Compact Rectenna for Space Application

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Abstract— This paper addresses an ultra-compact (2.8 cm^2) and wide bandwidth rectenna operating in the extended Ku-band. Experimental results demonstrate that the proposed rectenna can harvest a DC power ranging from 0.125 mW to 1.43 mW for frequencies between 14.5 GHz to 19.5 GHz and for resistive loads between 250 Ω and 4 kΩ. A maximum conversion efficiency of 55.3 % is obtained at 16.05 GHz for an incident power density around of 1.26 mW/cm^2. It is the first time, to the authors' knowledge, that such high harvesting performances are obtained using an ultra-compact Ku-band rectenna.

Index Terms— Rectenna, energy harvesting, satellite application.

I. INTRODUCTION

Nowadays high bit rate, reliable and long-life satellite-based broadcasting links are intensively used for key applications including (but not limited to) mobile communication, television and Internet. In order to provide such broadcasting links high-gain microwave operating in C, X, Ku, K or Ka band and located on panels positioned on the external surface of the satellite antenna are used. Health monitoring of these panels is a key issue involving the use of sensors, e.g., for thermal or for mechanical/structural monitoring. Deploying such sensors in small wireless networks to cover the targeted surface seems to be a very promising technical solution by saving the cost of deploying long wires in harsh environments [1]. Because the battery are forbidden for such applications energy harvesting techniques [2] should be a possible solution for DC powering the sensors and transceivers for wireless sensor networks [1]. In some areas located on antenna panels of broadcasting satellites, the electric field available from the spill-over loss of microwave antennas can reach the maximum levels (effective values) of 106 V/m in Ku-band and 127 V/m in K-band [1]. We present here the design and measurement of an ultra-compact rectenna for the Ku-band electromagnetic energy harvesting. A minimal and ultra-compact topology with a wide band behavior is reported here for the first time.

II. ULTRA-COMPACT RECTENNA: TOPOLOGY AND DESIGN

Rectennas are intensively used for wireless power transfer or electromagnetic energy harvesting applications. Several designs and topologies have been proposed for various applications covering GSM/UMTS, GPS, C and X bands. The frequency spectrum covering the Ku band and above has been addressed in the past mainly for wireless power transfer application [3],[4]. Recall that, as defined by Radio Society of Great Britain, the Ku band covers frequencies ranging from 12GHz to 18GHz. Energy harvesting of the ambient electromagnetic power at such high frequencies was not yet deeply investigated because of the lack of powerful environmental electromagnetic sources for terrestrial applications. Recently several research works have been reported on the rectenna design for electromagnetic energy harvesting at frequencies covering mainly the 24 GHz (ISM) band [5],[6]. Fig. 1 shows a photo of the manufactured rectenna for Ku-band application and the associated FEKO simulation model. The rectenna is composed by a dual dipole-like antenna (DDLA) directly connected to a Schottky diode. A similar topology, operating at 2.45 GHz, was proposed in [7]. A zero-bias GaAs beam lead planar doped diode (Aeroflex/Metelics MZBD-9161) was selected for this design. The main selection criteria were the thermal and RF behavior of this diode regarding the targeted space application. A capacitance (1.5pF) connected in parallel with the diode is used to short any undesirable high frequency and acts as a low pass filter.

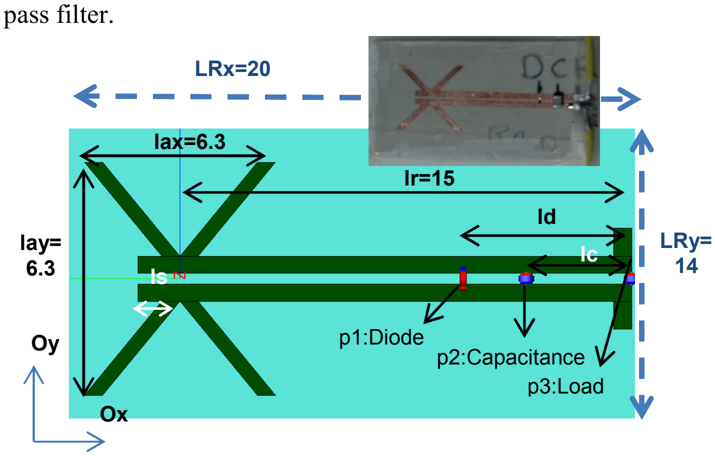

Fig. 1. Top view (not to scale) of the simulation model (Feko) of the fabricated rectenna. The inset shows a photo of the prototype.

