Ultra-compact Ku band rectenna

Alexandru Takacs, Hervé Aubert, Samuel Charlot

Ultra-Compact Ku band Rectenna

A. Takacs[1,2], H. Aubert[1,3],S. Charlot[1]

[1] *CNRS, LAAS, 7 avenue du colonel Roche, F-31400 Toulouse, France*

[2] *Univ. de Toulouse, UPS, LAAS, F-31400, Toulouse, France*

[3] *Univ. de Toulouse, INP, LAAS, F-31400, Toulouse, France*

Abstract — This paper addresses an innovative and ultra-compact rectenna designed for energy harvesting or wireless power transfer applications. The presented rectenna uses a printed cross dipoles antenna array and a rectifier implemented with only one silicon Schottky diode. Experimental results show that 1.15 mW of DC power can be obtained for an optimal load impedance of 500 Ω using a compact rectenna (2.5 cm^2 or 0.6 square wavelength) illuminated by an electric field of 60 V/m at 14.7 GHz.

Index Terms — Rectennas, microwave energy harvesting, wireless power transfer

I. Introduction

Microwave spectrum (beyond 10 GHz) presents an increased interest for wireless power transfer [1] or energy harvesting [2] applications. Rectenna topologies working at such frequencies were designed in the past [2]-[7] by using exclusively GaAs Schottky diodes. One of the main challenges of rectenna design, especially at such high frequencies, is to provide a high-efficiency by using a compact design and low-cost electronic components (e.g., silicon Schottky diodes). This paper addresses an innovative rectenna topology and the associated design methodology. The topology and the associated design rules are presented in Section II. The experimental results reported in Section III demonstrate that this topology allows implementing an ultra-compact and high efficiency microwave rectenna.

II. Rectenna Topology and Design

The proposed topology selected to meet the two main design goals (i.e., conversion efficiency and structure compactness) is shown in Fig. 1. It is composed by: (i) a compact antenna array of two crossed printed dipoles located on the top of the PCB; (ii) a rectifier using only one Schottky diode. The rectifier (except the Schottky diode) is located at the bottom side of the PCB. A ground plane can be positioned below antenna/rectenna to immunize the rectenna performances from the electromagnetic properties of any mechanical support, to increase the gain of the antenna and consequently, to enhance the overall efficiency of the rectenna.

A. Antenna design

Three criteria were taken into account during antenna design and optimization: (i) *compactness*: the total size occupied by the antenna should be as small as possible, (ii) *high gain/high efficiency*: for maximizing the amount of the RF power available at the input of the rectifier and, (iii) *input impedance matching*: antenna input impedance (Z_{inA}) has to match the input impedance of the rectifier (Z_{inR}) for maximizing the power transfer between antenna and rectifier ($Z_{inA}=Z_{inR}^*$, where Z_{inR}^* denotes the complex conjugate of Z_{inR}) at the targeted operating frequency.

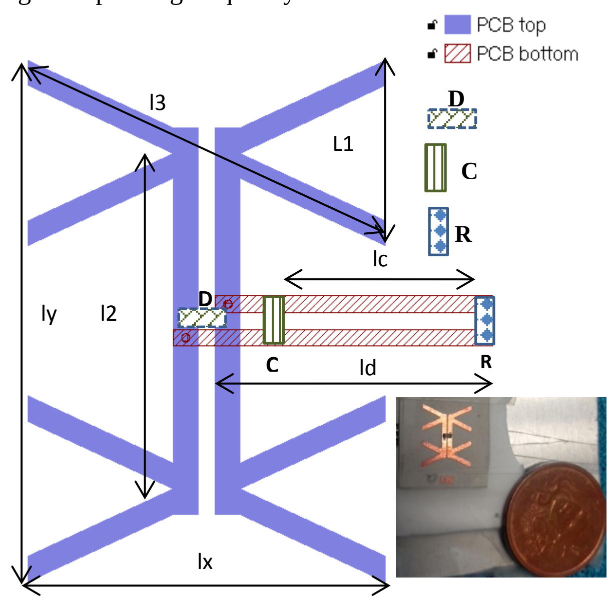

Fig. 1. Top view (not to scale) of the layout of the rectenna, its main geometrical dimensions and a photo (inset, right corner) of the manufactured rectenna

