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A COMPACT RECTENNA DEVICE AT LOW POWER LEVEL

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Abstract—This article describes the design and performances of a rectenna that collects low incident power density levels, at a single ISM-band frequency ($f_0 = 2.45\,\mathrm{GHz}$). A new rectenna topology consisting only of an antenna, a matching circuit, a Schottky diode, and a DC filter has been modeled using a global simulation. A circular aperture coupled patch antenna is proposed to suppress the first filter in the rectenna device, and in addition, the losses associated with this filter. The harmonics rejection of the antenna is primarily used to reduce the rectenna size. The implementation of the filter in the antenna structure, combined with a reduction of the rectenna size, gives several advantages in several applications where the size and weight are critical criteria. The maximum energy conversion efficiency in this configuration is 34% and is reached for a load of $9.2\,\mathrm{k\Omega}$ and a RF collected power of $S_{RF} = 17\,\mu\mathrm{W/cm}^2$ ($\approx -10\,\mathrm{dBm}$ RF incident upon the diode).

1. INTRODUCTION

Rectifying antenna (rectenna), which can capture and convert electromagnetic power to electric power, plays an important role in free space wireless power transmission (WPT) [1]. This feature is an attractive solution to supply a node in a Wireless Sensor Network (WSN) [2] or the electronic circuits of the radio frequency identification (RFID) [3].

In the literature, several publications deal with the rectenna, and a good review of which is given in [1, 4, 5]. The initial

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development of rectenna focuses on its efficiency for great power reception and conversion. But in the last few years, excluding high power applications, wireless power transfer has been often used in microwave radiation with relatively low power densities [6, 7]. This approach offers the possibility to use the rectenna as an energy module in a WSN.

To this end, we have chosen to develop a rectenna operating at very low power densities (several $\mu W/cm^2$). Indeed, the rectenna efficiency at low power level is an important feature (0 dBm, and −10 dBm), because it would allow one to power a node or a tag located far away from the RF transmitting source. For this purpose, we must take into account several considerations, such as the size, and a good conversion efficiency. The proposed rectenna structure is illustrated in Fig. 1.

In this study, a dual problem is solved to reduce the rectenna size and to assume high conversion efficiency at low power level. The first step in solving this dual problem consists of finding a correct match between the antenna and the rectifier circuit input impedance at the fundamental frequency. To match the diode input impedance with the standard 50 Ohms, an open-stub is designed. This matching network is realized by adjusting the length (Ls) and width (Ws) of the stub, with a test and error estimation. The second step is the integration

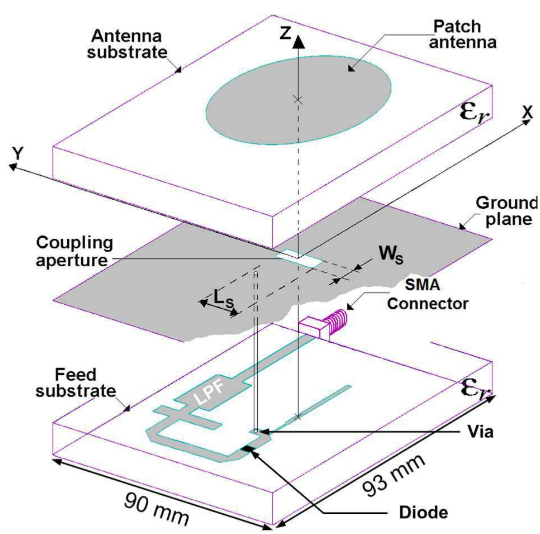


Figure 1. Illustration of the proposed aperture coupled staked microstrip rectenna.

of the band pass filter (BPF) F1 with the antenna (Fig. 2) [8, 9]. This BPF is one main component in the process of rectifying the RF wave. Furthermore, we propose to reduce loss conduction, radiation and matching associated with this BPF, in order to improve the conversion efficiency. Thus, several configurations have been used for the antenna harmonics tuning, such as holes, pins, slots, and the design of the radiating patch. Here, a simple circular aperture coupled patch (CACP) is used.

