A Wideband and Compact Circularly-Polarized Rectenna for Low Power Application

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***Abstract*— This paper presents a wideband and compact circularly polarized rectenna composed by an Archimedean spiral antenna that covers the S and C frequency bands and a silicon Schottky diode. This rectenna (rectifier + antenna) is used for electromagnetic energy harvesting over a wide frequency band, in order to power autonomous wireless sensors used for satellite health monitoring. For low incident power densities (around 14 µW/cm²) the measured efficiency of at least 19% between 2GHz and 3.5GHz can be achieved using this rectenna. The efficiency may reach 37% at some frequencies in this wideband operating bandwidth.**

Keywords—rectenna; Archimedean spiral antenna; electromagnetic energy harvesting; efficiency.

I. Introduction

The geostationary broadcasting satellites use high-gain directive RF/microwave antennas in order to establish high-reliable data links between the satellite and Earth. These antennas located on the satellite panels are fed with a high RF power (typically in the range of 100 W) in order to overcome the very high propagation losses. A very promising solution for surveying the health of antenna panels is to use small autonomous Wireless Sensors (WSs) composed by one or more sensors connected to a low power transmitter/transceiver. WSs used for thermal or for mechanical/structural health monitoring (SHM) of antenna panel save the cost and the mass of deploying long wires in harsh environments. In some areas located on antenna panels of broadcasting satellites, the electric field generated by the spill-over loss of microwave antennas is significant. The maximum levels (effective value) can reach 40 V/m in C-band, 49.5 V/m in X-band, 106 V/m in Ku-band and 127 V/m in K-band. These high-frequency electromagnetic field levels are available on satellites and can be almost constant as far as the data links are functional. The concept of electromagnetic energy harvesting for powering autonomous WSs for SHM of the broadcasting satellite antenna panels was detailed in [1]. Several linearly-polarized rectennas were designed, manufactured and characterized in order to prove the feasibility of such concept [1]-[2]. But most of the environmental E-field available on broadcasting satellites is generated by circularly-polarized microwave antennas. A wideband circularly polarized rectenna operating in C and S bands is addressed in this paper. We note also that very few papers deal with the design and the experimentation of circular polarized antennas covering the C and S bands [3]-[4]. The proposed topology is described in Section II, and the obtained experimental results are presented and discussed in the Section III.

II. Description of the Rectenna

The proposed rectenna is composed by a circularly-polarized compact and wideband Archimedean spiral antenna and a silicon Schottky diode SKYWORKS SMS7630. The miniaturization technique [5] applied here for reducing the diameter of the antenna consists of stacking resonant metallic rings below the radiating surface. Using rings with irregular contours (such as, e.g., crenelated, sinusoidal or pre-fractal contours) allows reducing the antenna diameter without significantly modifying the axial ratio, gain and highest operating frequency of the wideband antenna [6]. In this paper, one ring only is used for surrounding the spiral but, additional rings could be stacked below the surface in order to reduce more the diameter of the antenna [7]-[8]. The resulting wideband and compact antenna exhibits very good performances in terms of gain and circular polarization purity over a wide bandwidth (2 to 6 GHz, covering most of the available S and C band) [9]. Fig. 1(a) and 1(b) display respectively the fabrication layout of the antenna and rectifier. Fig. 1(c) shows the photo of the final rectenna prototype obtained by assembling antenna and rectifier parts.

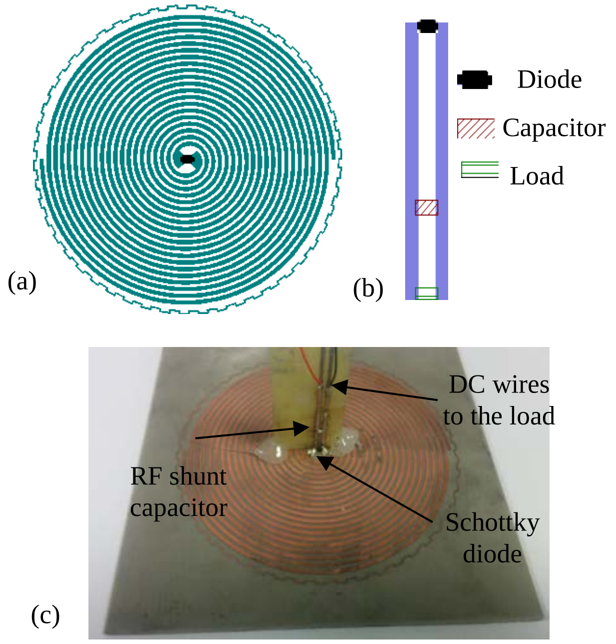

Fig.1. Topology of the proposed rectenna: (a) antenna layout (top view), (b) rectifier layout, and (c) manufactured rectenna (photo).

