Improved Performance of a Rectenna Array for Wireless Low Power Transportation

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IMPROVED PERFORMANCE OF A RECTENNA ARRAY FOR WIRELESS LOW POWER TRANSPORTATION

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Abstract
The study presented here focuses on the design of a simple and compact rectenna (rectifying antenna) to enhance the performance at a relatively low power levels. The rectifier is realized with a single schottky diode SMS-7630 in reverse topology and optimised at the fundamental frequency f_0 = 2.45 GHz. Although a single narrow-band design is conductive enough to achieve high efficiency, we know that the amount of the DC output power is limited. To overcome this issue, one solution would be a rectenna array designed for collecting more HF power to produce more DC power. The opportunity in this study would be to increase performances of a ground receiving rectenna, and more precisely for those located on the edges of the array where the RF power density are low. To estimate the DC power, we started with the study of a 2x5 planar array of small metamaterial-inspired antennas. Each antenna incorporates its own rectifier to collect DC power and is assembled in series manner. The size of the overall rectenna array is 110*90mm^2. Finally, our most recent studies show an increase of the collected DC voltage with the presence of a reflector at a distance of 3λ/4 to the back of the rectenna array.
Keywords: rectenna array, wireless power transmission, NFRP antenna

1. Introduction

The years pass and we realize that energy is more and more vital for the economic development of the world and is becoming a substantial part of modern societies' everyday life. However, the days of cheap energy seem to be over. Today, the world faces challenges such as climate change, increasing import dependence and higher energy prices. Developing the renewable energy sector is essential if we are to achieve a sustainable and secure energy supply for the future [1].

Solar power collected in space and transmitted to the Earth's surface has been proposed for many years as a potential space option [2,3]. This approach using Wireless Power Transportation (WPT) technology aims to eliminate the cable connections conventionally necessary for transmitting electricity. In a wireless power transmission system, the transmitted energy can be collected by a rectenna system, which consists of two main modules: an antenna and a rectifier. In the receiving side of the energy harvesting process, the RF waves are captured by the antenna which is the key part of the rectenna. The receiving antenna produces an AC signal at its output from the captured microwave radiation. Then, the rectifier converts the received AC current to DC power. The newly successful test results lead the way to applying the technology in numerous terrestrial and space fields. Mitsubishi Heavy Industries, Ltd. (MHI) has recently revived the interest for WPT with a ground-based demonstration testing of a WPT system [4].

If the present standard for continuous microwave exposure (20 mW/cm^2, corresponding to 200 W/m^2) would be imposed as the upper limit on ground, the average allowed flux on the rectenna would be as small as 100 W/m^2. Moreover, this flux decreases when moving away from the center, hence the importance of optimizing array performance for low power levels. In this paper an array of ten rectennas has been developed and mesured operating at low power levels.

This paper is structured as follows. Section 2 begins with the study of the rectenna design. In this section, all the advantages to the Near-Field Resonant Parasitic (NFRP) antenna design are developed. The optimization of the rectifying circuit at f_0=2.45GHz, using a single shorted stub and transmission line matching circuit between its input impedance and the antenna impedance, is also presented. Finally, the overall test setup and experimental results on the performance of the array are described and discussed in the subsequent section and also show an increase of the collected DC voltage with the presence of a reflector to the back of the rectenna array.

2. Rectenna element design

Rectenna is the third stage of the WPT process. The first studied element of the RF to DC energy conversion system is the receiving antenna.

2.1 Antenna design

At low power levels, a high gain antenna is preferable as more RF power can be collected and thus more DC power will be present at load level. The gain of an antenna is however proportional to its equivalent surface. Thus a compromise has to be made between the gain and the surface of the antenna. However, the size of the array must be small to make it practical and inexpensive. In this regard, the antenna element design and its miniaturization play an important role. In this work, a Near Field Resonant Parasitic antenna (NFRP) based on the works of Ning Zhu and Ziolkowski [5] to harvest electromagnetic energy is presented in Fig. 1a. This NFRP antenna may be defined as an electrically small antenna by a weighting factor ka = 0.976 and is designed for ISM band. The antenna is first simulated and then measured using a vector network analyzer (VNA) for this impedance and reflection coefficient S11 (see Fig. 2). The main resonant frequency of the NFRP antenna is located at 2.45 GHz. The -10 dB bandwidth is 20 MHz from 2.35 GHz to 2.55 GHz. Finally, the NFRP antenna allows to reduce the area of the overall rectenna to 11*50 mm^2 without band pass filter in input.