The first part of this paper presents the rectifying circuit design problem of a single rectenna circuit. The CACP with harmonic rejection property is primarily used to minimize the circuit size and losses. Simulation and optimization of the derived rectenna model are presented in the subsequent parts. Furthermore, the experimental results on the rectenna are described, and finally conclusions and extensions of this study are discussed.

2. RECTENNA DESIGN

2.1. Rectifying Circuit

Rectifier is a nonlinear circuit, which converts RF power into DC power. The main characteristic of the operating effectiveness of a rectenna is its efficiency, determined by the losses, which arise during its conversion into DC power. The general block diagram of a conventional rectenna is shown in Fig. 2.

The mathematical relation that describes the conversion efficiency is given by (1).

$$\eta_{rec1} = \frac{P_{DC}}{P_r} = \frac{V_{R_{CP}}^2 / R_{CP}}{P_r} \tag{1}$$

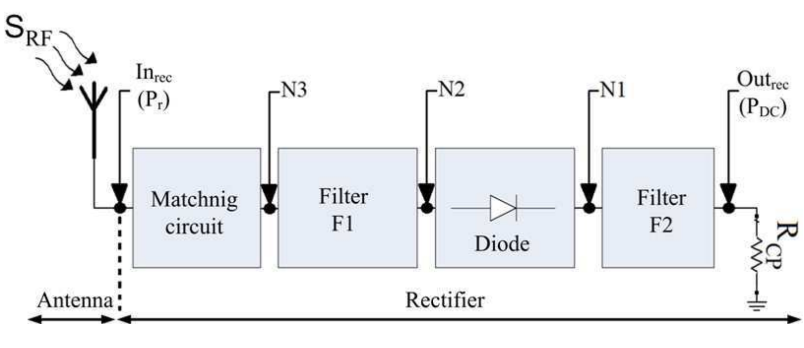
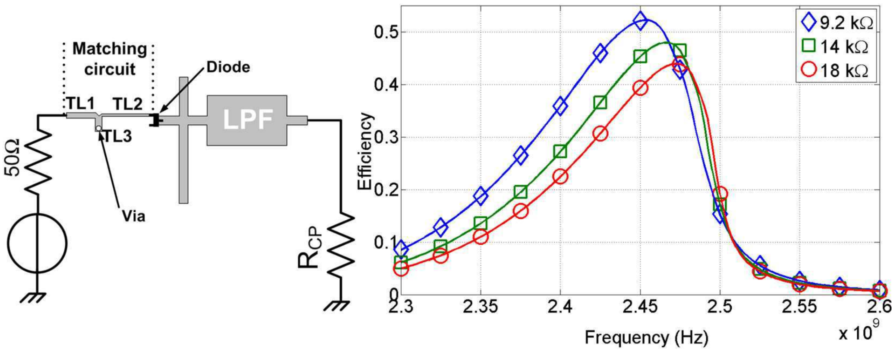


Figure 2. Block diagram of a conventional rectenna.

with $V_{R_{CP}}$ (V) the output voltage drop across the load, R_{CP} (Ω) the load charge value, P_r the RF input power at the receiving antenna's output port, point In_{rec} on Fig. 2, and P_{DC} the DC power entering at the load charge (R_{CP}).

The efficiency of the rectifier depends mainly on Schottky diode. The diode used in the rectenna is the HSMS-2860 from Agilent. It has a series resistance $Rs = 5\,\text{Ohms}$, zerobias junction capacitance $C_{jo} = 0.18\,\text{pF}$, and breakdown voltage $Vb = 7\,\text{V}$. The diode is a critical part in the realization of the rectifier. A correct modeling of this device is mandatory to the achievement of precise simulations. In our case, we proposed a rectifier with high conversion efficiency at low power level ($P_r = -10\,\text{dBm}$). Under this condition, an advantage is the possibility to use the Schottky diode model in the simulator (including the simulator internal package parasitics), without additional parasitic packaging model. To achieve this goal, the model was implemented in the Advanced Design System (ADS) simulator software.