A. *Compact Archimedean spiral antenna*

The Archimedean spiral antenna is composed of two arms with a constant width flaring away from the center, imbricated with each other and having the same origin. Each arm of the spiral antenna is defined by the equation 1.

$$R = a.\theta \tag{1}$$

Equation 1 states that the radius r of the antenna increases linearly with the angle θ. The parameter "a" is a constant that controls the expansion of the Archimedean spiral arm. The second arm is the same as the first but rotated 180°. The feeding of the antenna is placed directly across the two arms of the spiral. The perimeter associated with the internal radius R_{MIN} determines the highest operating frequency f_{MAX} while the perimeter associated with the external radius R_{MAX} determines the lowest operating frequency f_{MIN} as follows [6]:

$$f_{MIN} = c/2\pi R_{MAX} \tag{2}$$

$$f_{MAX} = c/2\pi R_{MIN} \tag{3}$$

where c denotes the velocity of light. The theoretical input impedance (obtained from the Babinet's principle) of the spiral antenna (without the metallic ring) is of 185Ω. Practically, the real part of the impedance is less than 185Ω with a low (inductive) reactance of few Ω. The designed spiral antenna is printed on Neltec substrate (Nx9240: substrate thickness: 1.5 mm, relative dielectric permittivity: 2.4 and dielectric loss tangent 0.0016). Fig.2 shows the simulated (by using HFSS software) input impedance Z_{IN} of the spiral antenna loaded by one crenelated ring shown in Fig 1 (a). The input impedance is approximately constant over the entire frequency band and is about 140Ω +j5Ω.

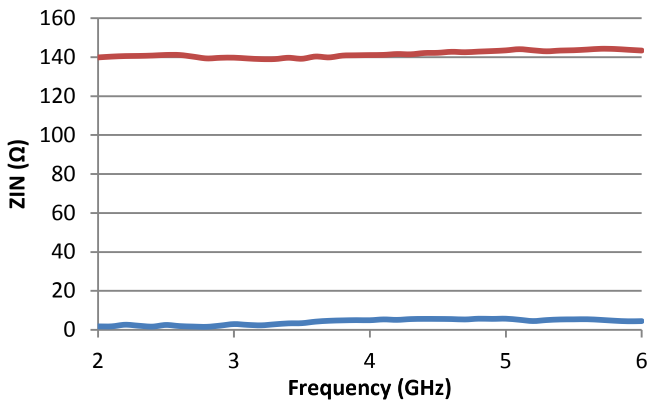

Fig. 2. Input impedance Z_{IN} of the designed Archimedian spiral antenna loaded by one crenelated metallic ring as a function of the frequency (simulation results obtained from HFSS sofware): real part of Z_{IN} (red curve) and imaginary part of Z_{IN} (blue curve)

The antenna radiates in the two directions normal to the radiating surface. The simulated highest gain as a function of frequency is shown in Fig 3. The radius (R_{MAX}) of this antenna is 3.8 cm (4 cm by including the crenelated outer ring).

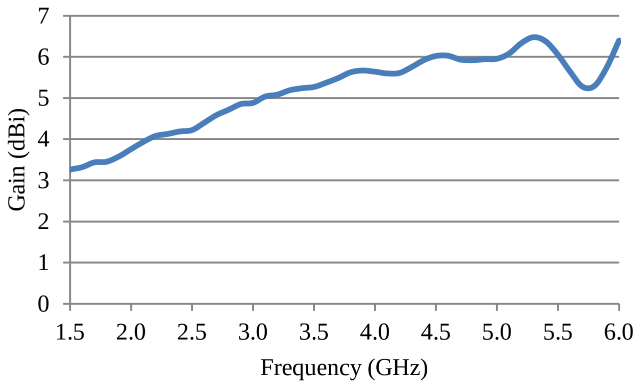

Fig. 3. Gain of the designed Archimedian spiral antenna loaded by one crenelated ring as a function of the frequency (simulation results obtained from HFSS sofware)

