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# DESIGN AND EXPERIMENTS OF A 3G-BAND RECTENNA FOR RADIO FREQUENCY ENERGY HARVESTING

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**Key words: Ambient radio frequency (RF), Energy harvesting, Rectenna, Printed antenna, Broadband antenna, Rectifier, Radio frequency (RF)-to-dc converter.**

**RF energy harvesting is the process by which ambient electromagnetic energy from different sources in the environment is captured, converted and stored. It can provide an alternative energy capable of replacing, totally or partially, the batteries of a number of micro-systems and devices that have low energy requirements. In particular, solar energy harvesting has been commonly used to overcome this barrier. However, it should be noted that wireless sensor networks (WSN) operating on solar power suffer form energy shortage during nighttimes. Therefore, to solve this problem, we exploit the use of 3G broadcasts airwaves as energy sources to power wireless sensor nodes. This paper focuses on the design, optimization and experiments of 3G-band rectenna, based on a modified double slot coplanar waveguide (CPW) antenna. It contains also an RF-to-dc conversion circuit based on a zero bias Schottky diode SMS 7630. The reported rectenna have been fabricated and measured for 2100 MHz band. It achieves 400 mV voltage over an optimum load of 1700 Ω and about 50 % efficiency when the incident RF power is –7 dBm. The developed antenna is able to harvest the electromagnetic energy in several communication standards: GSM 900 and 1800, Universal Mobile Telecommunications System (UMTS), Long Term Evolution (LTE) and Wi-Fi. Numerical results and experiments are presented and discussed in this paper.**

## 1. INTRODUCTION

Over the last few years, wireless applications such as frequency modulation radio (FM), TV, GSM, Wi-Fi, 3G, LTE, ... etc., from low to high powers have proliferated in our environment and multiplied broadcasting stations in the townscapes. Most of these broadcasts are omnidirectional and permanent. This availability of radiant energy has interesting uses in a number of low consumption applications. Accordingly, a quantification of electromagnetic power in the surrounding environment was realized at different places in Paris, for several distances from different base stations. These measurements were performed with the portable electromagnetic fields meter (CORNET ED85EX). It operates in the frequency band ranging from 1 MHz to 8 GHz and ranges from –55 dBm to 0 dBm sensitivity [1]. A measurement campaign was conducted in various locations, high streets, mainly railway stations and shopping centers. The RF bands measured in the study are listed in table 1. This measurement has shown a large variability of the ambient electromagnetic field. These measures are timed and registered in order to get an idea of the evolution of RF signals. Figure 1 shows the measured RF power in some locations. The highest average power densities measured in outdoor were predictably in the GSM 1 800, 3G (2 100 MHz) and 4G (2 600 MHz) bands. The highest peak power density measurement was –7 dBm at "Place de la République" with Orange operator in the GSM 1 800/LTE 2 600/UMTS 2 100 band [2].

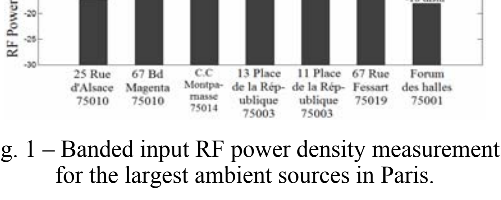

Fig. 1 – Banded input RF power density measurements for the largest ambient sources in Paris.

*Table1*

Radio frequency bands measured in the energy density study

| Band | Frequencies (MHz) |
|---|---|
| GSM/4G LTE 900 | 791–960 |
| GSM/4G LTE 1800 | 1710–1876 |
| 3G (MTx) | 1920–1980 |
| 3G (BTx) | 2110–2170 |
| ISM WiFi 2.4 GHz | 2400–2495 |
| 4G LTE 2600 | 2500–2690 |

