directivity. In addition, the input impedance matching to 50 Ohm is necessary to ensure proper operation of the antenna. The line dimensions are calculated using Agilent's Lincalc software [25]. To feed a two-element antenna array, a T-shaped junction is used. There are several configurations of the T-junction with different calculation methods. The example used is the case where the input impedance is well matched, however, the output impedances are terminated with the double value of the input impedance. In this situation, the value of the input impedance is 50 Ohms, then the output impedance will have the value of 100 Ohms.

The simulation results of the return loss (S11) of the four-elements antenna array Figure 6 are shown in Figure 7 (a). The Momentum solver provided by Advanced Design System have been used and an FR4 substrate having dielectric constant $\varepsilon_r$=4.4, substrate thickness h=1.6 mm and the loss tangent is 0.025 have been employed. We can conclude, from the graph, that the four-elements array is well matched at 5.8 GHz and that the effects of the coupling between the resonators are minimal due to the chosen distance between them. The other performance indicators are depicted in Figure 7 (b), the purpose of this work have been reached by achieving the desired gain and directivity at 5.8 GHz.

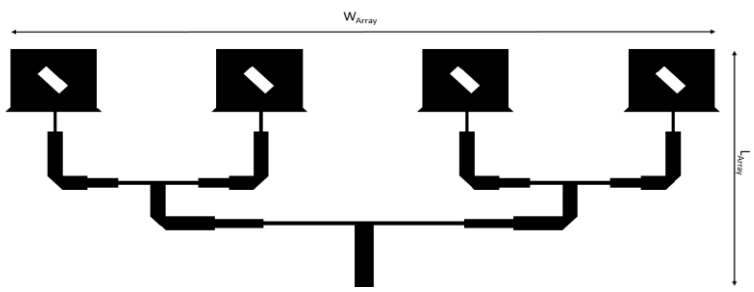
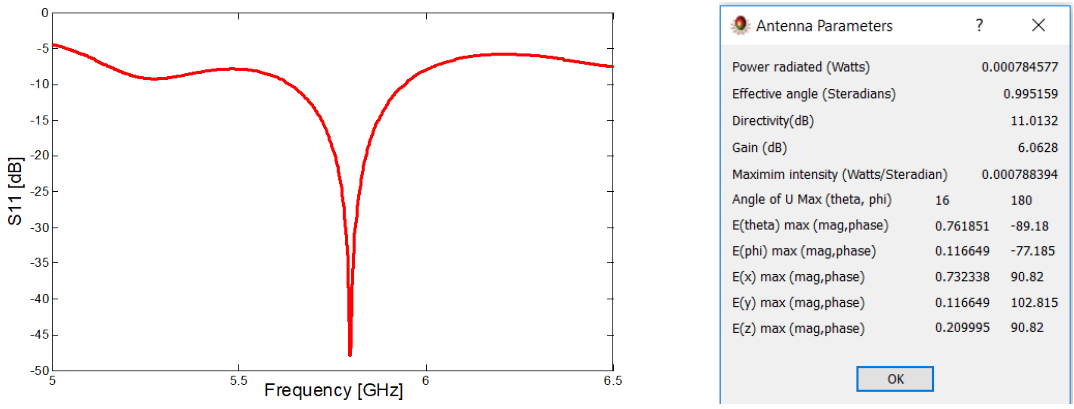



Figure 6. The proposed patch antenna array



(a) (b)

Figure 7. (a) Simulated reflection coefficient versus frequency (b) Far field antenna parameters

## 4. Achievement and Measurement

After presenting the antenna and its operating concept, we will present the different measurement results of the prototype and compare them to the simulations. The best environment to measure the performance of an antenna is in free space, however, this is not practical, so the anechoic chamber was presented. "anechoic" means nothing reflected off the wall of the chamber. In an ideal anechoic chamber, any electromagnetic wave propagates outside and nothing is reflected back, which is actually produced in the free space. An anechoic chamber is a metal that protects the room with all internal surfaces covered with radiation absorbing material (RAM). RAM can absorb most incident electromagnetic waves. The single antenna and antenna array were characterized experimentally by performing several series of measurements using the measurement bench shown in Figure 8.

The reflection coefficient was first measured using a vector network analyzer, then radiation pattern measurements were performed. The transmitting part is composed of an RF generator and a transmitting horn antenna able to rotate around its horizontal axis, thus allowing the change of the azimuth angle Φ of the incident E field at the receiving antenna. We have used as a substrate the FR4 with dielectric permittivity constant 4.4, thickness of 1.6mm and loss tangent of 0.025. Figure 9 compares the variation of the simulated reflection coefficient S11 and the one measured as a function of frequency. The results indicate that the measured S11 has a slight shift towards high frequencies but the antenna remains matched to the band of interest (ISM-5.8 GHz). As shown in figure 10, the structure presents a stable and directive radiation pattern at 5.8 GHz.