B. *Rectifier*

The rectifier circuit consists of a Schottky diode SKYWORKS SMS7630 that rectifies the radiofrequency (RF) signal delivered by the antenna, the 10 pF RF shunt capacitor that rejects the fundamental frequency and its harmonics, and a load (sensor impedance). Coplanar striplines (CPS) are used here to interconnect the various parts of the rectifier. A single diode mounted in shunt configuration is used. This choice is motivated by the two following justifications: (i) as the available E-field is quite low, the use of a single diode (instead of multiple diodes) is preferred for reaching good efficiencies and (ii) according to [10], the input impedance of the rectifier is estimated to be of 180 Ω with a small (capacitive) reactance of few Ω, that is, an impedance close to the complex conjugate of the antenna input impedance. Fig. 4 shows the ADS schematic of the rectifier circuit. The diode is connected at the input port of the antenna. The impedance of the port is chosen to be the very close to the input impedance of the antenna. Moreover, the distance between the diode and the capacitor is of 1cm. This distance was carefully adjusted in order to compensate the reactance of the diode, then improving the matching between the antenna input port and the rectifier. A co-simulation technique was adopted by using: (i) the harmonic balance simulator of the ADS in order to take into account the non-linearity of the diode and, (ii) the full-wave electromagnetic simulation (performed by using Momentum module of the ADS) for the overall CPS supported structures.

The SMS7630 Schottky diode was chosen due to its low threshold voltage, which allows operating at low RF input power. The SMS7630 diode has the following parameters: ohmic resistance $R_s = 20\Omega$, junction capacitance $C_{j0} = 0.14$ pF, saturation current $I_s = 5$ µA, forward voltage $V_f = 0.34$V, reverse breakdown voltage $B_v = 2$V and the current at reverse breakdown voltage $I_{bv} = 0.1$mA.

A low cost FR4 substrate was used (substrate thickness: 0.8 mm, relative dielectric permittivity: 4.4 and dielectric loss tangent: 0.018) for fabricating the rectifier. The simulations performed by using the model of Fig. 4 demonstrates that the maximum harvested DC power of 128µW is reached at the frequency of 3.2 GHz. The (simulated) resulting efficiency is then of 40%.

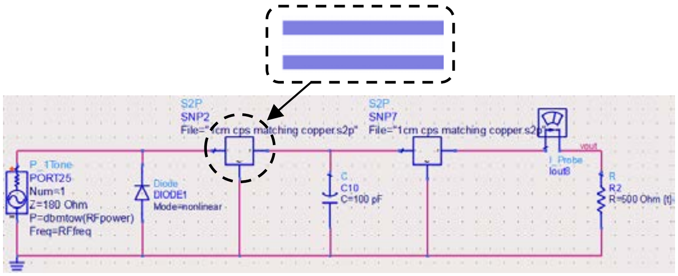

Fig. 4. Circuit model used for the co-simulation of the rectenna: the harmonic balance technique available in the ADS simulator is applied for taking into account the non-linearity of the diode while the Momentum module of the ADS is used for the fullwave electromagnetic similation of the overall CPS supported structures.

III. Experimental Results and Discussion

The compact spiral antenna loaded by one crenelated metallic ring is printed on Neltec substrate and its size is about 9x9cm². The diode is mounted on the center of the antenna, the capacitor and the load are mounted on the CPS supported PCB, connected in parallel with the antenna and the diode (via the CPS). In order to derive the optimal load impedance, wires are used for connecting the rectenna to an adjustable resistor.

The experimental setup shown in the Fig. 5 was used for measuring the performances of the rectenna. A microwave signal generated from an Anritsu MG3694B generator is injected at the input of a transmitting (Tx) antenna. A wideband balun is used here in order to match the spiral input impedance (180Ω) to the input impedance of the power generator (50Ω).