In the last years, a great focus has been given to the possibility of harvesting the electromagnetic energy in the wireless standards bands. A new technology providing green energy, from ambient electromagnetic fields intended to be wasted, has been developed. The key component of this new technology is called a rectenna for rectifying antenna [3]. The basic architecture of a rectenna is shown in Fig. 2. It consists of a receiving antenna which captures radio-frequency (RF) waves, and an RF-to-dc (direct current) rectifying circuit which converts the received microwave energy into electrical energy. The RF-to-dc conversion process produces high order harmonic components because of the non-linear characteristic of diodes (or transistors) components. These frequency components are highly unwanted; they could decrease efficiency and create electromagnetic pollution, it is essential to filter them. An input HF filter, placed between the antenna and the rectifier ensures impedance matching and also prevents high order harmonics to be radiated by the antenna. This approach allows maximizing the amount of power transferred between the antenna and the rectifier and also maximizes the conversion efficiency. Besides that, the output filter transmits the dc component to the load and filters all high frequencies (HF). Thereby, all high order harmonics are confined between the input HF and the dc output filters [4]. Dipoles and patch, with linear or circular polarization and high gain, are mostly used to

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make rectennas [5]. Circular polarization is a very important feature in the design of rectennas dedicated to harvest energy in multipath environment. It allows maintaining a constant output dc voltage regardless the polarization angle of the incident waves [6, 7]. Recently, several rectennas have been proposed in the literature [3–15]. Rectennas dedicated and operating in the ultra high frequency radio frequency identification (UHF RFID) have been also proposed in [8–11]. In [8], it has been shown that the conversion efficiency exceeds 30 % with 100 µW RF input power. Authors in [9] propose a triple-band rectenna able to operate at 900, 1 760 and 2 450 MHz. A conversion efficiency of 40 % at 900 MHz for an RF input power of 2.1 mW has been achieved. The solution proposed in [10] uses a monopole-based rectenna for microwave energy harvesting of the UHF RFID systems. A conversion efficiency of 54 % with a power density of 80 µW/cm² has been achieved. A compact modified bow-tie rectenna with four-diodes bridge rectifier has been presented in [11]. Experimental results show that at 866 MHz UHF RFID frequency, 65 % RF-to-dc conversion efficiency has been obtained when the incident power density is 60 µW/cm².

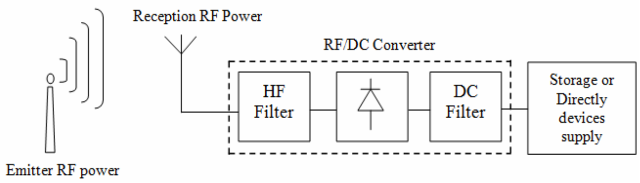

Fig. 2 – Block diagram of a conventional rectenna.

Rectennas devices operating in other frequency ranges have been proposed in [12–15]. In [12] a hybrid sensitive rectenna at 2.45 GHz has been proposed. The measured conversion efficiency achieves a maximum of 65% when the incident RF power is 30 dBm. Industrial scientific medical (ISM) band rectenna at 2.45 GHz, using a ring loaded monopole has been proposed and discussed in [13]. When the incident power density on the monopole is 155 µW/cm²; the maximum measured conversion efficiency reaches 65 %. Rectenna working at 2.45 GHz, and using a compact dual circularly polarized patch antenna has been proposed in [14]. A conversion efficiency of 63 % is obtained with a power density of 525 µW/cm². In [15], the authors proposed an ISM band dual patch rectenna, capable of achieving more than 80% RF-to-dc conversion efficiency at low/medium power densities. It exhibits 73 % measured efficiency at a low power density of 14 µW/cm² and 84 % at 43 µW/cm².

This paper focuses on the design, optimization and experiments of 3G-band rectenna circuit dedicated to harvest electromagnetic waves in surroundings at 2 100 MHz frequency band. The antenna part is designed and optimized under Ansys HFSS software [16]. It consists of a modified double slot antenna optimized to work in the [0.9–3] GHz band. An experimental measurement shows that the proposed rectenna achieves a conversion efficiency of about 50 % when the captured RF power level is only –7 dBm. The paper is organized as follows. Section 2 presents the modified double slot antenna as well as the experiments carried out on the designed antenna. The RF-to-dc rectifier and the realized experiments are presented in Section 3. The experiments of energy harvesting carried out on the rectenna circuit are presented in Section 4. Finally, conclusion is given in Section 5.

