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To cite this version:

Alexandru Takacs, Abderrahim Okba, Hervé Aubert, Samuel Charlot, Pierre-François Calmon. Recent Advances in Electromagnetic Energy Harvesting and Wireless Power Transfer for IoT and SHM Applications. 2017 IEEE International Workshop of Electronics, Control, Measurement, Signals and their Application to Mechatronics (ECMSM), May 2017, San Sebastien, Spain. pp.299-302, 10.1109/ECMSM.2017.7945868 . hal-01611643

HAL Id: hal-01611643

https://laas.hal.science/hal-01611643v1

Submitted on 6 Oct 2017

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Recent Advances in Electromagnetic Energy Harvesting and Wireless Power Transfer for IoT and SHM Applications

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***Abstract*— This paper addresses the recent advances obtained in LAAS-CNRS Toulouse concerning the development of compact, high-efficiency and multiband RF/microwave energy harvesting devices for autonomous wireless sensors. Several topology of rectenna designed for the Structural Health Monitoring of the satellite antenna panels and for Internet of Things application are discussed.**

Keywords—energy harvesting, rectennas, space application

I. Introduction

In last decade the demand for **E**nergy **A**utonomous **W**ireless **D**evices (EWAD) experienced an increasing interest. This interest was mainly motivated by the expansion of both traditional and emerging applications including but not limited to **S**tructural **H**ealth **M**onitoring (SHM), **W**ireless **S**ensors **N**etworks (WSN) and **I**nternet of **T**hings (IoT). The paradigm of the energetically autonomous wireless devices (sometimes named also batteryless wireless devices) became a reality due to the recent advances in the field of (i) low-power power electronics (concerning the ultra-low power transceivers, sensors and DC boost convertors and regulators), (ii) **E**nergy **H**arvesting (EH) and (iii) **W**ireless **P**ower **T**ransfer/transmission techniques (WPT). The energy harvesting supposes that the environmental energy (e.g. solar, mechanical/vibrational, thermal or electromagnetic/RF) is converted locally in DC energy that is used to supply the EWAD. WPT is an alternative solution to EH when the environmental energy lacks and the electrical energy should be provided at distance by the means of electromagnetic waves intentionally generated by a transmitter. By definition, WPT is a technique where electrical energy is transmitted from a power source to a load without the connection of electrical conductors. This paper addresses the recent advances obtained in last years by our team in the field of RF/microwave energy harvesting for space application and in the field of RF EH/WPT for IoT/SHM applications. The key element in any efficient RF EH/WPT systems is the rectenna (an acronym for **rect**ifier **ant**enna). The results obtained in the field of rectenna design for RF/microwave energy harvesting for SHM space application are presented in Section II while the results obtained for IoT applications are described in Section III.

II. Electromagnetic Energy Harvesting for Space Application

The geostationary broadcasting satellites uses high-gain directive RF/microwave antenna in order to establish high-reliable data links between the satellite and the Earth. These antenna located on the satellite panels are feed with a high RF power (typically in the range of 100 W) in order to overcome the very high propagation losses between the satellite and the Earth. A very promising solution for surveying the health of antenna panels is to use small autonomous **W**ireless **S**ensors (WS) composed by one or more sensors connected to a low power transmitter/transceiver. These WS used for thermal or for mechanical/structural monitoring of antenna panel saves 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 almost constant as far as the data links are functional. The concept of electromagnetic energy harvesting in order to power autonomous WS for SHM of the broadcasting satellite antenna panels was first proposed in [1]-[2] and then developed in [3]. Several rectennas were designed, manufactured and characterized in order to prove the feasibility of such concept. There are presented in the following section.

A. *Rectennas: Topologies, Design Methodology and Results*

The generic topology of a rectenna is depicted in Fig. 1.