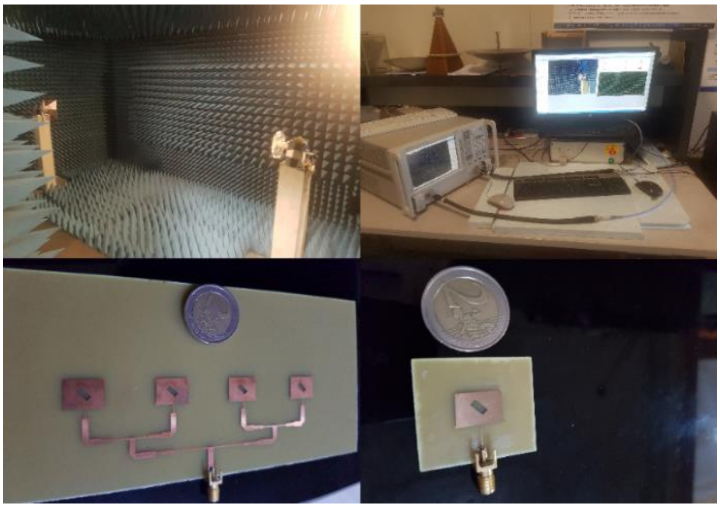
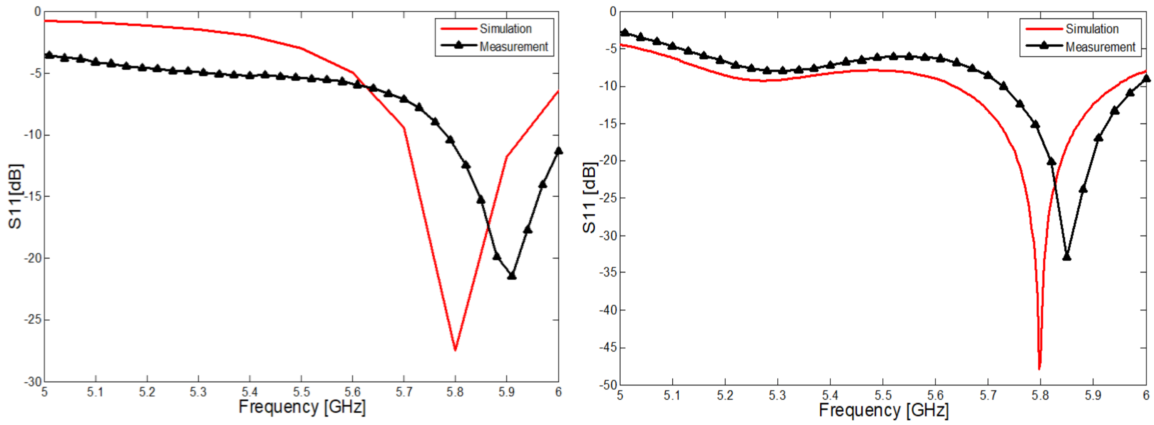


Figure 8. Fabricated antenna and antenna array




(a) (b)

Figure 9. Simulated and measured results. (a) S11 versus frequency (for Single element antenna) (b) S11 versus frequency (for Antenna Array)

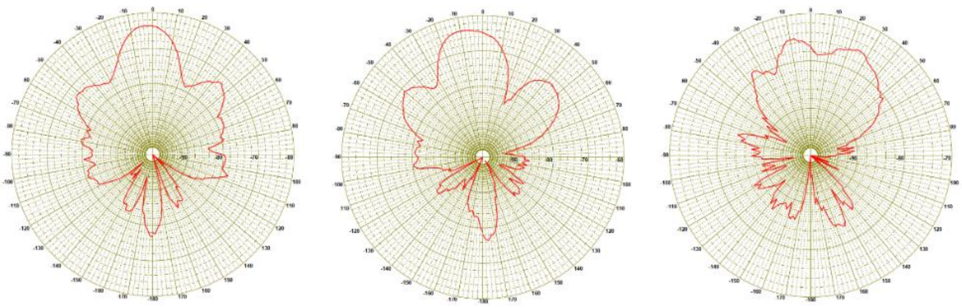


Figure 10. The measured E-plan antenna array radiation pattern at 5.8 GHz for azimuth plan of 0, 45 and 90°

## 5. Conclusion

The work presented in this paper is devoted to the design, optimization, fabrication and measurement of a circular polarized patch antenna array operating at 5.8 GHz of the Industrial Scientific Medical (ISM) band. The aim of this study is to cover the needs in applications involving wireless power transmission especially for Rectenna implementations. Firstly, we have started with a single element antenna validated by simulations and measurements, then moved on to an array configuration by associating four elements of the proposed patch antenna in order to enhance the coverage, gain and directivity. Consequently, the rectenna performances are significantly improved. Simulation results have been confirmed by measurements, a gain of 6 dB and directivity of 11 dB have been reached. The measurement results demonstrate that we have a good matching input impedance at 5.8 GHz with a directive radiation pattern. The proposed antenna array will be suitable for wireless transmission applications with high gain and circular polarization.

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