The rectenna was fabricated on Rogers 6002 substrate (relative permittivity: 2.94, loss tangent: 0.0012, thickness: 508 µm). The dimensions (in mm) of the rectenna are shown in Fig. 1. The coplanar stripline presents strips width of w=0.8 mm and a gap size of g=0.4 mm. A metallic plate acting as a reflector was positioned at 2 cm below the DDLA in order to increase the antenna gain in the operating frequency band.

The antenna is composed by two crossed dipoles excited by the coplanar stripline. No matching circuit is used between antenna and the diode/rectifier input. The matching between antenna and the diode/rectifier as well as the backscattering suppression of the higher order harmonics of the operating frequency were achieved by properly controlling the input impedance of the antenna and the diode/capacitance mounting position. The proposed design methodology combines full-wave electromagnetic simulation and non-linear circuit simulation. The main goal is to simultaneously achieve a high gain for the DDLA with an acceptable matching between this antenna and the rectifier in a large bandwidth and for various load impedance and incident RF power. This was done in order to maximize the overall conversion efficiency of the rectenna. The design procedure consists of the following steps:

(i) the DDLA was first designed, simulated and optimized using FEKO software for operation in the desired frequency band. The diode was replaced by a voltage port while the capacitance (1.5 pF) and the load (e.g. 500 Ω) were modeled as port loads. The antenna radiation pattern and the distribution of the electric currents on the metallic strips were analyzed in order to insure the proper radiation mechanism and to maximize the gain on the vertical Oz axis (that is, in the direction perpendicular to the rectenna plane);

(ii) the input impedance (Zin_a) as well as the gain along the Oz-axis (theta=0°; phi=0°) of the DDLA (simulation model shown in Fig. 1) was computed in the targeted frequency band as a function of the diode/capacitance mounting position;

(iii) non-linear (harmonic balance) simulation was performed by using the AWR model shown in Fig. 2 for the so-called 'rectifier' (composed by the diode, the capacitance and the load). The coplanar stripline sections supporting the rectifier were modeled as a sub-circuit at the electromagnetic level because of the lack of an appropriate transmission line model in AWR. A generic non-physical diode model available in AWR was customized with the MZBD-9161 diode parameters. The input impedance (Zin_r) of the rectifier was determined as a function of the diode/capacitance mounting position;

(iv) the diode and capacitance position was tuned in order to assure the matching condition, that is Zin_a= Zin_r* where the asterisk denotes the complex conjugated.

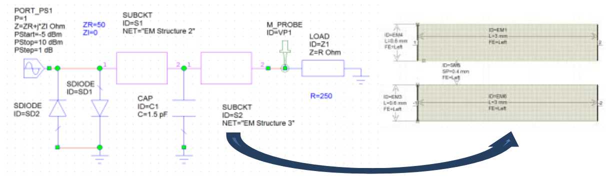

Fig. 1. AWR model used for the rectifier simulation.

III. Simulation and Experimental Results

The simulated impedance (Zin_a) viewed at port *p1* (see Fig. 1) with the port *p2* loaded by C=1.5pF and the port *p3* loaded by RL=250Ω was calculated from FEKO simulation software (method of moments) based on the planar (infinite) multilayered substrate approach. Fig. 3 displays Zin_a for ld=5.5mm and lc=3.5mm. The input impedance of the rectifier Zin_r computed from AWR simulation is shown in Fig. 4 for a RF input power at rectifier input port ranging from -10 dBm to 15 dBm. The real part of this impedance decreases as the frequency or RF input power increases. The imaginary part is always negative and increases as the frequency or RF input power increases.