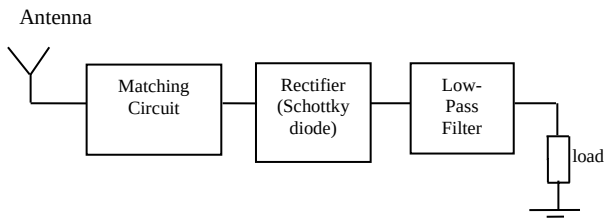

Fig. 1. Generic topology of a rectenna

The key elements of any rectenna are: (i) the antenna that converts the incoming electromagnetic waves in a RF/microwave signal and (ii) the rectifier that converts the alternative (RF) signal into DC. A matching circuit/filter must be intercalated between the antenna and the rectifier in order to

maximize the power transfer between the antenna and the rectifier and to avoid the backscattering (via antenna) of the harmonic frequencies generated by the non-linear elements (e.g. Schotkky diodes, transistors, etc) during rectifying process. The low-pass filter must: (i) maximize the transfer of the DC to the load, (ii) cut-off the RF/microwave frequencies (the main frequency corresponding to the frequency of the incoming waves and its harmonics frequencies generated during the rectifying process) and (iii) optimizing the impact of the input impedance of the load on the rectifier performances. The load represented in Fig. 1 can be: (i) a power management unit (composed by a DC-to-DC convertor/regulator and a storage element - i.e; supercapacitor, rechargeable battery, etc. -) used to regulate the DC power delivered to the input of the WS or (ii) the WS itself. The electromagnetic energy illuminating the satellite antenna panels is almost constant [3] thus for such application the WS can be feed directly by the rectenna. From an application point of view a successful rectenna design can satisfy several criteria concerning mainly: (i) the DC power and voltage delivered to the load, (ii) the efficiency of the RF-to-DC conversion, (iii) the size, (iv) the fabrication cost. Moreover for the targeted application (EH for satellite SHM) the proposed topology should be as simple as possible using components already qualified or pre-qualified for space applications.

In order to prove the feasibility of EH onboard of geostationary satellites several rectenna were fabricated in our laboratory on Rogers 6002 substrate [4] (relative permittivity: 2.94, loss tangent: 0.0012, thickness: 508 µm, metallization thickness: 35 µm). There are represented in Fig. 2.

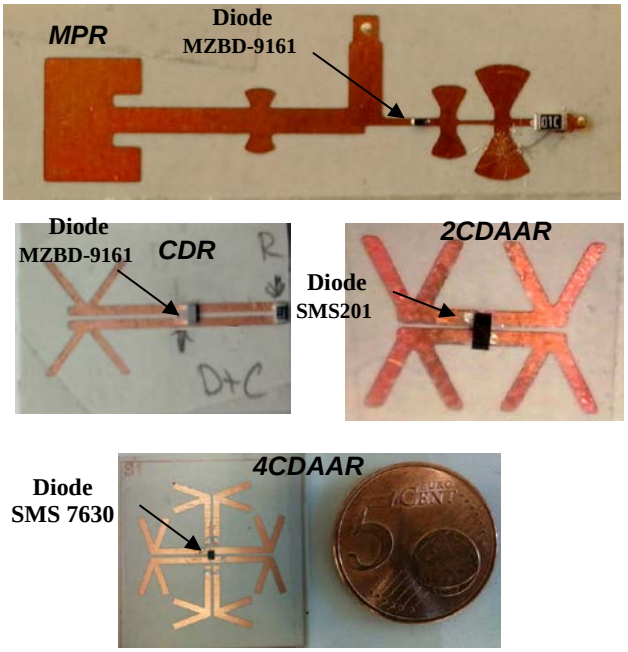

Fig. 2. Rectennas for EH of the electromagnetic energy onboard of the broadcasting geostationary satellites: MPR (Microstrip Patch Rectenna), CDR (Cross Dipole Rectenna), 2CDAAR : (two Cross Dipole Antenna Array Rectenna), 4CDAAR (four Cross Dipole Antenna Array Rectenna)