2.2 Rectifier design

The next step is to design the rectifying part of the RF harvesting circuitry. That is, once the antenna receives the input RF signal, it converts a part of the incoming power supply to DC supply voltage. This must be designed in order to achieve the highest total system efficiency. A basic configuration with only one schottky diode for the rectifying circuit is retained as shown in Fig. 3. Commonly called as single-stage rectifier, it consists of a diode connected in series with a capacitor and a load in parallel. The operation of the single stage rectifier is as follows. First, the induced voltage at the output of the matching circuit passes through the schottky diode. The rectified current output is then pumped to the chip capacitor. The energy stored on this capacitor supply the DC power to the load once the rectifier reaches its steady-state mode. The SMS7630 Schottky diode was selected for its zero bias characteristics and its already proven performance at 2.45 Ghz. A shunt capacitor of 10 pF, with a quality factor Q = 10 at 2.45 GHz, acts as a filter to smoothen the ripple in the output.

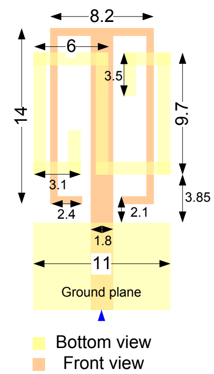

Fig. 1. NFRP Antenna design (mm)

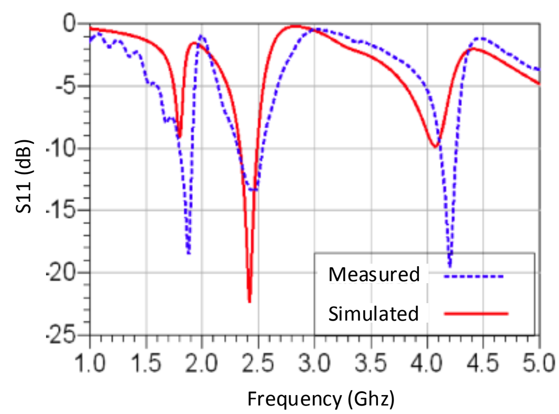

Fig. 2. S11 simulated and measured

In order to optimize the rectenna for maximum power transfer, the antenna impedance must be matched to the impedance of rectifier diode. We propose a matching circuit with a single shorted stub and a transmission line, which is simple and easy to design. This part focuses on the optimization of the rectifier element at low power operation. The diode is matched by the length L_1 of a shorted stub and the length T_{L2} of a series microstrip line in a narrow bandwith for the specific RF power. Under a planar method of moments, a tuning optimization method is performed with the software Agilent Advanced Design (ADS), to find the global rectifying circuit. The optimized lengths values are: L_1 = 2.9 mm, T_{L2} = 10.9 mm and the width of all the lines is fixed to 50 Ω. The efficiency of the fabricated rectifier at low power levels is depicted in Fig. 4.

The highest conversion efficiency which occurs when the rectifying circuit exhibits a resistive load R_{Load} = 3.5 kΩ with an optimal efficiency $\eta_{MAX} \approx 50$ % at a collected power $P_{collected}$ =-1dBm. After the validation of the rectifying circuit and the NFRP antenna separately, the rectenna is realized on the same unit ARLONs AD series substrate with $\varepsilon_r = 3.2$, a thickness of 0.762 mm and a loss tangent of 0.003.