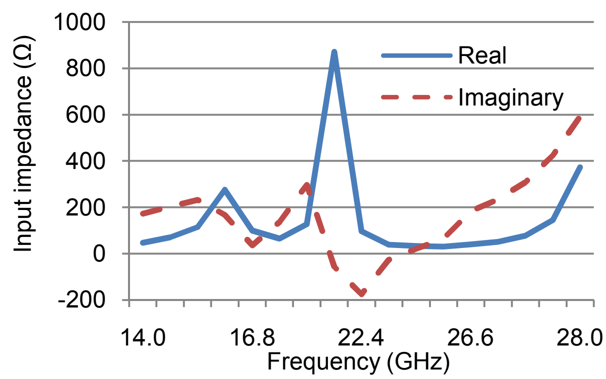

Fig. 3. Simulated (FEKO) impedance Zin_a at port *p1* (see Fig. 1) when the port *p2* is loaded by C=1.5pF and the port *p3* is loaded by RL=250Ω (ld=5.5mm and lc=3.5mm)

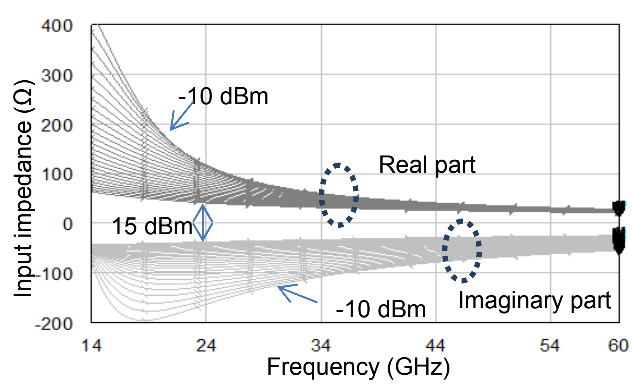

Fig. 4. Simulated (AWR) input impedance Zin_r of the rectifier when the port *p2* is loaded by C=1.5pF and the port *p3* is loaded by RL=250Ω (ld=5.5mm and lc=3.5mm.)

Fig. 5 reports the simulated gain (FEKO) in dBi along the Oz-axis (theta=0°; phi=0°) and the measured gain of the horn antenna (VT220HA20-SK from Vector Telecom) used for the experimental setup described in the next section. As shown in this figure DDLA has at least 8dBi of gain along of Oz-axis for frequencies between 14 GHz and 20 GHz.

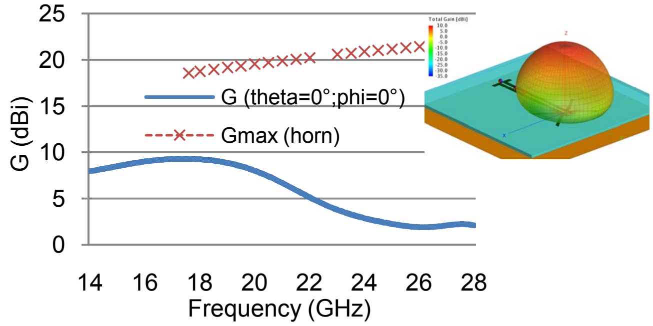

Fig. 5. Simulated (FEKO) gain along Oz-axis of the DDLA and the measured maximum gain of horn antenna used for measurement. The inset shows the simulated 3D radiation pattern of the rectenna.

In order to characterize the performances of the proposed rectenna an experimental setup (inset of Fig. 6) was used. A continuous wave microwave signal (RF power: 24 dBm) generated by the Anritsu MG3694B was injected at the input port of a horn antenna (VT220HA20-SK from Vector Telecom) used for illuminating the rectenna under test with a linearly polarized E-field. The measured loss due to the coaxial cable and connectors between antenna and the signal generator was 2 dB in the Ku band. An automatic acquisition routine was implemented in Labview software from National Instruments in order to facilitate the acquisition process. A variable resistor RL was used for loading the rectenna. Fig. 6 shows the DC power injected in the load impedance as a function of RL at 16.05 GHz.

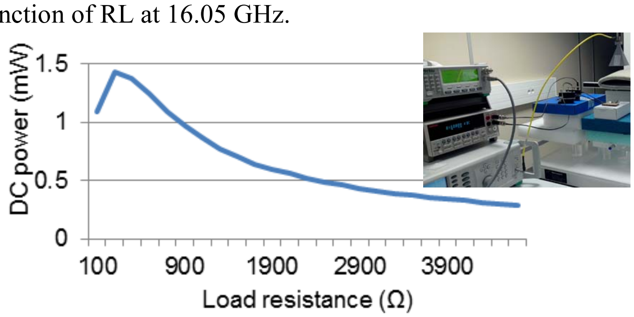

Fig. 6. Measured DC power obtained from a RF power of 24 dBm delivered by the signal generator as a function of the load resistance RL at 16.05 GHz.