## 2. DESIGN, OPTIMIZATION AND EXPERIMENTS OF THE MODIFEID DOUBLE SLOT ANTENNA

The proposed antenna is etched on low cost FR4 epoxy substrate with 1.6 mm thickness, relative permittivity $\varepsilon_r$ of 4.4 and 0.02 loss tangent. It consists of a modified wideband double slot antenna, derived from a conventional structure proposed in [17] and designed to work in the [1–3] GHz frequency band. The antenna, with ground-plane dimensions of 75 mm × 80 mm, is simulated and optimized under Ansys HFSS software. The design variables $r_1$, $r_2$, $r_3$ and $d$ are indicated in Fig. 3a. The radiating structure is constituted of two imbricated circular slots of radii $r_1$ and $r_3$, etched on the ground plane. It is fed by a 50 Ω CPW (CoPlanar Waveguide) line of 3 mm width. The slots width between the line and the ground plane is 0.4 mm. The choice of a CPW structure on one coppered layer allows radiation within both half-planes. The initial structure was modified and optimized. The objective is to increase the frequency bandwidth, especially to cover the GSM 900 band. As shown in Fig. 3b, many parts of copper were removed around the antenna. Also, notches were etched on the disc of radius $r_2$ and a small disc was added in the center of the minor slot. As a final step, one ellipse and two small circles were added on the major slot in order to improve the input impedance matching of the antenna over the frequency band of interest. The HFSS simulated input reflection coefficient ($S_{11}$) of antennas D1 (Fig. 3a) and D2 (Fig. 3b) are plotted and compared in Fig. 4. It can be observed that the bandwidth ($|S_{11}| < -10$ dB) of the proposed design D2 is improved. Indeed, the antenna D1 proposed in [17] operates from 1.17 to 3 GHz, whereas the antenna D2 proposed in this paper covers the frequency band ranging from 917 MHz to over 3 GHz.

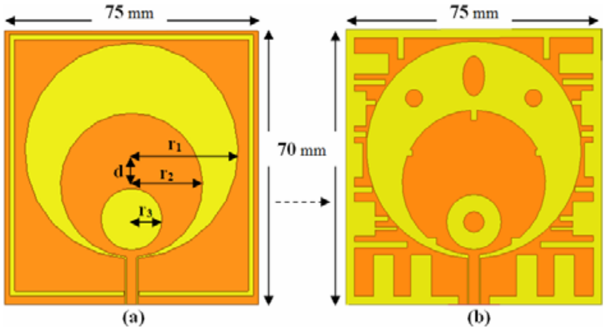

Fig. 3 – Design topology of double slot antenna: a) Conventional structure of double slot antenna D1; b) modified double slot antenna Design D2.

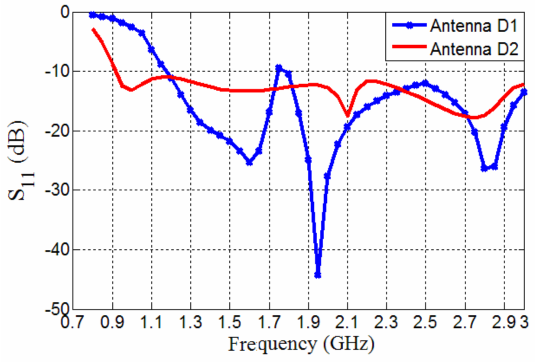

Fig. 4 – Comparison between the reflection coefficients corresponding to antennas D1 and D2.

The proposed antenna has been realized and experimentally measured; the prototype is shown in Fig. 5. Figure 6 shows a comparison between the simulated and measured input reflexion coefficient ($S_{11}$) against frequency between 0.7 GHz and 3 GHz. Measurements of the reflection coefficient were performed by using Vector Network Analyzer (VNA). Results are in good agreement with simulations. From measurements, it seen that the proposed modified double slot antenna exhibits an input reflection coefficient ($S_{11}$) less than –10 dB in the frequency ranges from 0.866 to 1.41 GHz and from 1.7 to 3 GHz. This corresponds to a relative bandwidth of 103 %. The reported antenna is able to harvest electromagnetic waves in several standards bands: GSM900, GSM1800, DECT, UMTS, Wi-Fi and LTE. Also, the antenna radiation pattern and maximum gain have been characterized.

Table 2 shows the measured gain in the broadside direction for different frequencies ranging from 0.9 to 3 GHz. A maximum gain of 4.94 dB was observed at 2.1 GHz.