To minimize the rectifier size, we chose to suppress the band pass filter (BPF) F1 of this rectifier. In addition, the conversion efficiency (η_{rec1}) is increased by the suppression of inherent losses associate to the BPF. Fig. 2 shows a single diode in series configuration. This topology implies a via in the matching circuit for the diode biasing. This matching circuit was composed of three lines stubs TL1, TL2, and TL3 (Fig. 3(a)). All physicals dimensions of the final matching circuit are obtained by a test and error estimation and are given in Table 1. Concerning the output low pass filter (LPF), this study uses



(a) (b)

Figure 3. (a) Illustration of the rectifier circuit simulation. (b) Simulated RF/DC conversion efficiency of rectifier for $P_r = -10\,\text{dBm}$, and three resistor values ($9.2\,\text{k}\Omega$, $14\,\text{k}\Omega$, and $18\,\text{k}\Omega$).

Table 1. Relates matching circuit dimensions.

	length [mm]	width [mm]
TL1	7	1.42
TL2	12.52	0.52
TL3	1.5	3.73

the same structure of [10]. Fig. 3(b) presents the efficiency simulation of the rectifier versus frequency for three R_{CP} values: $9.2\,\mathrm{k\Omega}$, $14\,\mathrm{k\Omega}$ and $18\,\mathrm{k\Omega}$, at $P_r = -10\,\mathrm{dBm}$ (The $9.2\,\mathrm{k\Omega}$ gives the highest conversion efficiency). The maximum energy conversion efficiencies η_{rec1} in this configuration are respectively 52%, 48% and finaly 43%.

2.2. Antenna Design

Antenna design is important in the proposed rectenna. The antenna absorbs the incident microwave power, and the rectifier converts it into a useful electric power. In this paper, in order to reduce the size of the rectenna, we propose to combine the BPF and the antenna into a single unit. Consequently, for size reduction, a circular antenna with harmonic rejection properly was proposed. Equation (2) gives the resonant angular frequency response (w_r) of a circular microstrip patch antenna (CMPA) [11].

$$J_n(A_e \cdot w_r \sqrt{\epsilon_r \cdot \epsilon_0 \cdot \mu_0}) = 0 \tag{2}$$

where $J_n(x)$ is the Bessel function of n order, and A_e is the effective radius of the patch, ϵ_r and ϵ_0 respectively the relative and μ_0 vacuum permittivity and the vacuum permeability. Solving Equation (2), the harmonic resonant frequencies are $1.66 \cdot f_0$, $2.08 \cdot f_0$, $2.9 \cdot f_0$, and so on. The circular antenna produces a bad impedance matching (which is useful for the efficiency) at the different harmonics generated by the diode. In this case, the harmonics are bounced to the antenna input port and go back to the diode. This process allows a frequency combination at the diode and increases the RF/DC conversion efficiency. As a result, the CMPA allows us to consider that the BPF is integrated on the antenna. In order to decrease the radiation interferences between the patch and feeding circuit, a circular aperture coupled antenna (CACP) is used. The layout is shown in Fig. 4. The slot on the ground plane is placed at the patch center, which favors the fundamental mode in the patch. The slot size (W_S, and L_S) and patch radius (R_p) give respectively the characteristic impedance of the slot (Z_{Slot}) and the patch (Z_{Patch}). These properties are utilized to acquire a matched design. The input impedance of

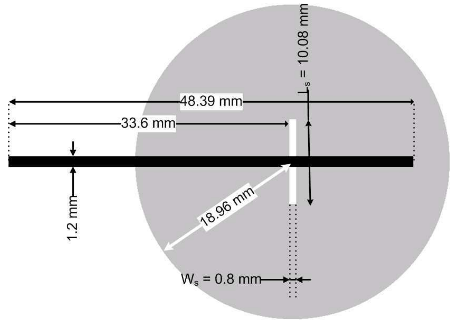


Figure 4. Circular microstrip patch antenna design.

the antenna varies with the position and the coupling between Z_{Slot} and Z_{Patch}. The optimization is performed at $f_0 = 2.45\,\text{GHz}$ with W_s, L_s, R_p parameters, and we obtain a good impedance matching with $W_s = 0.8\,\text{mm}$, $L_s = 10.08\,\text{mm}$, and $R_p = 19.1\,\text{mm}$. The simulation results (by using commercial EM simulation software ADS-2009) of this optimization give an input impedance of the antenna $Z_{ant} = (52 + j3.8)\,\Omega$ at f_0. The error between this absolute value and $50\,\Omega$ is equal to 4%. The gain of this antenna is equal to 4.3 dB, and it directivity is equal to 6.5 dB (simulated values).