The microstrip patch rectenna (MPR, Fig. 2) is composed by a rectangular patch, a stub based matching circuit and a rectifier using a MA4E-1317 Schotkky diode combined with a distributed low-pass filter (LPF) [3]. The backside is fully (homogenous) metalized. The main drawback of MPR topology is that the rectenna is quite large because of the adopted 'in-line' design. The used antenna is 'narrow band' (the relative frequency bandwidth for a 'classical' rectangular patch is in the range of 5%). Consequently this topology cannot be accommodated for a broadband/multiband band design. The cross dipole rectenna (CDR, Fig. 2) [5] is composed by a printed cross dipole antenna (CDA) and a rectifier using MZBD-9161 diode [5]. A non-resonant matching technique by properly controlling the mounting position of the Schottky diode and of the DC shunt capacitance was used. The backside of the substrate is not metalized, but a metallic reflector can be positioned bellow CDR in order to increase the rectenna performances. In practice the metallic structure of the satellite antenna panel can be used as reflector. A compact innovative rectenna design was proposed in [6]. This rectenna (2CDAAR, Fig. 2) uses a cross dipole antenna array formed by 2 CDA and a rectifier using a low cost silicon diode (SMS 201) mounted in shunt configuration. The capacitance used for the LPF as well as the resistor emulating the load is mounted on the substrate backside. This design can be optimized in order to obtain a high-efficiency rectenna at a given frequency or a broadband rectenna. A rectenna using a four cross dipole antenna array (4CDAAR, Fig. 2) was proposed in [7]. The rectenna uses a SMS 7630 diode from Skyworks [8] mounted in the center of antenna array. The LPF formed by a 1.5 pF DC capacitor and the resistive load is implemented on the backside of the substrate. 4CDAAR exhibits very good performances at the first resonant frequency (in Ku band) of the Cross Dipole Antenna Array (CDAA) and also a multiband behavior at frequencies corresponding to the higher resonant modes of the 4CDAA [9].

Reproducing in Laboratory the electromagnetic environment existing on satellite panels is not an easy task. The experimental setup shown in Fig. 3 was used for rectennas characterization.

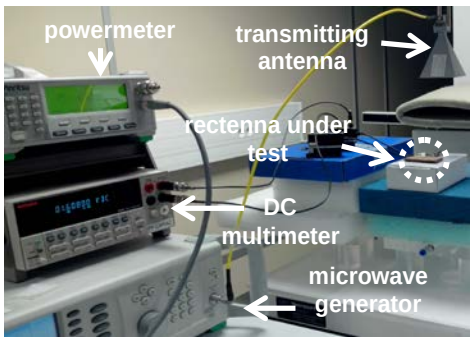

Fig. 3. Experimental setup

A microwave signal provided by an Anritsu MG3694B generator is injected at the input of a transmitting antenna (e.g.

horn) using a coaxial cable. During the measurement, the rectenna was aligned in order to match the polarization of the transmitting antenna. The transmitting antenna (horn) is placed at a distance d above the rectenna and illuminates the rectenna with a linearly polarized E-field. The harvested DC voltage is measured by using a DC multimeter. The DC power can be derived from the measured DC voltage (the load is known). An automatic acquisition routine is implemented in Labview software from National Instruments to speed-up the acquisition process. From the measured DC voltage/power the efficiency of the rectenna can be computed as follows [10]:

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

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 simulated gain of the (rectenna's) antenna and λ is the free-space wavelength of the illuminating electromagnetic wave at a given frequency.

The power density S (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 at the input of the transmitting horn antenna (gain G_t) and positioned at a distance d from the rectenna, as follows:

$$S = \frac{E^2}{120.\pi} \cdot 100 = \frac{30.P_t.G_t}{d^2.120.\pi} \cdot 100 \qquad (2)$$

The experimental results obtained for 4CDAAR by using the experimental setup represented in Fig. 3 are depicted in Fig. 4. A maximum DC power of 4.5 mW can be harvested at 12 GHz when 4CDAAR is illuminated by an E-field of 82.5 V/m. The highest efficiency of 4CDAAR according to eq. 1 is approximately 40% for illuminating E-field amplitude ranging between 51 V/m and 83 V/m [9]. These results confirms that this rectenna can be used for satellite EH/SHM applications. In fact the consumed DC power for a low-power WS is in the range of 1-2 mW (few µW for the sensors and 1-2 mW for the state-of-the-art transmitters).