Figure 7 shows the H-plane radiation pattern for the selected five frequencies 0.9, 1.8, 2.1, 2.45 and 2.7 GHz, which indicates an omnidirectional radiation patterns.

*Table 2*

Experimental antenna (D2) gain

| Frequency (GHz) | 0.9 | 1.8 | 1.9 | 2.1 | 2.4 | 2.45 | 2.7 | 3 |
|---|---|---|---|---|---|---|---|---|
| Gain (dBi) | 1.25 | 2.09 | 2.91 | 4.94 | 4 | 2.61 | 2.68 | 1.98 |

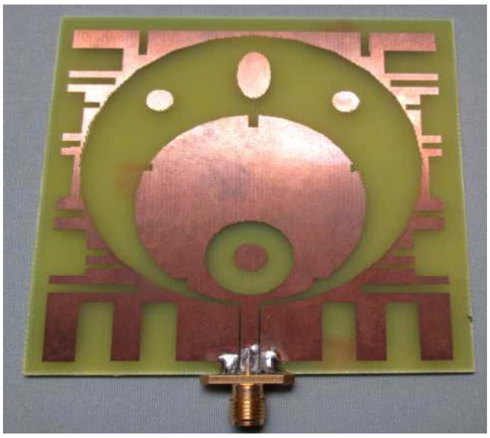

Fig. 5 – Photography of the realized modified double slot antenna.

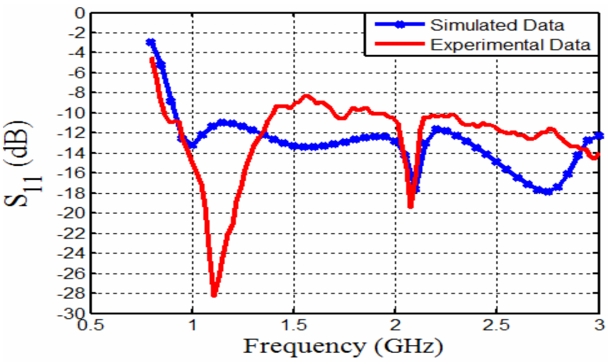

Fig. 6 – Comparison between measured and simulated $S_{11}$ obtained for the prototype of the modified double slot antenna (D2).

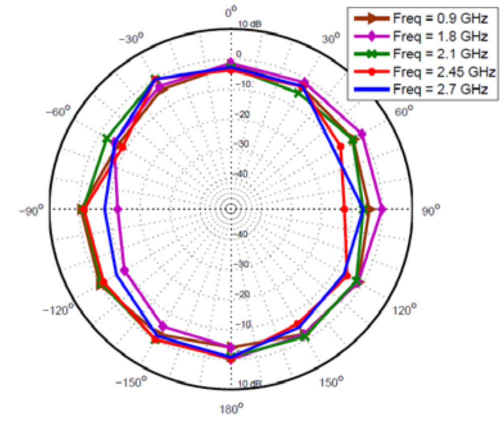

Fig. 7 – The antenna (D2) H-plane radiation pattern.

## 3. RF-TO-DC RECTIFIER: DESIGN AND EXPERIMENTS

In order to experimentally validate the performances of energy capturing of the proposed antenna at 2 100 MHz frequency band, a CPW RF-to-dc rectifier has been designed and simulated under advanced design system (ADS) software [18]. Simulations were performed by mixing harmonic balance and momentum electromagnetic simulators. The schematic representation of this rectifier is shown in Fig. 8. The structure is simple and efficient, it consists of a parallel inductor [19] placed at the input of the circuit to provide matching, a series Schottky diode [20] which rectify RF waves, and an output bypass capacitor as dc filter. The values of the lumped elements and distances between them were optimized in order to maximize the RF-to-dc conversion efficiency (η), which is defined as the ratio between the dc power that transmitted to the load and the captured RF power. It is expressed as

$$\eta[\%] = 100\frac{P_{dc}}{P_{rf}} = 100\frac{P_{dc}}{P_{dc}+P_{loss}}, \tag{1}$$

where $P_{dc} = V_{out}^2/R_L$ and $R_L$ is the load resistance, $P_{dc}$ is the dc output power across $R_L$. $V_{out}$ is the dc output voltage across $R_L$, and $P_{loss}$ is the losses power.