3. MEASUREMENT RESULTS

3.1. Antenna and Converter Fabrication

The antennas and converter were fabricated on ARLON AD320 with the following parameters values: dielectric constant $\epsilon_r = 3.2$, substrate thickness $h = 0.762\,\text{mm}$, conductor thickness $t = 35\,\mu\text{m}$, $\sigma = 5.88 \times 10^7\,\text{S/m}$ (conductivity of the patch, microstrip, and ground plane), $\tan(\delta) = 0.003$ (loss tangent). The PCB (Printed Circuit Board) was manufactured by a computer controlled milling machine.

3.2. Rectifier Efficiency

An automated acquisition data software (Labview) is used to save multiple sampling points ($V_{R_{CP}}$ and P_r). The resulting output files are then analyzed using computer software. This measuring process is proposed to reduce the electromagnetic noise on the measurement devices [12].

Figure 5 illustrates the measured conversion efficiency, η_{rec1}, of the rectifier as function of the frequency (2.3 GHz to 2.6 GHz) and for several resistive load values at $P_r = -10\,\text{dBm}$. Between the simulated

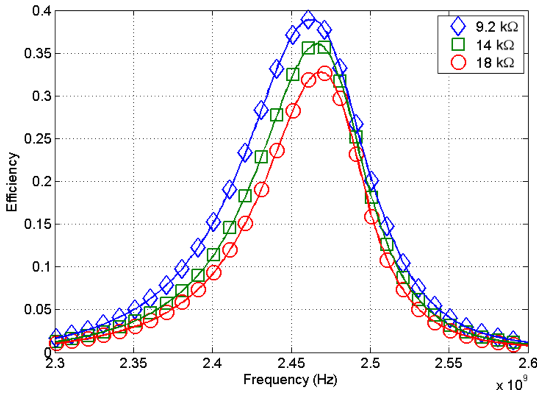


Figure 5. Measured conversion efficiency of the rectifier versus the input signal frequency, for three load values (9.2 kΩ, 14 kΩ and 18 kΩ). The input power level is equal to $P_r = -10\,\mathrm{dBm}$.

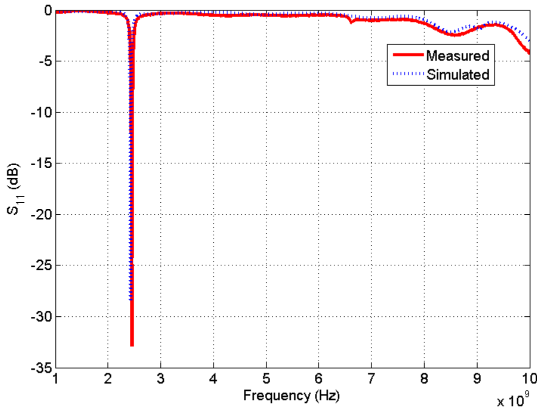
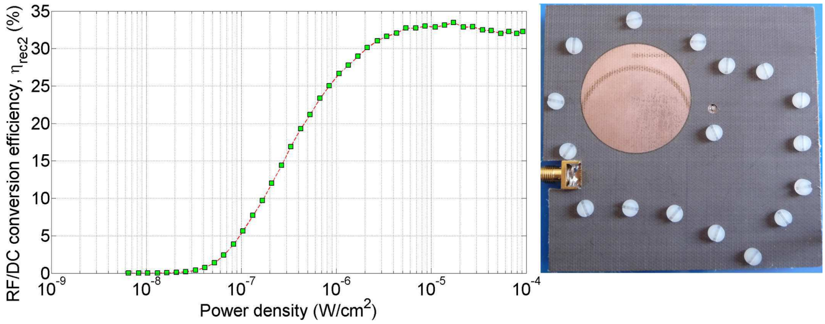


Figure 6. Measured and simulated of the return loss — CACP.

and measured results we have an error approximately equal to 13%. This error is governed by the fabrication process and more specifically on the via realization in the matching structure. Considering future prototypes, one resistor value is selected: $R_{CP} = 9.2\,\mathrm{k\Omega}$.

