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Experimental study of rectenna coupling at low power level

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Abstract. The experimental results presented in this paper focus on the performance of a rectenna array by studying the effect of mutual coupling between two rectennas. The measurements in several planes of the space are investigated and used to help us to define the minimum distance for future rectenna arrays that can be used at a low power density level. The single element chosen for the array is composed of a rectifier circuit and a CSPA (Circular Slot Patch Antenna). This study shows that at a distance greater than 6 cm ($>\lambda/2$) between two rectennas in reception, we observe that the DC received voltage is constant in the Y plane. While, in the X plane, the DC received voltage remains constant whatever the distance is. We deduce that these rectennas are uncoupled in this case. We can consider each rectenna like an independent system.

1. Introduction

Recently, the emergence of various wireless power technologies [1], [2] to eliminate the last cable has generated significant research interest in this area. The concept is to eliminate in the future the need for problem-prone wiring and constraints battery replacement. Indeed, this study is motivated by two types of applications: (a) powering of low-power sensor and (b) RF energy recycling being aware of the energy consumption to the natural environment.

In this study we focused our attention on the power collecting system: the rectenna (the RF/DC converter) [3]. Due to the safety regulations, we considered low power level densities. But in order to increase the collected power we have to use a rectenna array.

The challenge is to maximize the rectenna array power conversion efficiency for low input power levels density. To this end, we have chosen to experimentally study the effects of the mutual coupling of two rectennas in two planes of the space on the RF/DC conversion. The single element rectenna is composed of a compact circular slot patch antenna (CSPA), coupled with a simple and efficient rectifying circuit.

The article begins with the study of the rectenna design. In this section, all the advantages to the CSPA antenna design are developed. The optimization of the rectifying circuit at $f_0=2.45\text{GHz}$, using a matching quadripole (four-ports) between its input impedance and the antenna impedance, is also presented. Finally, the overall test setup and experimental results on the mutual coupling between two rectennas are described and discussed in the subsequent parts.

2. Rectenna design

The rectifying circuit presented in this section has a simple structure. This structure is also compact and efficient for low input power signals.

CSPA antenna

In this work, a circular slot patch antenna, first introduced in [4], is designed, as the collecting element. Our choice was to use this type of antenna because it has many advantages in a rectenna design development. These advantages are: a bad impedance matching (which is useful for the rectenna efficiency at the different harmonics generated by the diode ($2f_0$, $3f_0$ and $4f_0$)), a good increased bandwidth, equal to 23.4%, the reducing antenna sizes, two major lobes in opposite direction, and fabrication simplicity. An illustration of the antenna is first proposed in Figure 2(a) and Figure 2(b). This antenna realization uses the methodology as in [5]. Concerning the antenna design optimization, we used a parametrical optimization.

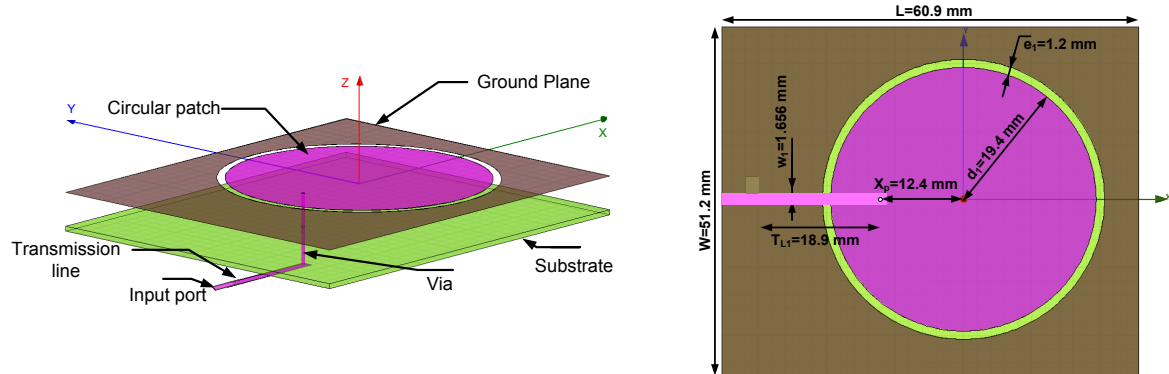


Figure 2(a). Illustration of the proposed CSPA.

Figure 2(b). CSPA dimensions.

