Compact C-band Rectenna for Satellite Applications

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***Abstract*—This paper addresses the design and the characterization of a compact C-band rectenna for satellite applications. The proposed flat dipole rectenna achieves an efficiency of 58.2% at 3.25 GHz when illuminated with an electromagnetic power density of only 33.9 µW/cm^2. The proposed rectenna is also compact; its size is 1334 mm^2 that is only 16% of the square wavelength at 3.25 GHz.**

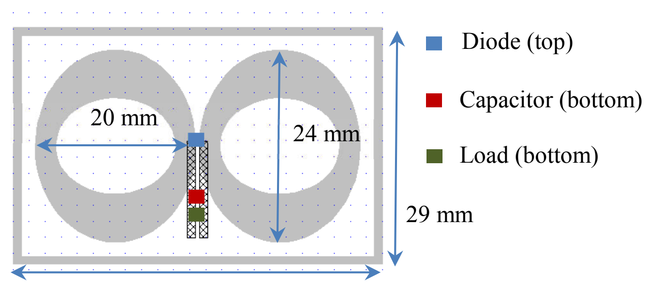
***Index Terms*— RF and microwave energy harvesting, rectenna, wireless power transmission**

I. Introduction

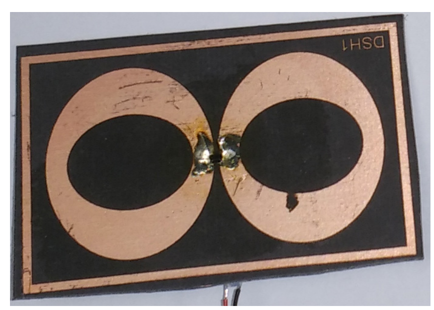
The high gain microwave antennas, mounted on the external panels of the geostationary telecommunication satellite, are fed by high RF & microwave power (in the range of 100 W). The electric field generated by the spill-over loss of these microwave antennas can reach the following highest levels (effective values): 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 [1]. Consequently, an important amount of electromagnetic energy is available around the satellite and illuminates the antenna panels. The harvesting of the electromagnetic energy generated by the microwave antennas was identified as an interesting solution to power autonomous wireless sensors. These autonomous wireless sensors can be deployed along the surface of the panels for structure health monitoring [1]. This paper presents recent results obtained in C-band using an innovative rectenna. The proposed rectenna is composed of a flat dipole antenna enclosed by a rectangular ring and a single diode rectifier. The topology and the design methodology are detailed in Section II while the experimental results are presented in Section III.

II. Proposed Rectenna: Topology and Design

The topology of the proposed rectenna is presented in Fig. 1. It consists of a broadband flat dipole antenna (enclosed by a rectangular ring) integrated with a rectifier using a Schottky diode mounted in shunt configuration. The rectangular ring was properly dimensioned in order to lower the resonant/operating frequency of the flat antenna. Due to the use of the outer rectangular ring the size of the flat dipole antenna/rectenna is only of 46 mm x 29 mm. The rectifier is composed of a HSMS2850 Schottky diode from Avago, a shunt capacitor (100pF) and a resistive load. The diode is mounted on the top of the rectenna (as illustrated in Fig. 1) while the shunt capacitor and load are connected on the back-side of the rectenna. Two metallic via-holes are used in order to connect the diode (mounted on the top of the PCB) with the shunt capacitor (located of the bottom of the PCB). The position of the shunt capacitor is critical and impacts the impedance matching between the antenna and the rectifier. Simulations and experiments (not shown here) were performed and the optimal distance (between the shunt capacitor and the diode) is 1.3 cm. Elliptical holes, properly dimensioned (outer radius: 7.5 mm, inner radius: 6 mm) are inserted on the flat dipole in order to reject the high order harmonics generated by the rectifier.



a)



b)

Fig. 1. Flat Dipole Rectenna (FDR): (a) the layout and the main dimensions and (b) photo of the manufactured rectenna.

The Flat Dipole Rectenna (FDR) was designed to operate at 3.4 GHz. At this frequency the satellite antenna panel is illuminated (due to the spill-over losses of the C-band broadcasting antenna) by an electric field: 2 V/m < E-field < 15 V/m (1 µW/ cm^2 < electromagnetic power density < 59.7 µW/cm^2) [2].