3.3. Antenna Input Impedance

Figure 6 shows the measured and simulated return losses of the CACP antenna. As can be observed, the proposed antenna shows a resonant frequency equal to 2.45 GHz, with −25 dB return loss. This proposed



(a) (b)

Figure 7. (a) Measured RF/DC conversion efficiency as a function of the power density, when the emitting power rises from $P_t = -2\,\mathrm{dBm}$ to $P_t = +40\,\mathrm{dBm}$. (b) Rectenna prototype.

antenna provides second and third harmonic rejection property. The fourth harmonic provides a -3 dB return loss. Good agreement is obtained between the simulated and experimental results.

3.4. Rectenna Efficiency Evaluation Method

As defined previously (Equation (1)), the conversion efficiency η_{rec1} is defined as the ratio of DC power P_{DC} to received power P_r. Measurement of P_r is not a straightforward procedure as the prototype does not have a measurement point to evaluate P_r. But using the Friis equation, P_r can be approximated by $P_{r_{Friis}}$ (3) [13].

$$\eta_{rec2} = \frac{P_{DC}}{P_{r_{Friis}}} = \frac{(4 \cdot \pi)^2 \cdot R^{\alpha} \cdot \frac{V_{R_{CP}}}{R_{CP}}}{P_t \cdot G_t \cdot G_r \cdot \lambda_0^2 \cdot \gamma} \tag{3}$$

where P_t and G_t represent the transmit power and transmitting antennas gain, G_r the receiving antenna gain, λ_0 the free-space wavelength of the incoming wave, and R the distance between the antennas. α equal to 2 and γ equal to 0.7 are inherent in the measurement process, which is not performed in anechoic chamber [12].

The effective area of the receiving antenna is evaluated using the following equation:

$$A_e = \frac{\lambda_0^2 \cdot G_r}{4 \cdot \pi} \tag{4}$$

And finally, in order to calculate η_{rec2}, parameters' numerical values are given in Table 2.

Table 2. Relates the antennas performances, given by the simulator Momentum.

G_t	G_r	A_e	R
6.7 dB	4.3 dB	32 cm^2	1.54 m

Furthermore, the rectenna efficiency will be studied as a function of the power density. The power density of the incident wave is determined by:

$$P_D = \frac{P_{r_{Friis}}}{A_e} = \frac{P_t \cdot G_t \cdot \gamma}{4 \cdot \pi \cdot R^{\alpha}} \tag{5}$$

The RF/DC conversion efficiency as the function of power density is depicted in Fig. 7. From this figure, load resistance chosen for the rectenna test as a function of power density is equal to 9.2 kΩ. The measured conversion efficiency provides more than 25% RF/DC conversion over 1 μW/cm^2. An efficiency of 34% occurs at an input power density of S_{RF} equal to 17 μW/cm^2, which is approximately $P_r = -10$ dBm.

4. DISCUSSION AND CONCLUSIONS

We have proposed in this study a rectenna with an aperture coupled patch antenna operating at a single ISM-band frequency (2.45 GHz). The CACP with a stub length equal to 110 mm avoids the re-radiation of harmonics generated by the diode during the rectifying process. This results can be achieved by the integration of the band pass filter of the rectenna in the proposed aperture coupled patch antenna. This integration allows a compact rectenna structure. This feature can be interesting to accommodate limited space systems like in wireless sensors networks, where the rectenna circuit can be used as an energy module.

In this work, we have proposed a 34% conversion efficiency rectifier, at low input power level ($P_r = -10$ dBm). In view of these results, in a future work, the objective is to increase the rectenna performance at lower power level (at $P_r = -20$ dBm).

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