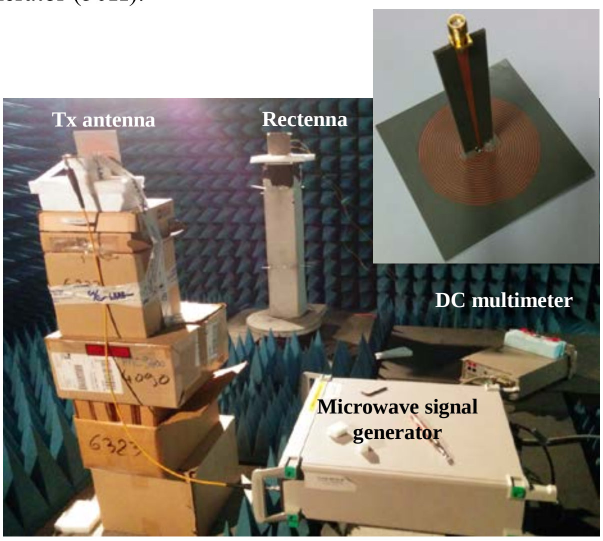

Fig. 5. Experimental setup for measuring the performances of the rectenna

The Tx-antenna illuminates the rectenna under test with a circularly-polarized electromagnetic field. The harvested DC voltage is measured by using a DC multimeter and the DC power is derived from this voltage as long as the load impedance is known. The measured losses due to the coaxial cables, the connectors and the balun are close to 1.2 dB in the entire operating frequency band. The Tx and Rx antennas are two identical spiral antennas, the Tx antenna is connected to the wideband balun while the Rx antenna is connected to the rectifier.

The efficiency η (in %) of the rectenna can be computed by using the following expression [11]:

$$\eta = \frac{P_{DC}}{S \cdot A_{eff}} \cdot 100 = \frac{4 \cdot \pi \cdot P_{DC}}{S \cdot G_R \cdot \lambda^2} \cdot 100 \qquad (4)$$

where P_{DC} is the harvested DC power, S is the incident electromagnetic power density, A_{eff} is the antenna effective area, G_R is the gain of the spiral antenna and λ is the wavelength of the illuminating electromagnetic wave. The power density (µW/cm^2) can be computed as a function of the E-field effective value E (V/m) on the antenna surface or as a function of the RF power P_t injected to the input of the transmitting spiral antenna of gain G_t and positioned at the distance d from the rectenna, as follows:

$$S = \frac{E^2}{120 \cdot \pi} \cdot 100 = \frac{30 \cdot P_t \cdot G_t}{d^2 \cdot 120 \cdot \pi} \cdot 100 \qquad (5)$$

The E-field and the power density illuminating the rectenna can be computed as function of G_t , P_t and d by using eq. (5). The gain of Tx-antenna, and consequently the E-field which illuminates the rectenna, is not constant over the wide operating bandwidth. The resulting harvested DC power at the input port of a resistive load (500Ω) is displayed as a function of frequency in Fig. 6. DC power higher than 70µW is harvested between 2GHz and 3.5GHz for E-field varying from 6.2 V/m to 7.2 V/m. In Fig. 6 the E-field may vary between 5.5 V/m (at 6 GHz) and 10 V/m (at 1.5 GHz), depending on the Tx-antenna gain.

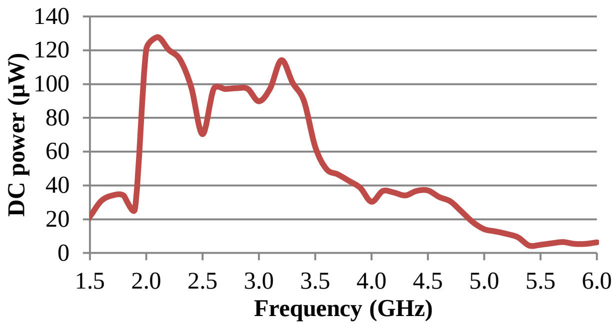

Fig. 6. Measured DC power at the input port of the rectenna load (500Ω) as function of frequency. The illuminating E-field varies from E=5.5 V/m to E=10 V/m, depending on the Tx-antenna gain at the considered frequency.

The spiral rectenna allows obtaining efficiency higher than 19.5% between 2GHz and 3.5GHz. An efficiency of 37% is reached at f=3.2GHz for an E-field of 7.2V/m, as shown in Fig. 7. The efficiency exceeds 5% in the 1.6 GHz to 5.2 GHz frequency band. Fig. 8 displays the efficiency at 3.2 GHz as a function of the E-field computed at the surface of the rectenna. The efficiency is higher than 20% and as expected, it reaches 37% for an incident field of 7.2 V/m. Fig. 9 shows the measured DC power at 3.2 GHz (for a rectenna load of 500 Ω) as a function of the illuminating E-field.