Fig. 7 represents the DC voltage measured for three resistive loads (250 Ω, 1 kΩ and 4 kΩ) as a function of frequency. The DC voltage increases as the load impedance increases and is higher than 0.2 V for any resistive load impedance between 250Ω and 4 kΩ in a wide bandwidth, i.e., for frequencies ranging from 14 GHz to 20 GHz. The DC power delivered to the load RL is shown in Fig. 8. We note that the harvested DC power increases as the load resistance decreases. A maximum value of 1.43 mW is obtained (RL=250Ω) at 16.05 GHz. For any load impedance between 0.25kΩ and 4kΩ the harvested DC power is found to be higher than 0.125 mW in a wide frequency band, i.e., for frequencies ranging from 14.5 GHz to 19.5 GHz. It is the first time, to the authors' knowledge, that such wide band harvesting performances are obtained using an ultra-compact Ku-band rectenna.

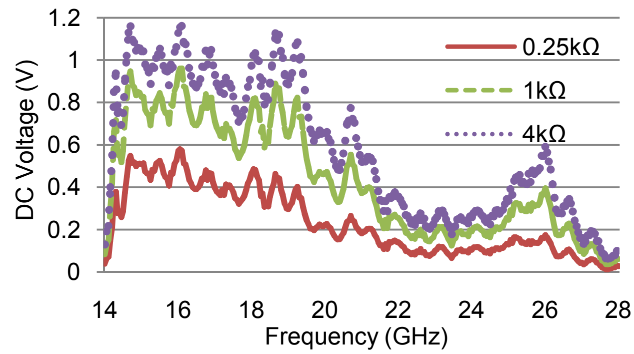

Fig. 7. Measured DC voltage at the input ports of the load impedance obtained for a RF power of 24 dBm delivered by the signal generator and for various load impedance.

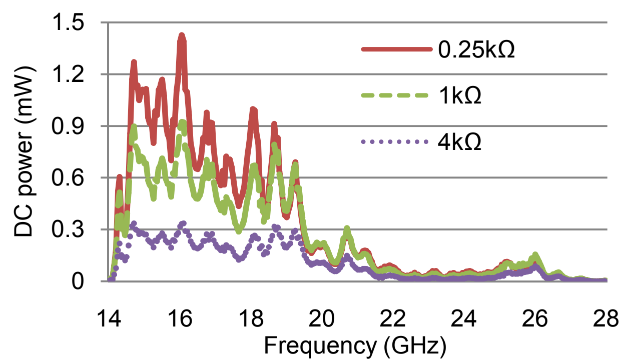

Fig. 8. Measured DC power delivered to the load obtained for a RF power of 24 dBm provided by the signal generator and for various load impedances

The efficiency η (in %) of a rectenna can be computed by using the following worst-case definition [2]:

$$\eta = \frac{P_{DC}}{S \cdot A_G} \cdot 100 \qquad (1)$$

where P_{DC} is the harvested DC power, S is the incident electromagnetic power density and A_G (in cm^2) denotes the area of the radiating surface. The power density ($\mu W/cm^2$): can be computed as a function of E-field effective value E (V/m) on the antenna surface or as a function of the RF power P_t delivered to the transmitting horn antenna of gain G and positioned at the distance d from the rectenna under test, as follows:

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

Here P_t=22 dBm, G=18 dBi and d=25 cm. Thus E~69.28 V/m and S~1273 µW/cm^2. The area A_G=LRy x (LRx-ld) of DDLA is 0.83 cm x 0.63 cm=0.523 cm^2. The maximum DC power (1.43mW) is obtained for RL=250Ω at f=16.05GHz leading to a maximum efficiency of 55.3%. Nevertheless at least 0.125mW (efficiency>5%) can be obtained in a wide frequency band (14.5 GHz to 19.5 GHz) for load resistance 100Ω < RL < 4kΩ. Works are under way for improving the low conversion efficiency obtained for some frequencies close to 17GHz and 18GHz. Additional results will then be presented at the conference. Conclusion

An ultra-compact (2.8 cm^2) rectenna and the associated design methodology for extended Ku band application were reported. The proposed design presents a wide-band behavior (5GHz) for a large range of load resistance (from 100Ω to 4kΩ). DC powers ranging from 0.125 mW to 1.43 mW can be harvested for an incident E-field of 69V/m (i,e., a power density around 1.27 mW/cm^2).

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[1] This reference has been removed because it establishes a direct connection to the authors' names

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