B. Rectifier design

A low-cost silicon Schottky diode (SMS201 from Aeroflex Metelics) in a molded plastic (DFN) package was adopted for this design. This diode can be used for broadband zero bias detectors or power detection up to 10 dBm (frequency below 26.5 GHz). The SMS201 diode has a good thermal behavior and can be mounted using a classical soldering process at high temperature (260°C) while the GaAs diodes require a more sensitive mounting process at a lower temperature (< 150°C). A RF shunt capacitor is connected between the diode and the load resistor as shown in Fig. 1. The simulation model of the rectifier was implemented into AWR software (Fig. 2). The diode was modeled based on the Metelics application note [8]. The rectenna was designed and fabricated on Rogers 6002 substrate (relative permittivity: 2.94, loss tangent: 0.0012 and thickness: 508 µm).

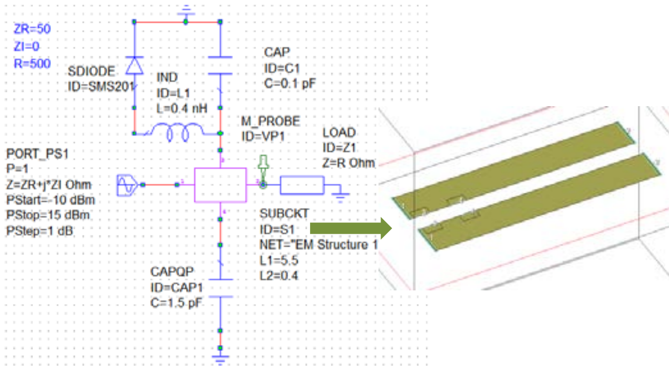

Fig. 2. Simulation model (AWR) of the rectifier.

C. Design methodology and optimization process

Rectenna design, simulation and optimization at such a high frequency involve the use of full-wave electromagnetic simulation tools combined with non-linear (e.g. harmonic balance) electrical circuit models.

First, non-linear simulations were performed by using the AWR model reported on Fig. 2 and an optimal value was determined for the shunt RF capacitor (C=1.5 pF) and for the load resistance (R=500 Ω). The coplanar stripline sections supporting the rectifier were modeled as a sub-circuit at the electromagnetic level due to the lack of appropriate transmission line models in AWR. The via-hole used to connect the diode (mounted on the top side of the PCB) with the bottom of the PCB (the rectifier, except the diode, is located on the bottom side of the PCB) was not simulated in our model. A parametric analysis was performed in order to find the best position for the capacitor mounting. At this stage of the simulation it was found that the distance between the diode and the capacitor (ld-lc) should be as small as possible.

Second, a simulation model of the antenna array (top side of the PCB) was performed using Feko electromagnetic software. The main geometrical parameters of antennas are: the length of the crossed dipole arms (ld), the angle between crossed dipoles (α), the array step (l2), the strip width (w) and, the gap between the strips of the coplanar stripline (g). The length of the crossed dipole arms (ld) and the array step (l2) must be close to the half-wavelength at the operating frequency. In order to increase the gain of the antenna array and to immunize the rectenna performances from the electromagnetic properties of any mechanical support a metallic ground plane was positioned bellow the PCB. At this step of the design the radiation pattern and the current distribution on the strip section of antenna array were checked to verify the proper radiation mechanism. The input of antenna array is loaded by the rectifier impedance.

The rectenna layout is very compact and the antenna performances can be impacted by the presence of the rectifier. Thus an improved simulation model was developed by taking into account the entire layout (top and bottom side of the PCB). The diode was replaced by a voltage port while the capacitance (1.5 pF) and the load impedance (500 Ω) were modeled as port loads. By using this simulation model the impact on antenna performances of the overall rectifier layout (except the non-linear behavior of the diode) was taken into account.