It can be noted that the antenna radiation pattern shows an advantage in the context of this study. Indeed, the radiation pattern exhibits two lobes in opposite directions ($+z$ and $-z$). This characteristic gives the possibility to use this antenna, in a rectenna application where the incident RF wave is composed of the direct, interfering and reflected signals. At $\theta=0^\circ$, the simulated antenna gain and directivity are respectively equal to 3.32dBi and 3.42dBi. At a θ angle of 180° , the gain and the directivity are respectively equal to 3.79dBi and 3.89dBi.

Rectifying circuit element design

A series configuration of the rectifying circuit was retained. It consists of a matching input circuit, followed by one Schottky diode placed in series configuration and a DC pass filter. A 12 pF chip capacitor, with a quality factor $Q=10$ at 2.45 GHz, is used to short the RF energy and pass the DC power to the resistive load. For the matching input circuit, a tuning shorted stub was used for both the diode biasing in the DC domain, and the impedance matching between the antenna and the rectifier. The rectifying circuit and the antenna are etched on ARLONs AD series substrate. The choice of the rectifier diode was focused on the SMS7630-001.

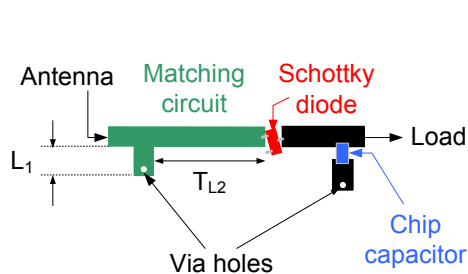


Figure 3(a) Layout of the rectifier circuit.

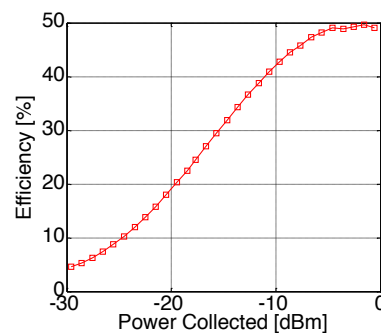


Figure 3(b) Measurement conversion efficiency of the rectifier versus the collected power for $R_L=3.5K\Omega$

A matching circuit is essential in providing the maximum power transfer from the antenna to the rectifier circuit. As it is shown in Figure 3(a), to match the input impedance of diode with the CSPA antenna impedance of 50Ω , a combination of a transmission line and a shorted stub is designed. The optimization of the impedance matching (see Figure 3(a)) consists of adjusting the length L_1 of the shorted stub and the length T_{L2} of the transmission line. Given the global rectifying circuit at $P_{\text{collected}} = -20\text{dBm}$ with $R_{\text{Load}} = 3.5\text{k}\Omega$, and using a Tuning method under Momentum in ADS software, the optimized length values are: $L_1 = 2.9\text{mm}$ and $T_{L2} = 10.9\text{mm}$. The width of the microstrip transmission line was chosen based on the input impedance of the antenna (50Ω) with $W_1 = 1.656\text{mm}$ (see Figure 2(b)). We measured the overall RF/DC conversion for one rectenna element. We have a good RF/DC conversion efficiency at around 20% for a collected power of $10\mu\text{W}$ and a maximum of 50% at $P_{\text{collected}} = 0.3\text{mW}$ (Figure 3(b)).

3. Measurement setup and results

After the validation of the rectifying circuit and the CSPA antenna separately, the rectenna is realized on the same unit substrate (figure 5).

Measurement bench

We measured the effect of mutual coupling between two rectennas in the two planes of space (X and Y). The measure is performed in free space, and the experimental measurement setup is shown in Figure 4, which is automatic and controlled by the software LabView. The RF signal generator is controlled, and allows the power and frequency to be varied. The RF injected power P_{inj} into the transmitter antenna is varied from +13dBm to +28dBm in order to obtain in reception a low collected power of rectenna. Moreover, the frequency range for these measurements is 2.42GHz to 2.47GHz. A linearly polarized patch antenna array is used for provides the RF power to rectennas. The purpose of this study is to experimentally estimate the DC voltage received V_{DCout} by a constant resistive of $10\text{k}\Omega$ connected at the output of each rectenna, as a function of a distance between rectennas in each plane of space. The wireless transmission distance R is equal to 1 meter.