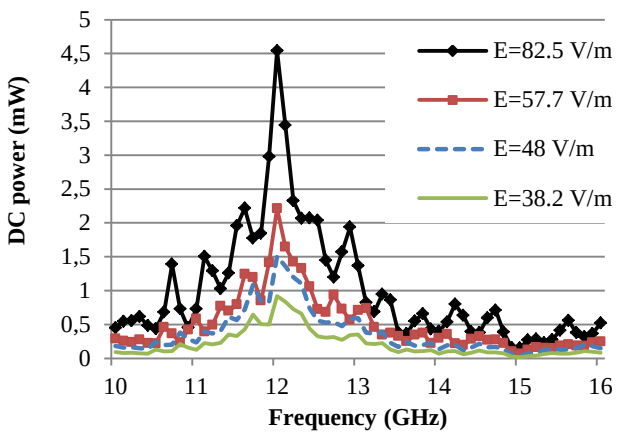

Fig. 4. Experimental results in Ku band obtained for 4CDAAR representing the harvested DC power at the input port of a resistive load (RL=300Ω) as a function of the frequency for various E-field amplitudes

The proposed rectenna designs (MPR, CDR, 2CDAAR, 4CDAAR) were optimized for various frequencies located in the Ku, K and Ka bands. The key parameters of manufactured rectennas (represented in Fig. 2) are listed in Table I. As shown in this table the proposed rectenna are compact and exhibits a high-efficiency in the range with other design operating at very high frequencies (beyond 15 GHz).

TABLE I
COMPARISON OF KEY PARAMETERS OF THE RECTENNA.

f (GHz)	η (%)	Diode Reference	Size (mm^2)	Reference & Comment
17.7	NR	MA4E-1317	480	MPR: harvested DC voltage/power : 1.6 V/0.256 mW on a load of 9.1 kΩ [3]
16.05	55	MZBD-9161	280	CDR: the maximum DC power of 1.4 mW is obtained for RL=250Ω, E~69.28 V/m (S~1.2 mW/cm^2), [5]
18.8	42	MZBD-9161	280	CDR: E-field of 91 V/m (S=2.2 mW/cm^2) for a load of 510Ω, [3]
14.7	48	SMS201	250	2CDAAR: E=60V/m (S=0.95 mW/cm^2) for a load of 500Ω, [11]
23.15	25	SMS201	250	2CDAAR: E=73 V/m (S=1.4 mW/cm^2) for a load impedance of 300 Ω, [6]
12	40	SMS 7630	625	4CDAAR: 51 V/m <E-fields< 82 V/m for a load of 500 Ω, [7]
24	24	MA4E-1317	NR	S=10 mW/cm^2, [12]
35	35	MA4E-1317	NR	S=30 mW/cm^2, [13]

* NR : Not Reported

III. RECTENNA FOR IOT/WPT APPLICATIONS

The RF EH techniques can be also applied in an IoT scenario. The RF energy is mainly available in the GSM, WiFi and DTV bands but the available levels are weak and time varying. Nevertheless the RF EH techniques, alone or in conjunction with WPT, can be a viable solution for implementing energetically autonomous WSN in an IoT scenario. There is an increasing interest to develop multiband or broadband rectenna in order to exploit any available RF energy source. A rectenna covering the frequency bands around 2.45 GHz: UMTS, ISM 2.45 GHz, LTE 4G, WiFi and partially WiMAX (IEEE 802.16e) was recently designed in our laboratory. There is composed by (Fig. 5): (i) a flat dipole antenna located on the top and bottom side of a FR4 substrate (thickness: 0.8 mm, dielectric constant: 4.4 and loss tangent: 0.018) (ii) a rectifier using a Skyworks SMS 7630 diode.

The experimental results for the fabricated antenna are represented in the Fig. 6 and Fig. 7. This antenna exhibits good performances in terms of input matching and radiation pattern: the frequency bandwidth (S11<-8 dB) is 800 MHz (from 1.9 to 2.7 GHz) and the maximum gain is 6.9 dBi at 2.45 GHz.