Finally the antenna layout (l3 and l2) as well as the position of the shunt RF capacitor were tuned in order to ensure the matching condition $Z_{inA}=Z_{inR}^{*}$.

III. Results

The layout of the optimized rectenna was accommodated with the manufacturing tolerances available in a University unit equipped for general (low frequency) PCB manufacturing. A metallic plane was positioned at 1.2mm below the rectenna with a 1.2 mm thick Rohacell (dielectric constant in the range of 1.08) intercalated as spacer between rectenna and its reflector. The main dimensions of the manufactured rectenna (see Fig. 1) are: lx=8.4mm, ly=12.4mm, l1=4.4mm, l2=8mm, ld=6.5mm, lc=5.5 mm l3=10 mm, w=0.6 mm and g=0.4 mm. The overall surface of the PCB is 2.5 cm^2 (0.6λ^2).

A. Experimental setup

An experimental setup (shown in Fig. 3) was used in order to recreate the electromagnetic environment existing on antenna panels of the broadcasting satellites. A microwave signal generated from an Anritsu MG3694B generator was injected at the input of a horn antenna which illuminated the rectenna under test with a linear polarized E-field.

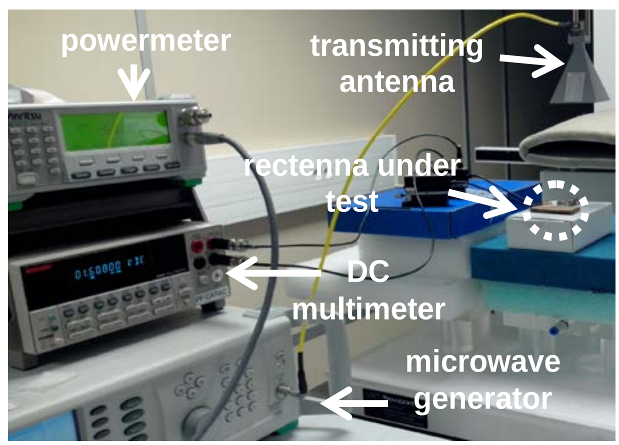

Fig. 3. Experimental setup.

An automatic acquisition routine was implemented in Labview software from National Instruments to speed-up the acquisition process. The harvested DC voltage was measured by using a DC multimeter. The DC power can be computed from the measured DC voltage as long as the load is known. The RF output power delivered by the signal generator was 24 dBm and the measured loss due to the coaxial cable and connectors between antenna and the signal generator was in the range of 2.5 dB in the operating frequency band.

B. Experimental and simulation results

The simulated radiation pattern (gain) at 14.7 GHz is shown in Fig. 4. A standard 3D Cartesian coordinate system with the vertical Oz axis perpendicular to the rectenna/antenna surface is chosen here.

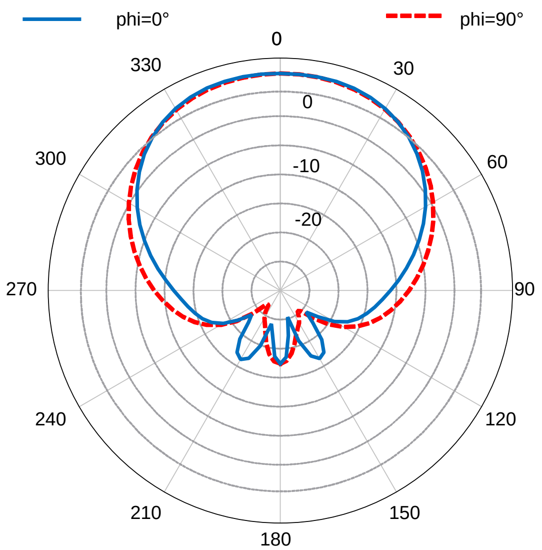

Fig. 4. Simulated (FEKO) gain of the antenna array: (xoz-plane: phi=0° and yoz-plane: phi=90°) at the frequency f=14.7 GHz.