III. Simulation and Experimental Results

The Flat Dipole Antenna (FDA) was designed from intensive electromagnetic simulations (method of moments, Altair

FEKO). The highest gain of the FDA is of 2 dBi and can be increased when a metallic reflector is properly positioned behind the antenna. The simulated gain (along the z-axis) of the FDA with the reflector (size: 157 mm x 92 mm) positioned at 27 mm behind the antenna is displayed in Fig. 2 as a function of the frequency. The simulated input impedance is shown in Fig. 3. In order to maximize the performances of the FDR a complex conjugate impedance matching technique (between the rectifier and the FDA) was adopted. The input impedance of the rectifier was initially estimated by using a close-form expression [3]-[4]. At this stage, the impact of the vias-holes, coplanar stripline (on the bottom side) and the mounting position of the RF shunt capacitor are neglected. The position of the shunt capacitor was tuned in order to maximize the FDR performances.

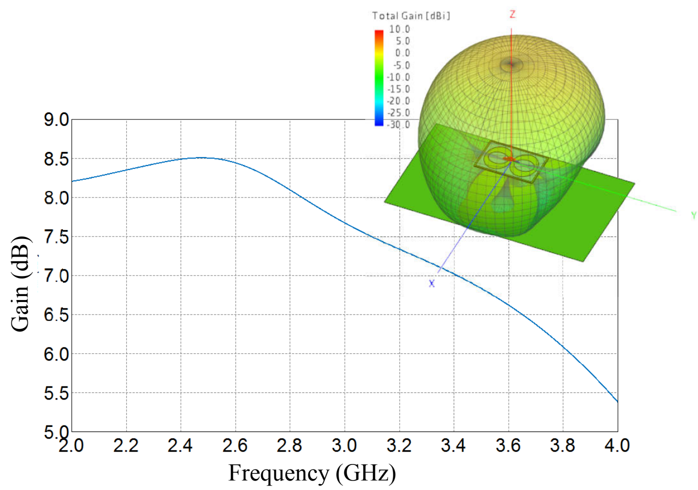


Fig. 2. Simulated (FEKO) maximum gain of FDA as a function of the frequency. The inset shows the 3D (gain) radiation pattern at 3.4 GHz.

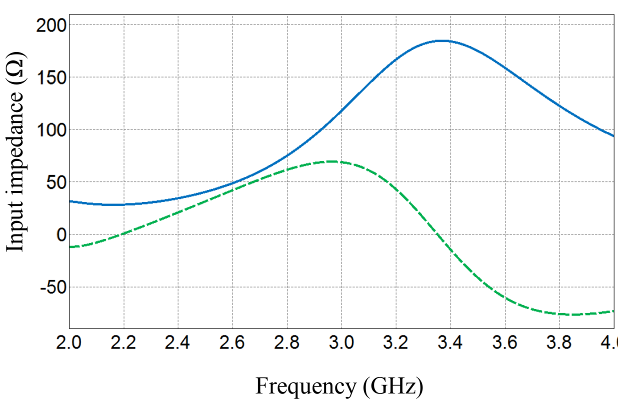


Fig. 3. Simulated (FEKO) input impedance of FDA as a function of the frequency (continuous blue curve: real part; dotted green curve: imaginary part).

The experimental setup positioned in an anechoic chamber (to prevent any interferences or undesirable multipath effects) shown in Fig. 4 was used to characterize the rectenna. A microwave signal generated from the Anritsu MG3694B generator is injected at the input of a transmitting (Tx) horn antenna through a coaxial cable. The horn antenna illuminates the rectenna under test, positioned in the far-field region of the Tx antenna, with a linearly-polarized E-field. An automatic acquisition routine is implemented in Labview software from National Instruments to speed-up the acquisition process. The harvested DC voltage is then measured by using a DC multimeter. The DC power can be derived from the measured DC voltage, as long as the load is known. The RF-to-DC conversion efficiency η (in %) of the rectenna can be computed by using the following expression [5]:

$$\eta = \frac{P_{DC}}{P_{RF}} \cdot 100 = \frac{P_{DC}}{S \cdot A_{eff}} \cdot 100 = \frac{4 \cdot \pi \cdot P_{DC}}{S \cdot G_R \cdot \lambda^2} \cdot 100 \qquad (1)$$

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 (rectenna's) antenna and λ is the free-space wavelength of the illuminating electromagnetic wave at the operating frequency. The electromagnetic power density S can be computed as a function of the E-field effective value E (V/m) on the antenna surface. This value is derived from microwave power P_t injected to the input port of the transmitting horn antenna (gain G_t) positioned at a distance d from the rectenna, as follows:

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

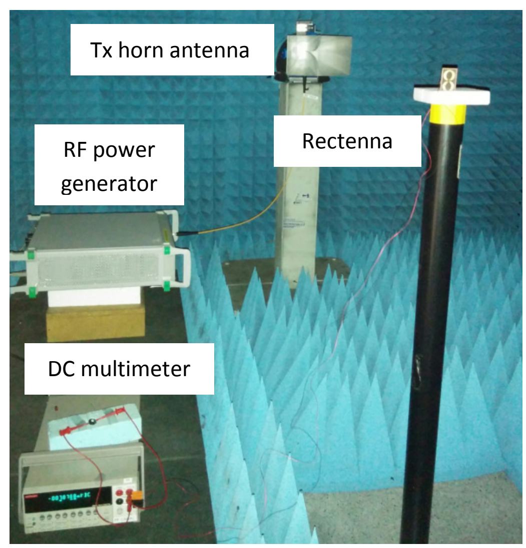


Fig. 4. Experimental setup used to characterize the manufactured rectenna.