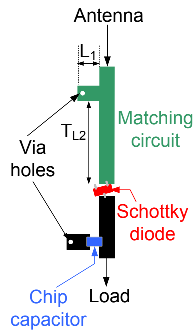

Fig. 3. Layout of the rectifier circuit

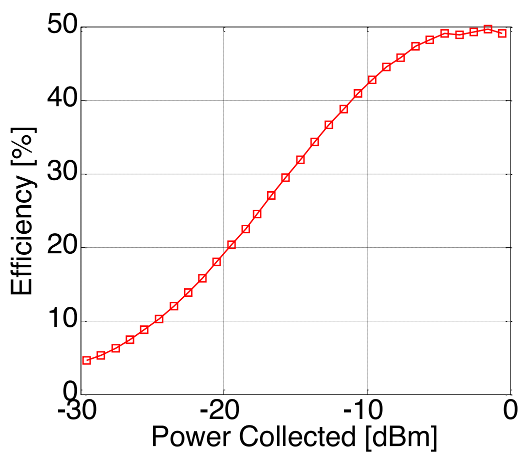

Fig. 4. Measured efficiency for R_{Load}=3.5 kΩ

3. Array design

Several rectennas can be configured to collect a greater percentage of DC power. The DC power converted independently by each rectenna can then be summed in parallel (current summing), series (voltage summing) or hybrid manner, and is channeled to a power management circuit. Thus, in this study, we consider a compact ten series rectennas array, which is depicted in Fig. 5. A series association allows the increase of the DC output voltage proportional to the number of rectennas but in practice, the results vary slightly due to incertitude concerning the non-linearity of converter with respect to input power level.

The interelement spacing *s* between two rectenna was chosen such that mutual coupling is low (i.e. *s* = 9 mm, |S21| < -10 dB) [6]. The overall size of the rectennas array is 110*90mm^2.

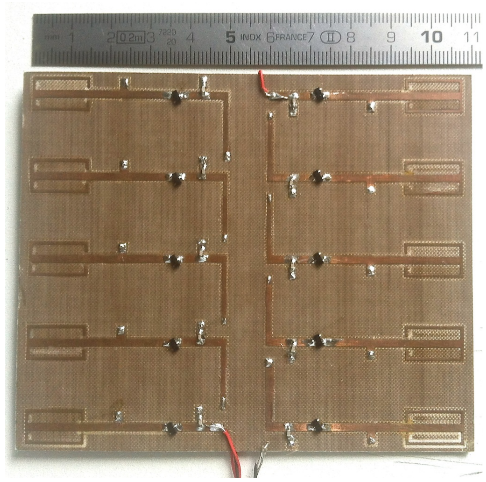

Fig. 5. Rectenna array

4. Experimental results

To evaluate the rectenna performance, we use a test system where a transmitting antenna is connected to a HF generator with a fundamental frequency fixed to 2.45 Ghz. The performance of the rectenna is verified by measuring the output DC voltage using a digital multimeter with a precision of 0.003% in DC. A linearly polarized bowtie antenna with a gain around +10dB over the frequency of interest is used to provide the RF power. Measurements were performed by placing the proposed rectenna array at a distance of 2 m from transmitting antenna and the source power was set at +25 dBm.

Figure 6 shows the output DC voltage V_{out} of the rectenna. The maximum output DC voltage is 2.824 V and corresponds to the open-circuit voltage (V_{Th}).

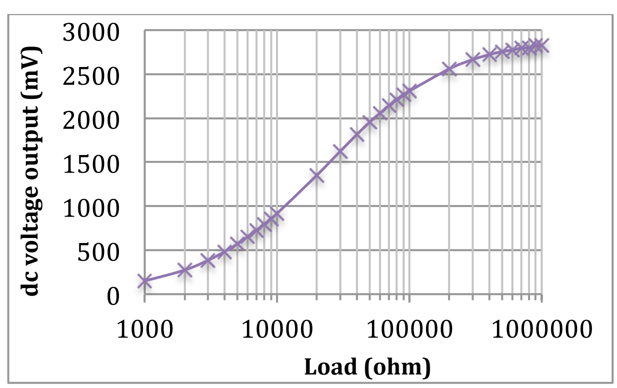

Fig. 6. Output DC voltage

Figure 7 shows the power delivered to the load as a function of R_L. We notice that the power is small for small or values of R_L but maximum for some value of R_L between 0 and +∞. The maximum power delivered to the load is 91 µW with an optimal load R_{Lopt} of 20 kΩ. According to the maximum power theorem, we know that the maximum power transfer takes place when the load resistance R_L equals the Thevenin resistance R_{th}. The maximum power transfer to the load R_L can be explain by :