The DC voltage on the input of a variable load (from 0.1 kΩ to 10 kΩ) was measured for the fabricated rectenna. Fig. 5 shows the DC power measured with a load impedance of 500Ω. The rectenna delivers the maximum power of 1.15 mW (load: 500 Ω) at 14.7 GHz. Fig. 6 shows the measured harvested DC power as function of the load impedance.

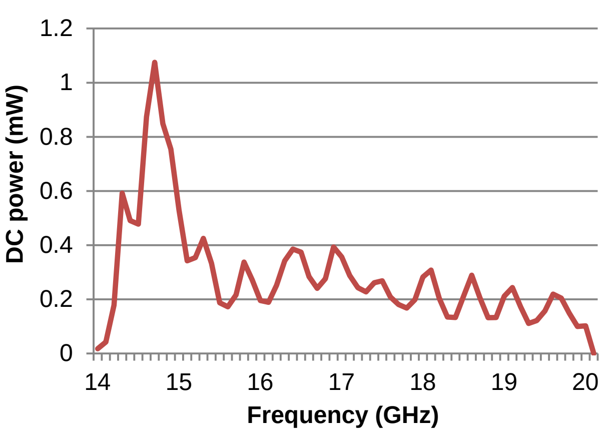

Fig. 5. Measured DC power on a load of 500 Ω as function of frequency.

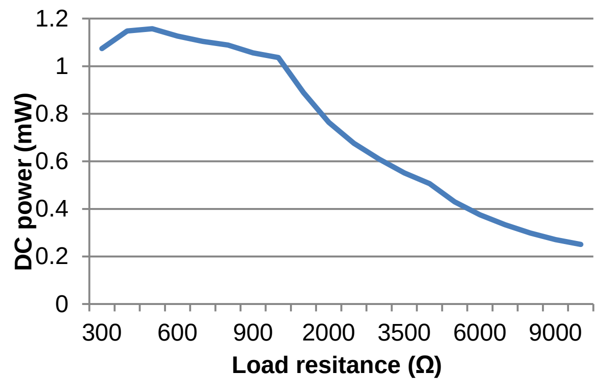

Fig. 6. Measured DC power at 14.7 GHz as function of the load resistance.

The efficiency η (in %) of the rectenna can be computed by using the following definition [9]:

$$\eta_1 = \frac{P_{DC}}{S \cdot A_G} \cdot 100 \qquad (1)$$

$$\eta_2 = \frac{P_{DC}}{S \cdot A_{eff}} \cdot 100 = \frac{4 \cdot \pi \cdot P_{DC}}{S \cdot G_R \cdot \lambda^2} \cdot 100 \qquad (2)$$

where P_{DC} is the harvested DC power, S is the incident electromagnetic power density, A_G (in cm^2) denotes the area of the radiating surface, A_{eff} is the antenna effective area, G_R is the gain of the (rectenna's) antenna and λ is the wavelength of the illuminating electromagnetic wave. The efficiency η_1 can be viewed as a 'worst-case' definition because $A_{eff} \leq A_G$ for any passive antenna. The power density (μW/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_t and positioned at the distance *d* from the rectenna, as follows:

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

Here $P_t \approx 21.5$ dBm, $G_t \approx 16.9$ dBi and d=19 cm. Thus E≈60 V/m and S~955 μW/cm^2. By taken into account the overall area of the rectenna $A_G \approx 2.5$ cm^2 a conversion efficiency around of η_1=48% (η_2=66% by taking into account the simulated gain of G_R=7.4 dBi depicted in Fig. 4) at 14.7 GHz (DC power of 1.15 mW) were obtained. A comparison with the state-of-the-art (operating frequency beyond 10 GHz) is presented in Table I (note that all the diodes -except SMS201- are GaAs diode). Few papers present the measured efficiency of the overall rectenna and, most papers report only the efficiency of the rectifier block of the rectenna.

