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Abderrahim Okba, Samuel Charlot, Pierre-François Calmon, Alexandru Takacs, Hervé Aubert. Multiband rectenna for microwave applications. IEEE Wireless Power Transfer Conference, May 2016, Aveiro, Portugal. pp.1 - 4, 10.1109/WPT.2016.7498799 . hal-01409599

HAL Id: hal-01409599

<https://hal.science/hal-01409599>

Submitted on 6 Dec 2016

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Multiband Rectenna for microwave applications

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Abstract— This paper reports recent results obtained in the Ku and K band by using a multiband rectenna. The targeted application is the electromagnetic harvesting of the spill-over losses of microwave antennas for powering autonomous wireless sensors used for satellite health monitoring. The experimental results demonstrate that this compact rectenna can harvest efficiently the incident electromagnetic energy at three different frequencies that roughly correspond to the resonant frequencies of the used cross dipoles antenna array.

Keywords— electromagnetic energy harvesting, wireless power transfer, multi-band rectennas, printed dipoles array, satellite application.

I. INTRODUCTION

The electromagnetic harvesting of the spill-over losses of microwave antennas was identified as a realistic solution to power autonomous wireless sensors for health monitoring of the antenna panels of the broadcasting satellites [1]. This paper presents recent results in Ku and K band obtained by using an innovative rectenna topology [2] composed of four printed cross dipoles antenna array and using a low cost Schottky diode [3]. Rectennas using a cross dipole antenna were also reported in [1],[4] while a rectenna using a two cross dipoles array was reported in [5]. The rectenna topology and the design methodology are presented in Section II. The experimental results reported in Section III and obtained by using the manufactured rectenna show that very good performances can be achieved in three frequencies bands.

II. RECTENNA TOPOLOGY AND DESIGN

The proposed topology is composed of an array of four cross dipoles (4CDAA) and a silicon Schottky diode – Skyworks SMS7630 [3]. The PCB layout and a photo of the manufactured rectenna are shown in Fig. 1. The antenna array and the diode are implemented on the top of the PCB while the RF shunt capacitor is mounted on the bottom side of PCB. A reflector metallic plate is added on the bottom side in order to improve the antenna gain. This compact topology (its size is fixed by the size of the antenna array) is an extension of a rectenna using two cross dipoles antenna array 2CDAA reported in [5] and a non-resonant matching technique was used. This non-resonant matching is implemented by properly controlling (i) the input impedance of the antenna array and (ii) the input impedance of the rectifier itself. The rectifier consists of the diode and the low pass RC filter (composed of the shunt capacitor and the load itself). The 4CDAA can be viewed as an array formed by four cross dipoles printed on the PCB. Each cross dipole consists of two dipoles in cross

configuration as shown in Fig. 1. The substrate used is Rogers 6002 (substrate thickness: 0.508 mm, relative dielectric permittivity: 2.94, dielectric loss tangent: 0.0012).

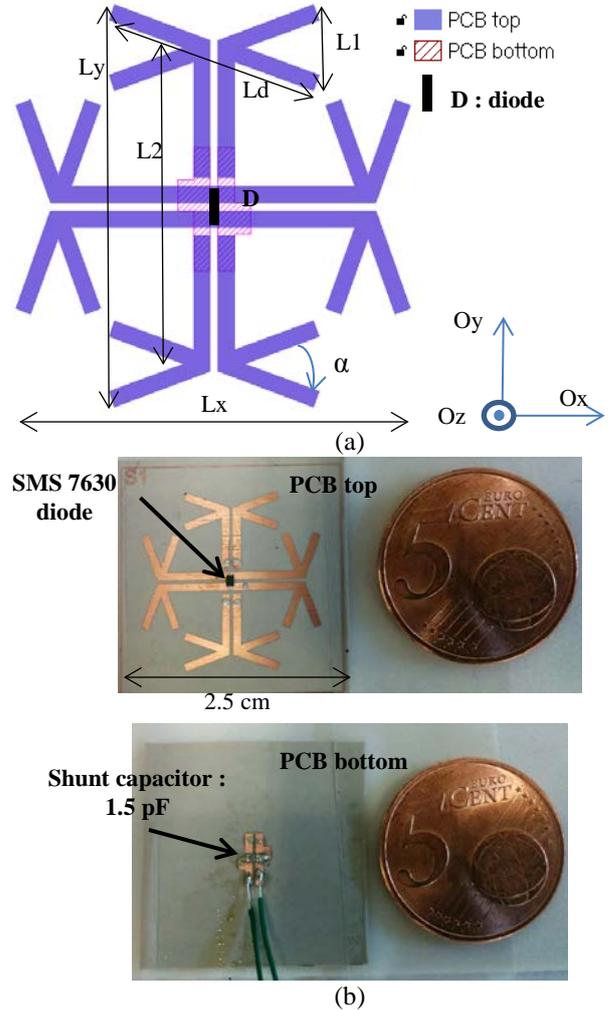


Fig. 1. (a) Top view (not to scale) of the layout of the 4CDAA rectenna, its main geometrical dimensions and (b) photos of top and bottom side of the manufactured rectenna. The wires shown here was used to connect a variable resistance in order to reach the optimal load.