A RF power density of 33.9 μW/cm^2 (that roughly corresponds to the average RF power density generated by the spill-over losses of the C-band broadcasting antenna at 3.4 GHz) was generated by adopting the following configuration: P_t=27 dBm (the coaxial cable and connector insertion losses of 1dB was removed from P_t), G_t=11.87 dBi and d=1.20 m.

The following approach was adopted in order to characterize our rectenna: (i) a frequency sweep was conducted for a selected load (1.5 kΩ) in order to find the optimal operating frequency (at this frequency the harvested DC power and the efficiency are maximized on the given load); (ii) the optimal load and then the maximum harvested DC power and the maximum efficiency were determined at this optimal operating frequency. The measurements were performed without and with a metallic plate, positioned at 2.7 cm behind of the rectenna. This metallic plate simulates the presence of the metallic part of the satellite antenna panels. The obtained results (measured DC voltage and DC power), as a function of the frequency, are depicted in Fig. 5 and Fig. 6, respectively.

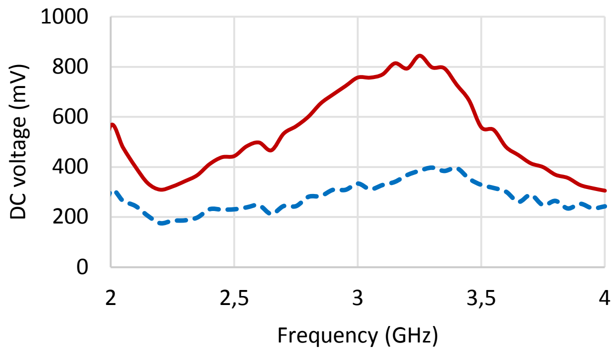


Fig.5. Measured DC voltage (mV) for the FDR (incident power density: S=33.9 μW/cm^2, load 1.5 kΩ) as function of the frequency: dotted blue curve (without any reflector plane), continuous red curve (with a metallic reflector positioned at 2.7 cm behind the rectenna)

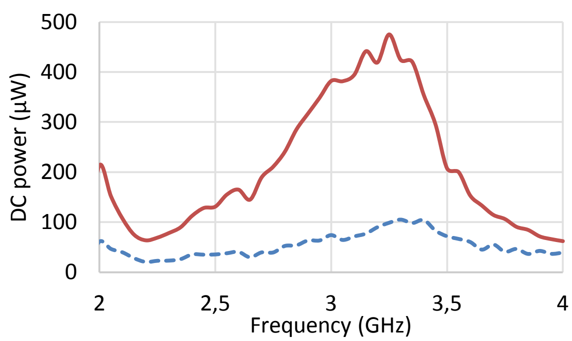


Fig.6. Measured DC power (μW) for the FDR (incident power density: S=33.9 μW/cm^2, load 1.5 kΩ) as function of the frequency: dotted blue curve (without any reflector plane), continuous red curve (with a metallic reflector positioned at 2.7 cm behind the rectenna)

As shown in Fig. 6, a maximum DC power of 475 μW was obtained at 3.25 GHz with a load of 1.5 kΩ when the reflector is positioned at 2.7 cm behind the rectenna. Due to the adopted antenna topology and matching technique, FDR exhibits also a wideband behavior: the half (DC-harvested) power frequency bandwidth is approximately of 20% (0.65 GHz). The optimal operating frequency is of 3.25 GHz instead of the targeted 3.4 GHz (that is a frequency shift of 4.5%), and it may be mainly caused by: (i) the approximation made when using the close-form expression for estimating the input impedance of the rectifier, and (ii) the technological inaccuracies when manufacturing and the assembling the FDR. This frequency shift (of the maximum efficiency operating point) of 4.5% is not so critical because the half (DC harvested) power frequency bandwidth is 20%.