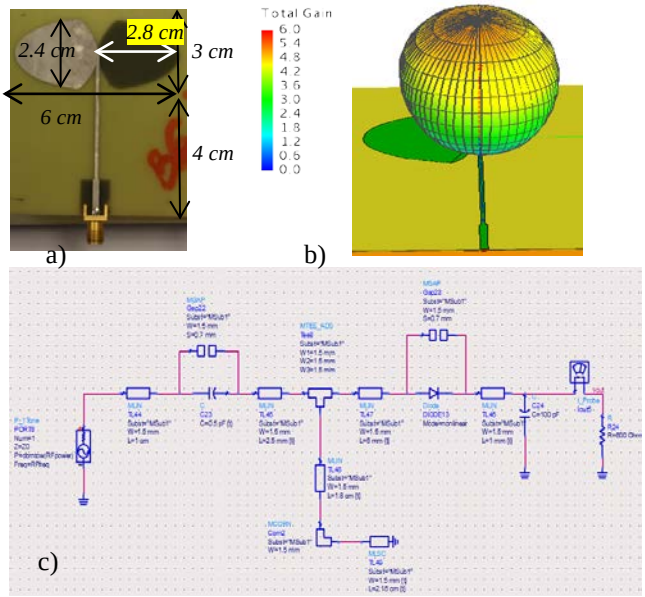

Fig. 5. a) Photo (top side) of the manufactured flat dipole antenna with its main dimensions, b) 3D radiation pattern (gain) simulated with FEKO, c) simulation model (ADS software) of the rectifier.

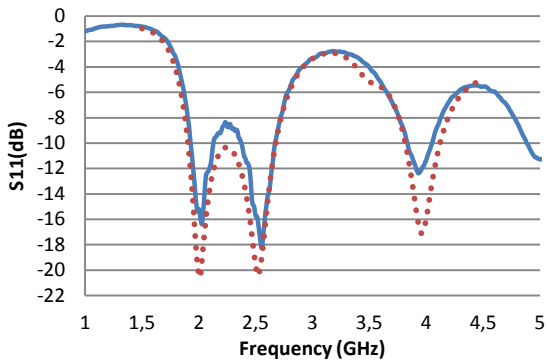

Fig. 6. Measured reflection coefficient (continuous blue line) as function of the frequency for the manufactured flat dipole antenna. The red dotted line represents the simulated reflection coefficient obtained by using FEKO software.

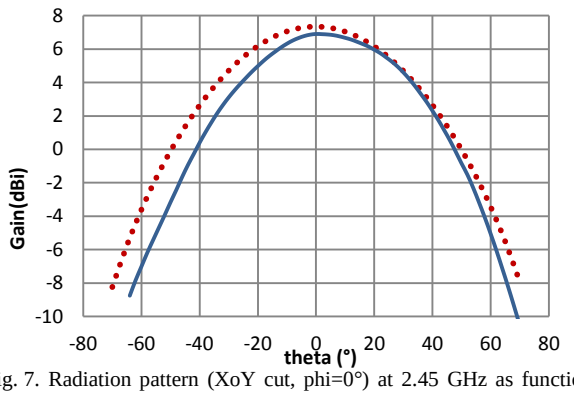

Fig. 7. Radiation pattern (XoY cut, phi=0°) at 2.45 GHz as function of the elevation (theta) angle. Measured (continuous blue line) and the simulated (FEKO, dotted red line) gain are represented as function of theta angle.

The simulation results obtained with ADS software predicts that the rectifier itself exhibits an efficiency of 48% at 2.45 GHz for an input RF power of 3 dBm. The maximum DC power (at the input of a load of 600 Ω) is 960 µW for a RF power of 3 dBm at the input of the rectifier. The rectifier is under manufacturing and more results concerning the rectifier and the rectenna (obtained by the integration of the flat dipole antenna with the rectifier) will be presented at conference.

IV. Conclusions

Several rectenna topologies recently developed at LAAS-CNRS were presented. The performances of the proposed rectenna designs in the Ku, K and Ka bands prove that the concept of the electromagnetic energy harvesting for the structural health monitoring of antenna panels onboard of the geostationary satellites can became a reality. Nevertheless a lot of research and engineering efforts should be deployed in order to fully qualify the proposed rectenna designs for space applications and to integrate such rectennas with wireless sensors in order to implement energetically autonomous wireless sensors on the satellite antenna panels.

Acknowledgment

The authors acknowledge the support of French Space Agency within the framework of several past R&T contracts

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