$$P_{MAX} = R_L * i^2 = \left(\frac{V_{Th}}{R_{Th} + R_L}\right)^2 * R_L \quad (1)$$

with V_{th} = 2.824V, $R_{th}=R_L$=20 kΩ.

With these parameters, the value of P_{MAX} is about 100 uW.

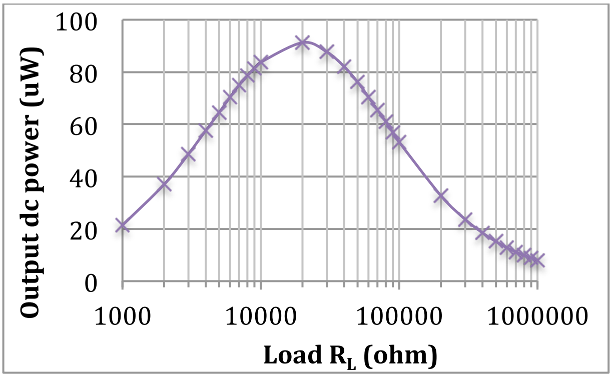

Fig. 7. Output DC power

In practice, for this maximum operating point, if we consider that $R_{th}=R_L$, we can conclude that there are about 9 uW of internes losses, i.e. about 9%.

A second study was performed using a reflector to the back of the rectenna array. The objective is to increase performance. Indeed, a reflector is relatively inexpensive, offers a higher gain and allows to have a wide bandwidth.

The reflector is moved in a range from 1 cm to 12 cm by step of 1 cm. It appears that maximum of open circuit voltage is reached when the distances are λ/4 and 3λ/4. We obtain an output DC voltage of 4.5 V at λ/4 and about 5V at 3λ/4 as it is shown on Figure 8.

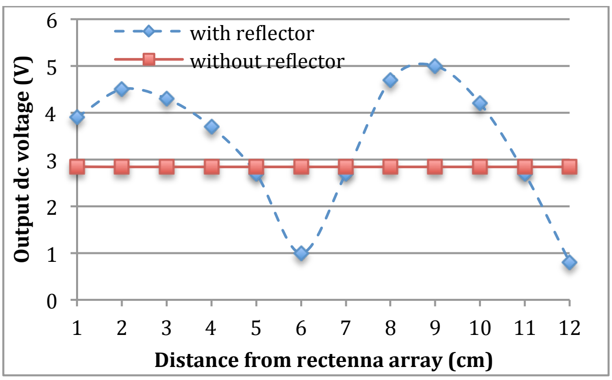

Fig. 8. Impact of the reflector on the output DC voltage

Finally, we can conclude that the optimum distance giving the maximum voltage is 3λ/4, which corresponds to a gain of 1.77 on the output dc voltage with a load of 1MΩ.

5. Discussion

This study shows the possibility of achieving a compact and efficient rectenna operating at low power levels. The networking of these rectennas in series topology confirms the increase of the output dc voltage but remains below the theoretical value. Finally, the addition of a reflector to the back of the array at an optimal distance improves performance of the global system.

6. Conclusions

This paper reports the design and experimental characterization of a ten rectennas array in the ISM band at 2.45 GHz operating at low power levels. These circuits were achieved in a simple and low-cost manner and experimentally tested. Thus, the results show that using a reflector at 9 cm to the back of the rectenna array, it is possible to increase the collected DC voltage. They present interesting DC output properties and are suitable for another energy harvesting applications.

Acknowledgements

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