A prototype has been fabricated on a FR4 substrate as shown in Fig. 9. Corresponding CPW line length and value of the lumped elements are given in Table 3. The circuit is characterized alone by connecting an RF generator to its input and a resistive load to its output. Each measurement is repeated for several load resistor values, eight resistor values are selected, which are 700, 900, 1000, 1 500, 1 700, 1 900, 2 000 and 3 000 Ω. Figures 10 and 11 show, respectively, the measured output dc voltage and conversion efficiency against the output load for several input RF power levels. The maximal efficiency is obtained when choosing a 1 700 Ω output load for any input RF power level.

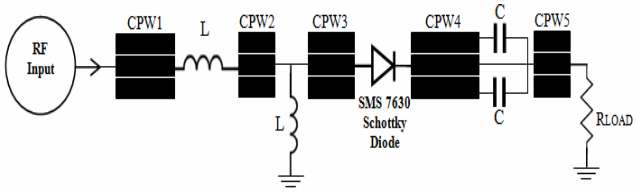

Fig. 8 – Representation of the series microwave rectifier.

*Table 3*

Parameters of the proposed rectifier

| CPW1 | L | CPW2 | CPW3 | CPW4 | C | CPW5 |
|---|---|---|---|---|---|---|
| 8.15 mm | 10 nH | 1 mm | 1.84mm | 11.5mm | 180 pF | 4 mm |

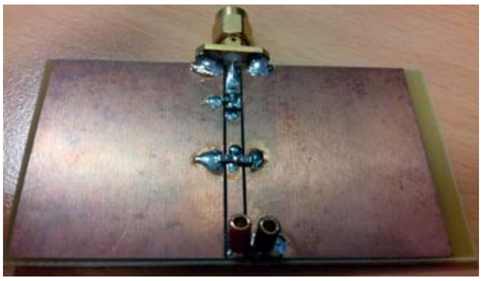

Fig. 9 – Photography of the realized series-topology microwave rectifier.

Using this optimal load (1 700 Ω), measurements of the conversion efficiency performed by varying the frequency of the incident signal on the rectifier is illustrated in Fig. 12. The maximum of conversion efficiency should be measured at 2 110 MHz, which is the highest energetically free frequency band.

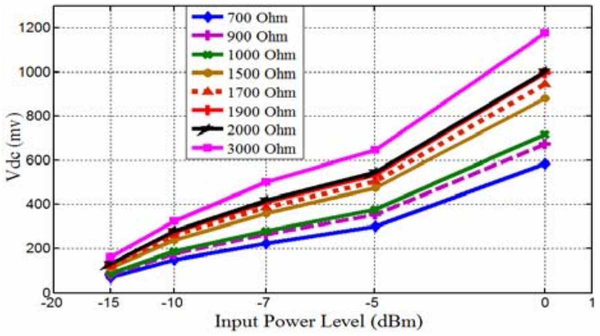

Fig. 10 – Measured output voltage against input RF power.

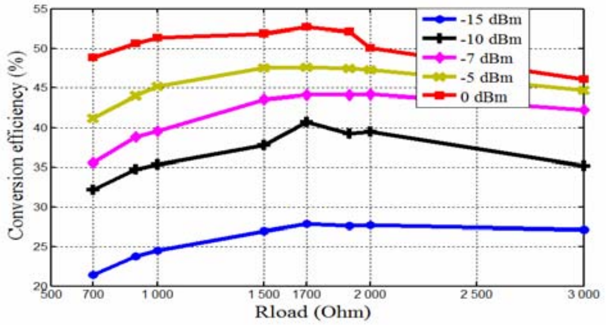

Fig. 11 – Rectifier efficiency as function of the power level for different values of the resistive load.

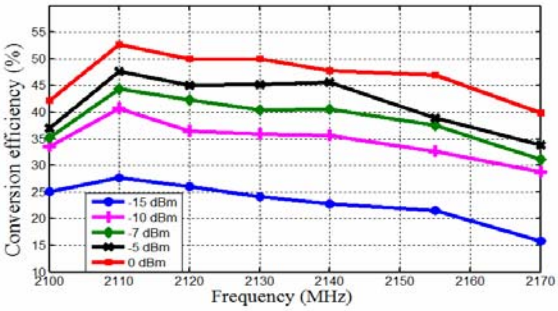

Fig. 12 – Rectifier efficiency with variation in input frequency.