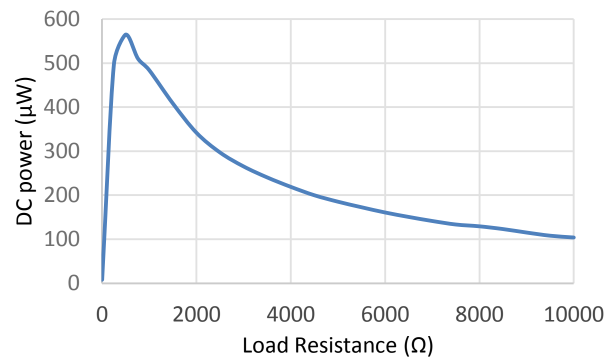


Fig.7. Measured harvested DC power as function of the load resistance for the FDR with a reflector positioned at 2.7 cm behind the rectenna (incident power density: S=33.9 μW/cm^2, frequency: f=3.25 GHz)

The optimal purely resistive load and the maximum efficiency were experimentally determined for FDR at 3.25 GHz. As shown in Fig.7 and Fig.8, the optimal load is of 500Ω. For this load, the harvested DC power and efficiency are of 565 μW and 58.2%, respectively. We note that the efficiencies reported in Fig. 8 are undervalued as the simulated gain G_R (=7.26 dBi, see Fig. 2) is adopted here for deriving the efficiencies.

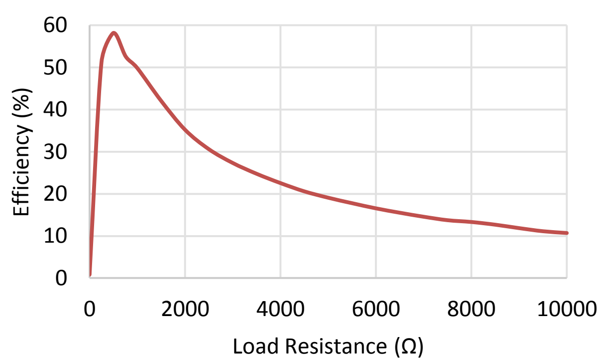


Fig. 8 Efficiency (%) as function of the load resistance for the FDR with a reflector positioned at 2.7 cm behind the rectenna (incident power density: S=33.9 μW/cm^2, frequency: f=3.25 GHz)

In Table I, the rectenna performances are compared with state-of-art designs operating at (almost) the same frequencies. The rectenna proposed in this paper was designed for energy harvesting applications (on board of broadcasting geostationary satellites) in C-band and operates efficiently for low value of the RF power densities.

Table I. Benchmark Results

Refs.	Operating frequency f_0 (GHz)	Power density (µW/cm²) or received RF power (dBm)	Harvested DC power (mW)	Rectenna efficiency (%)	Antenna Surface (λ_0 is the wavelength at f_0)
[6]	2.45	525 µW/cm²	4.97	63	10 x 11 cm² ($0.73*\lambda_0^2$)
[7]	2.45	13 dBm	NR	72.5	13.5 x 9.3 cm² ($0.83*\lambda_0^2$)
[8]	2.4	22 dBm	130	82.3	10 x 10 cm² ($0.64*\lambda_0^2$)
[3]	5.8	8.77 mW/cm^2	49.1	82.7	NR
[9]	5.8	12 mW/cm²	NR	76	NR
This work	3.25	33.9 µW/cm^2 (-0.1 dBm)	0.57	58.2	4.6 x 2.9 cm² ($0.16*\lambda_0^2$)

NR: Not Reported

In order to quantify the electromagnetic energy illuminating the rectenna and to compute the RF-to-DC conversion efficiency two approaches can be used. The electromagnetic energy can be expressed in terms of power densities (this work, [3], [6], [9]) or alternatively in terms of the estimated RF power at the input of the rectifier [7]-[8]. We note that most of the published designs (see, e.g., [3][9]) covering (the upper) C-band were designed for wireless power transmission applications at 5.8 GHz and optimized for very high levels of incident RF powers (8.77 mW/cm^2 or 12 mW/cm²). Compared with the reported designs operating in the ISM 2.45 GHz band, our rectenna is significantly more compact and operates very efficiently when illuminated with much lower electromagnetic power density (34 µW/cm^2 for this work as compared with 525 µW/cm² in [6]). The estimated RF power at the input of the rectifier is also significantly lower (-0.1 dBm for this work as compared with 13 dBm in [7] or 22 dBm in [8]).

IV. Conclusion

An innovative C-band rectenna using a compact flat dipole antenna was proposed. This rectenna operates very efficiently for low level of RF power densities. The maximum efficiency of 58.2% was obtained for the incident RF power density of 33.9 µW/cm^2. The rectenna size is only 16% of the square wavelength at 3.25 GHz.

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