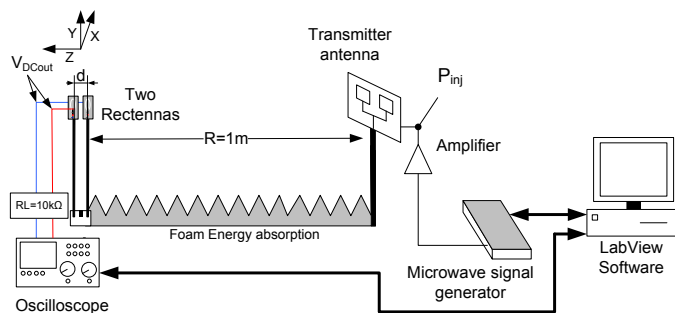


Figure 4. Experimental measurement setup.

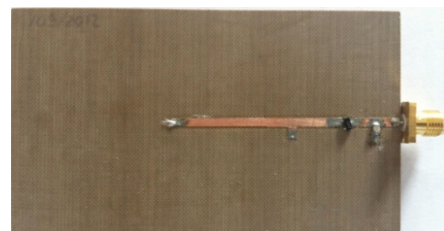


Figure 5. Photograph of the rectenna (back view)

For these results, it should be noted that averaging was performed during the measurement sessions due to the high sensitivity of the rectenna elements on the measurement environment and process mismatch.

Results

The study begins with the measurements of the effect of the mutual coupling in the X plane of the space. For this, each element rectenna is separate from their center, in the X plane, by a distance ranging from $d = 5\text{cm}$ to $d = 12\text{cm}$.

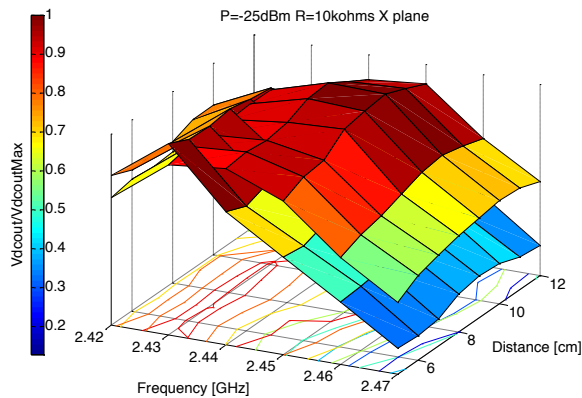


Figure 5(a) Coupling in the X plane at $P_{inj}=+13\text{dBm}$, $P_{collected}=-18\text{dBm}$

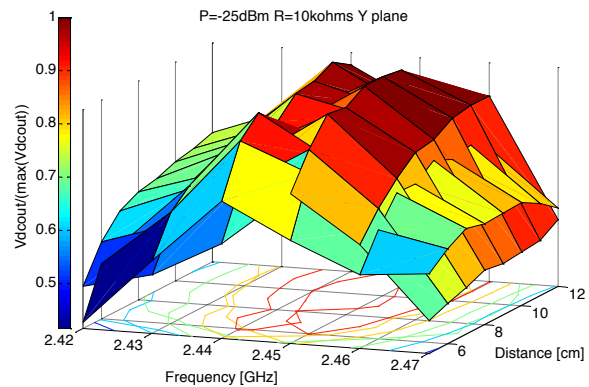


Figure 5(b) Coupling in the Y plane at $P_{inj}=+13\text{dBm}$, $P_{collected}=-18\text{dBm}$

On the figure 5(a), we can notice that the DC received voltage/ V_{DCout_Max} remains almost constant as a function of the distance between the two rectennas. Thus, no significant optimal distance can be observed.

On the same vein of improving the rectenna array power conversion efficiency for low input power levels density, the optimal distance is searched in the Y plane, as it is shown on figure 5(b). In this case, we observe that a maximum DC received voltage is achieved from a distance greater than 6cm.

4. Conclusion

The rectenna structure was formed using a single diode in series configuration coupled with a CSPA antenna. The design of this antenna with a circular slot patch antenna permits several advantages. At last, good bidirectional radiation patterns with appreciable gain are obtained over the operating bands.

In order to optimize a rectenna array, this experimental study show that, in the X plane, no mutual coupling and no optimal distance significant between two rectennas are observed. In contrast, in the Y plane, a maximum DC received voltage is achieved from a distance greater than $\lambda/2\text{cm}$ and thus determine a minimum distance for a maximum coupling. In view of these results, the future goal of this work will be the measurement evolution of the rectenna array efficiency in the Z plane.

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