TABLE I

COMPARISON WITH PUBLISHED RECTENNAS (BEYOND OF 10 GHZ).

f (GHz)	η (%)	Diode Reference	Size (mm^2)	Reference & Comment
35	35	M/A Com MA4E-1317	>110	[4]: efficiency (received RF power/output DC power) measured using a free space setup for S=30 mW/cm^2 and a load of 50Ω
24	54.6	M/A Com MADS-001317-1320AG	NR*	[5]: efficiency (received RF power/output DC power) measured using a near field setup for 130 mW of RF input power at the input of the rectifier and a load of 400Ω
25.7	17	M/A Com MA4E-2502L	328.5	[7]: only the efficiency of the rectifier part is reported; value obtained for a RF power of 8 dBm at the diode input and a load of 1500Ω
18.8	42	MZBD-9161	280	[2]: E-field of 91 V/m (S=2.2 mW/cm^2) for a load of 510Ω
24	24	M/A Com MA4E-1317	>1800	[6]: S= 10 mW/cm^2; use of a circular polarized antenna array
14.7	**48 (66)**	**SMS201**	**250**	**This paper: E=60 V/m; S=0.95 mW/cm^2 for a load of 500Ω.**
23.15	25	SMS201	250	[10]: E=73 V/m (S=1.4 mW/cm^2) for a load impedance of 300 Ω

* NR : Not Reported

IV. CONCLUSION

A compact rectenna ($0.6\lambda^2$) operating in Ku-band was designed and characterized. Despite of the use of a low-cost silicon Schottky diode the manufactured rectenna exhibits an efficiency of 48% at 14.7 GHz. This rectenna exhibits an excellent trade-off between compactness and efficiency.

ACKNOWLEDGMENT

This work was partially supported by CNES French Space Agency within the framework of R&T n° 115052 contracts. The electronic laboratory of University of Toulouse (Paul Sabatier) is acknowledged for PCB manufacturing.

REFERENCES

[1] B. Strassner, K. Chang, “Microwave Power Transmission: Historical Milestones and system Components”, *Proceedings of the IEEE*, Vol. 101, No. 6, pp.1379 -1395, June 2013.

[2] A. Takacs, H. Aubert, S. Fredon, L. Despoisse, H. Blondeaux, "Microwave power harvesting for satellite health monitoring," *IEEE Trans. on Microwave Theory Tech*, Vol.: 62, Issue: 4 , pp. 1090 - 1098, April 2014.

[3] T.-W. Yoo and K. Chang, “Theoretical and experimental development of 10 and 35 GHz rectennas,” *IEEE Trans. Microw. Theory Techn*., vol.40, no. 6, pp. 1259–1266, Jun. 1992.

[4] Y.-J. Ren, M.-Y. Li, K. Chang, "35 GHz rectifying antenna for wireless power transmission," *IET Electronics Letters*, vol.43, no.11, pp.602-603, May 24 2007.

[5] N. Shinohara, K. Nishikawa, T. Seki, K.Hiraga, "Development of 24 GHz rectennas for Fixed Wireless Access," *2011 URSI General Assembly and Scientific Symp*., pp.1-4, 13-20 Aug. 2011.

[6] S. Ladan, A.B. Guntupalli, K. Wu, “A High-Efficiency 24 GHz Rectenna Development Towards Millimeter-Wave Energy Harvesting and Wireless Power Transmission”, *IEEE Trans. Circuits and Systems I: Regular Papers*, vol. 61, no. 12, pp. 3358-3366, Dec. 2014.

[7] A. Collado, A. Georgiadis, "24 GHz Substrate Integrated Waveguide (SIW) Rectenna for Energy Harvesting and Wireless Power Transmission, in *Proc. of IMS'2013*, 2013.

[8] http://www.aeroflex.com/AMS/Metelics/pdfiles/SMS201.pdf

[9] Z. Popovic; E.A. Falkenstein, D. Costinett, R. Zane, “Low-Power Far-Field Wireless Powering for Wireless Sensors”, *Proceedings of the IEEE*, Vol. 101, No. 6, pp.1397 -1407, June 2013.

[10] A. Takacs, H. Aubert, A. Luca, S. Charlot, S. Fredon, L. Despoisse, "Rectenna Design for K Band Application", *2014 European Microwave Conference (EUMC'2014)*, Rome, Italy, 5-10 Oct'2014.