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Impact of the coupling effect and the DC-combining configuration on a compact rectenna array

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Abstract. This paper proposes an experimental study of the coupling effect of a rectenna array. The rectifying antenna consists of a compact and efficient rectifying circuit in a series topology, coupled with a small metamaterial-inspired antenna. The measurements are investigated in the X plane on the behavior of rectenna array, with series and parallel DC-combining configuration of two and three spaced rectennas from 3cm to 10cm. This study shows that the maximum efficiency is reached for the series configuration, with a resistive load of 10k Ω . The optimal distance is not significant for series or parallel configuration. Then, a comparison between a rectenna array with non-optimal mutual coupling and a more traditional patch rectenna is performed. Finally, a practical application is tested to demonstrate the effectiveness of such small rectenna array.

1. Introduction

With the development of very low-power wireless system, numerous researches have focused their attention on the feasibility of powering devices through the harvesting of ambient electromagnetic energy [1]. The main challenges in far field nondirective powering are a result of the low and variable power densities available at the receiving antenna.

Therefore, the study deals with the design, optimization and experimental characterization of a compact metamaterial-inspired antenna coupled with a rectifier. Then, to increase DC power over the load, the proposed rectenna has been interconnected to form arrays [2]. This is called DC-combining configuration where the outputs of each rectenna are combined in series, parallel or a hybrid manner. It has the advantages to ease the construction of the rectenna array oppositely to the RF-combining configuration. In RF-combining structure, the RF outputs of each antenna are combined before the rectifier circuit. The RF-combining configuration implies the use of sub-circuit to deal with power leakage and phasing between the antennas. This issue is eliminated when DC-combining is use, but the tradeoff of such configuration, is lower RF-to-DC conversion and the use of several rectifying element.

In this paper, we investigate the behavior of rectenna array using electrically small antenna. First, we inquire the effect of mutual coupling on two different DC-combining configuration, series and parallel for a finite number of elements. Then, a comparative study is conduct between a rectenna array and a single rectenna using a conventional patch antenna [3], having the same physical surface area. Last, an application of the rectenna array is tested, where a battery-less temperature sensor is powered over a distance of one meter.

2. Antenna design

The antenna used in this paper, as shown in figure 1, is a modified version of an antenna first introduced by Ning Zhu and Ziolkowski [4]. This Near Field Resonant Parasitic (NFRP) antenna maybe characterized as an electrically small antenna by a weighting factor $ka=0.976$ and is designed for ISM band. Moreover, this antenna naturally rejects the first harmonics, which allows the suppression of the pass-band filter at low power level. Indeed, due to the low power input, the effects of higher order harmonics are also negligible. This antenna, also referred as filtenna (filtering-antenna), allows the size reduction of the overall rectenna to $11*49\text{mm}^2$ (see figure 3).

The measured return loss parameter from 1GHz to 5GHz of the NFRP antenna is presented in figure 2. The antenna presents a dual frequency resonance (1.9Ghz and 2.45Ghz). It should be noted that they were performed at 2.54GHz due to experience feedbacks on offsets between simulations and practice. Indeed, when we simulate with Momentum in Agilent ADS software, the simulation uses an infinite substrate, in contrast to the realization, where the antenna's dimensions are finite.

An experimental characterization of the antenna gain at a distance of 1 meter is conduct at 2.45Ghz, using a bi-quad antenna with a gain $G_t=10\text{dB}$ as emitter source. The transmitted power is $P_t=+20\text{dBm}$. The measured collected power at the receiving antenna is $P_r=-17.5\text{dBm}$. The Friis equation (1) is used to determined the gain of the antenna with $\gamma=0.28$.

$$G_r = \frac{P_r \cdot (4 \cdot \pi)^2 \cdot D}{P_t \cdot G_t \cdot \lambda^2 \cdot \gamma} \quad (1)$$

The calculated gain $G_r=-1.74\text{dB}$ is negative due to the compactness of the antenna. This bad gain is a common compromise when using electrically small antenna.