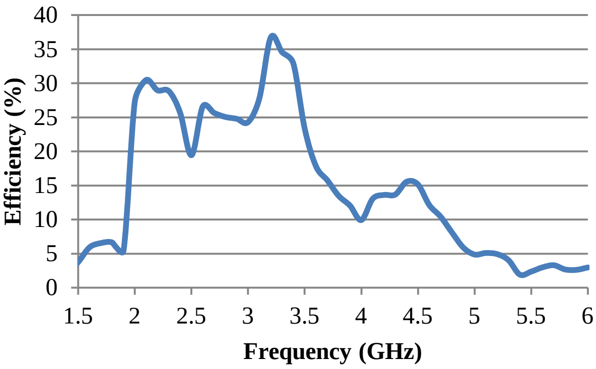

Fig. 7. Measured efficiency at the input port of the rectenna load (500Ω) as a function of frequency. The illuminating E-field varies from E=5.5 V/m to E=10 V/m depending on the Tx-antenna gain at the considered frequency.

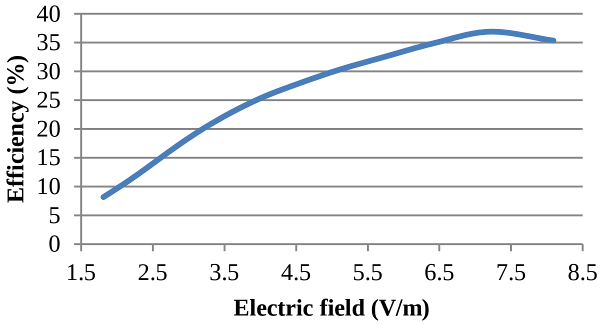

Fig. 8. Measured efficiency at the input port of a load (500Ω) as a function of the incident electric field magnitude.

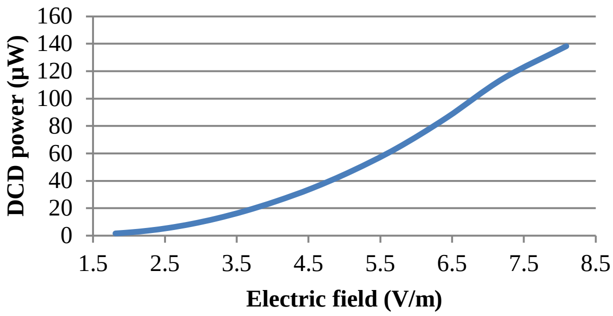

Fig. 9. Measured DC power at 3.2 GHz (for a rectenna load of 500 Ω) as a function of the incident electric field magnitude.

The load resistance of the rectennna that maximizes the received DC power was 500 Ω (results not depicted here).

It is quite difficult to compare our design with existing state of the art circularly polarized rectenna because there are very few designs covering the targeted frequency band. A 64-element rectenna array operating in 2-18 GHz frequency band was presented in [3]. The base element of the (DC connected) array is a rectenna using a log-periodic spiral antenna. The measured conversion efficiency ranges in the 2-8 GHz frequency band from 0.1% (incident power density of 0.05 µW/cm^2) to 20% (incident power density of 70 µW/cm^2). The size of this 64 rectenna array exceeds by far the size of our design. A rectenna using an Archimedean spiral covering the frequency band of 1-4 GHz and implemented on textile substrate is presented in [4]. The announced efficiency for this rectenna (spiral antenna radius: 115mm) was in the range of 30-40% when the available RF power was in the range of -65dBm but no measurement curves are presented and the experimental setup is not well described.

IV. Conclusion

A compact and wideband circularly polarized rectenna using an Archimedean spiral antenna was designed, fabricated and measured. The experimental results show that this rectenna exhibits good performances (harvested DC power higher than 70 µW and efficiency higher that 19.5%) over a wideband frequency band (2 to 3.5GHz). For an incident electric field of 7.2 V/m and a load (sensor impedance) of 500Ω, DC power close to 120µW can be reached with an efficiency of 37%. As compared with the state of art designs the proposed design exhibits a better trade of in term of efficiency, operating bandwidth and compactness.

Acknowledgments

The authors acknowledge the French Space Agency (CNES) and the French Defense Agency (DGA) for financial support and technical contribution. They acknowledge Jérémy Valleau for his contribution in the design and characterization of the compact spiral antenna loaded by one crenelated ring.

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