## 4. RECTENNA CIRCUIT: ENERGY HARVESTING EXPERIMENT

After the microwave rectifier experiments and validation, the rectenna composed of the antenna and rectifier has been used to harvest RF energy. Figure 13 shows the photography of the realized rectenna. The setup presented in Fig. 14 allows to measure the harvested voltage for different RF power levels. It contains an RF generator connected to a 3.5 dBi gain antenna [21]. Measurements were performed in the far field conditions, the distance between the rectenna and the transmitter was set to 1 meter.

Measurements for this type of system are usually performed in a controlled environment (e.g., an anechoic chamber or transverse electromagnetic cell), using a dedicated constant or variable amplitude single-tone RF signal source. Our measurements were realized in free environment; without an anechoic chamber allows the antenna to recover others RF signal.

Hence, the output dc voltage and overall efficiency as function of the power density were measured for different RF incident power on the antenna by varying the power level of the RF generator. The output load was set to the optimal value 1 700 Ω. Figure 15 presents the conversion efficiency for different frequency bands. For an RF signal with a power level of –7 dBm received by the modified double slot rectenna, an output dc voltage of 402 mV and an RF-to-dc conversion efficiency of 48 % at 2 110 MHz were measured.

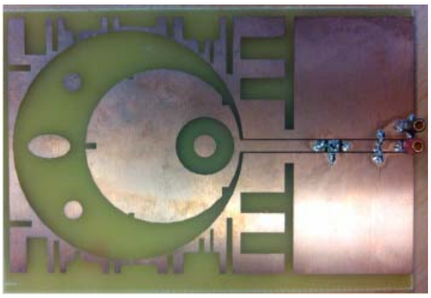

Fig. 13 – Photography of the realized rectenna.

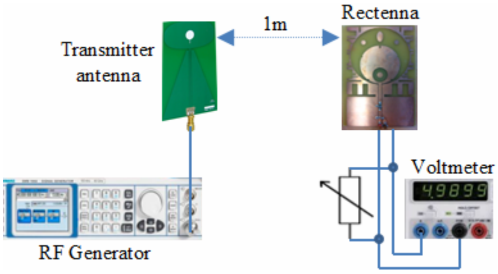

Fig. 14 – Rectenna measurement system.

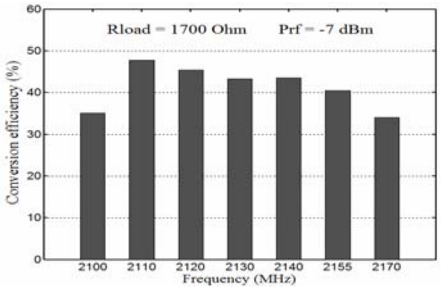

Fig. 15 – Measurements of the conversion efficiency performed by varying the frequency of the incident signal on the rectenna at 2 100 MHz band.

Finally, outside measurements were performed to validate the rectenna in the ambient environment. According to the various measurements of RF power in the surrounding environment and shown in Fig. 1, "Place de la République" seems to be an interesting measurement point since, the ambient RF energy is relatively high (–10 to –7 dBm).

Figure 16 shows the experiment used to collect the ambient RF waves. In this experience the rectenna load is always 1 700 Ω. The dc voltage harvested and measured at the output port of the rectifier using a voltmeter, is about 190 mV. This result is in good agreement with those of Fig. 10 where the dc voltage was about 200 mV for an input RF power level of –10 dBm.

Fig. 16 – Measurement of the proposed rectenna output dc voltage as a function of the ambient RF signal harvesting in urban environments.

## 5. **CONCLUSIONS**

In this paper, a wideband antenna for an RF energy harvesting applications has been proposed, designed and characterized. Experimental results demonstrate that the harvesting device here described is well suitable to operate in the 2 100 MHz frequency band at very low power levels (~ –10 dBm). The rectenna fabricated prototype on low cost FR4 substrate has a medium efficiency of 48 % with an input power density about –7 dBm.

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