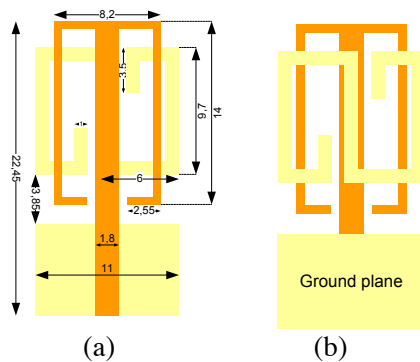


Figure 1. Small antenna design (mm)
(a) Front view (b) Back view

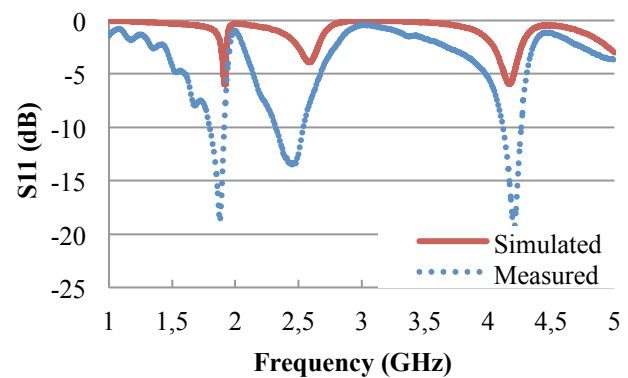


Figure 2. Simulated and measured return loss parameter

3. Rectifier design

The rectifier presented in a previous work [3] is simple, compact and efficient for low power input. A matching circuit is essential in providing the maximum power transfer from the antenna to the rectifier circuit. The optimization of the impedance matching consists of adjusting the length $L1$ of a shorted stub and the length $TL2$ of a 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 tuning method under Momentum in ADS software, the optimized length values are: $L1=2.9\text{mm}$ and $TL2=10.9\text{mm}$. The rectifier circuit shows a RF/DC conversion efficiency at around 20% for a collected power of $10\mu\text{W}$. The antenna and the rectifier is realized on the same unit substrate (AD320) with $\epsilon_r=3.2$, thickness= 0.762mm (see Figure 3).

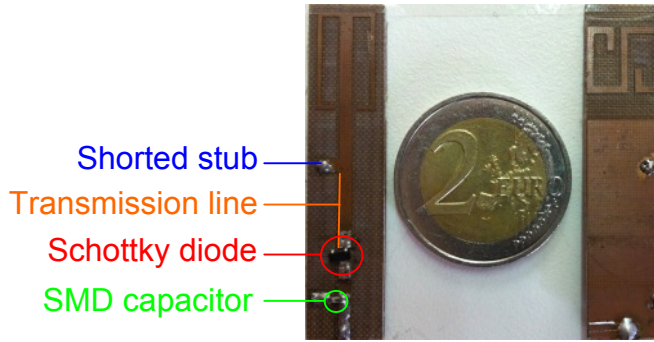


Figure 3. Picture of the global rectenna

4. Measurement and application

4.1. Experimental setup and measurements protocol

After the validation of the rectifying circuit and the NFRP antenna separately, several rectennas are realized individually and DC-combined in series or parallel. The rectennas are measured in free space, and the measurement bench is shown in figure 4. A linearly polarized patch antenna with a gain approximately of 6dBi provides the RF signal to the rectenna array.

The purpose of this study is to experimentally characterize the optimal distance between the rectennas to form an efficient array. Two rectennas and three rectennas are placed in the X plane, separated from 3cm to 10cm. For every distance, the DC-combining series and parallel are investigated. The voltage and current of every case are measured and averaged (100 measurements spaced of one second) at a distance of 1meter, with an injected power $P_{inj}=+20\text{dBm}$. Measurements are performed with a precision of 0.0035%.

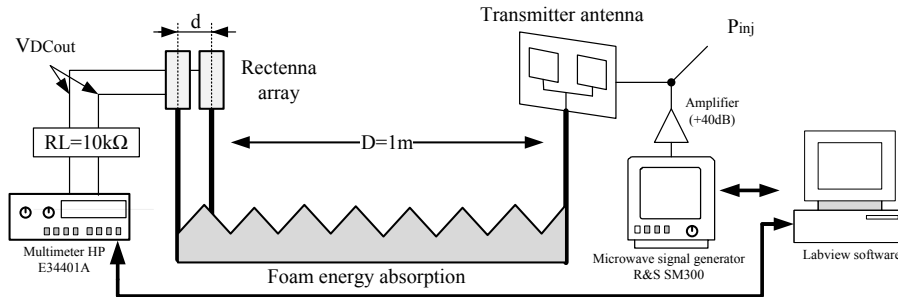


Figure 4. Measurement bench setup

4.2. Results, Comparison and application

The figure 5 shows the collected DC voltage over the distance between the rectennas for each configuration. It can be noted that, despite the coupling effect not being optimal for smaller distances between the rectennas, the converted DC power is improved compare to one single rectenna. From this observation, a more compact rectenna array is build. This rectenna array is composed of 5 rectennas spaced of 9mm, and has the same area size than a rectenna design in a previous work [3] for a comparative study (see figure 6). This previous rectenna was build for the same operating point and measured in a similar approach. Experimentally, with a resistive load $R_{load}=10\text{k}\Omega$ and the same measurement protocol, we obtain for the patch rectenna $VDC_{patch}=226\text{mV}$ and $VDC_{small}=1.03\text{V}$ for the DC-combining array in series configuration. The series configuration was chosen, due to its advantages to increase the voltage and being more suitable for higher resistive load.

Then, an experimental application is conduct to power a temperature sensor with a high input impedance $Z>10\text{k}\Omega$. Due to its high input impedance, we provide enough power with the DC-

combined array in series to power in continuous the sensor at a distance of one meter, as seen in figure 7. The minimum voltage needed to turn on the sensor is $V_{\text{sensor}}=1.37\text{V}$.

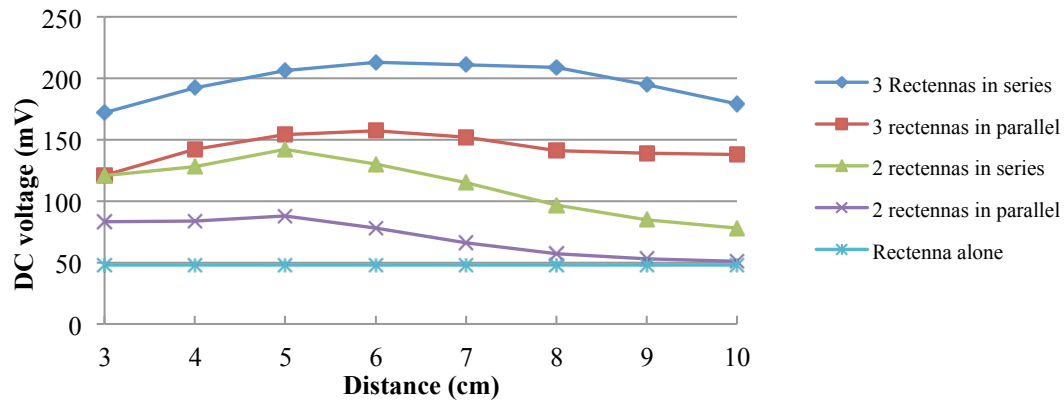


Figure 5. Collected DC voltage over distances between the rectennas for each configuration

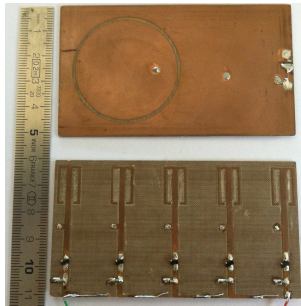


Figure 6. Size comparison between regular patch rectenna and small rectenna array

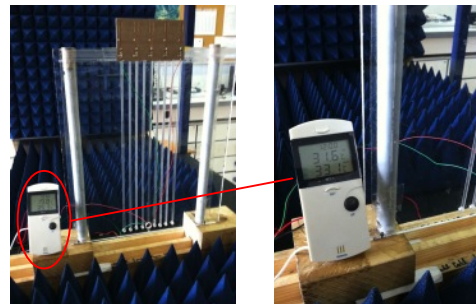


Figure 7. Wireless powering of a temperature sensor using DC-combined configuration with electrically small antenna

5. Conclusion

In this paper, a rectenna array with electrically small antenna was built using DC-combined configuration and compared to a conventional patch rectenna. We demonstrated experimentally that despite their bad gain and the effect of non-optimal mutual coupling, those arrays were useable to harvest RF energy. An application of such rectenna array has been studied. Depending on the distance and the power of the emitted source, it is possible to power constantly or periodically (using some storing elements) a low-power consumption device. Indeed, subsequently, we wish to power the same sensor at greater distance, by adding a pump charge circuit with the rectenna array.

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