The maximum theoretical gain (G_{max} in dBi) of such array can be predicted by using the following expression:

$$G_{max} = 10 \cdot \log(8) + G_d = 11.18 \text{ dBi} \quad (1)$$

where G_d is the gain of each lossless dipole. This gain can be increased by 3 dB when a metallic reflector is properly positioned below the antenna surface. The expected maximum

gain is 14.2 dBi when half-wavelength dipoles ($G_d=2.15$ dBi) are used. This theoretical gain should be considered as an upper bound for any practical 4CDAA design.

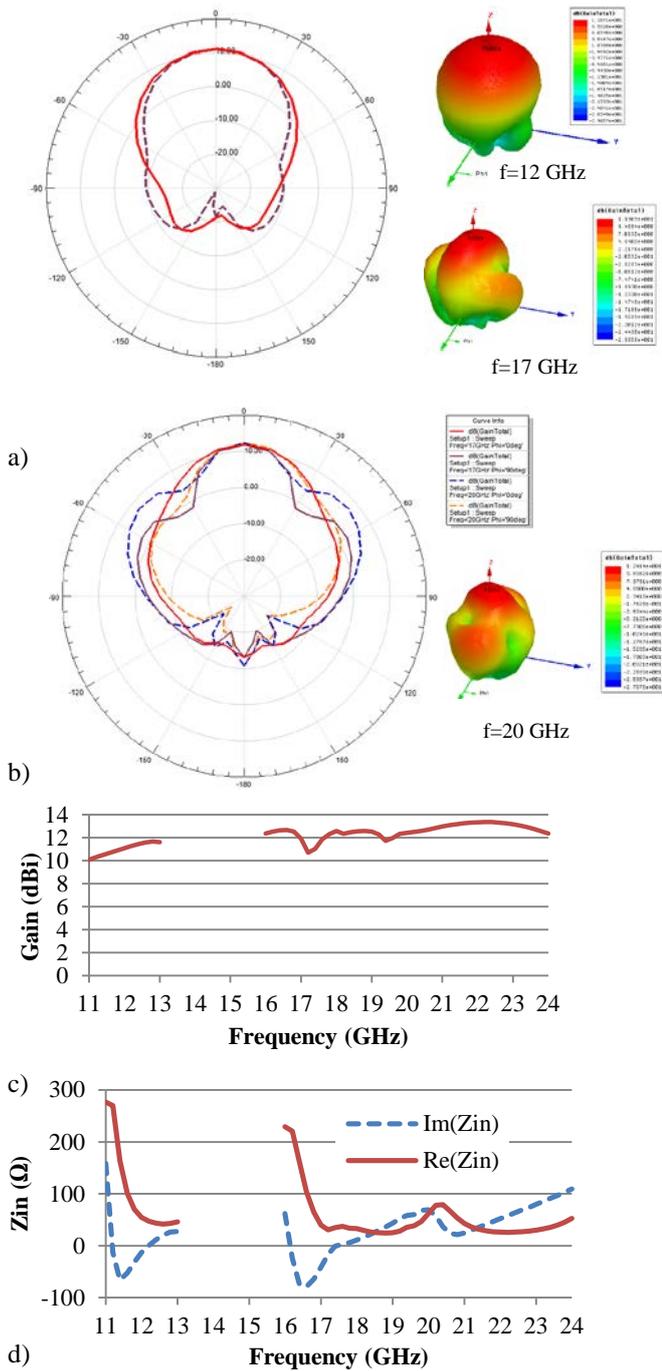


Fig. 2. (a) Simulated (HFSS) gain in the xOz plane ($\phi=0^\circ$) – continuous line – and in the xOy plane ($\phi=90^\circ$) – dashed-line of the 4CDAA at the frequency of 12 GHz, (b) simulated gain at 17 GHz and 20 GHz (the insets show the 3D radiation patterns for 12 GHz, 17 GHz and 20 GHz), (c) Simulated (HFSS) maximum gain of the 4CDAA vs the frequency, (d) the input impedance viewed at the input port of the diode vs frequency.

There are no accurate analytical formulas for designing such arrays but some rules can be used in order to start the design. The length of each dipole (L_d in Fig 1) should be

approximately half wavelength and the distance between the center of two opposite cross dipoles (L_2 in Fig.1) should be an integer multiple of half wavelength. The angle between the dipoles (α in Fig 1) impacts the polarization of the radiated field and the maximum achievable gain. Linear or circular polarization can be obtained by using this topology as function of the relative phase at the access ports of the crossed dipoles. Coplanar strip lines are used to feed each cross dipole. We target here a linear polarization. Thus the diode are mounted in the center of the array as represented in Fig. 1. The distance between the mounting position of the diode and each cross dipole should be in the range of half wavelength. Six metallic via holes were used to connect the top and the bottom side of the PCB. A shunt capacitor is mounted on the bottom side of the PCB. The main dimensions of the fabricated (optimized) rectenna are: $L_1=4$ mm, $L_2=15.3$ mm, $L_d=10.6$ mm, $L_x=L_y=19.5$ mm. Intensive full-wave electromagnetic simulations were performed by using Ansys HFSS software in order to optimize the 4CDAA. The proposed 4CDAA has a multi-band behavior. At the first operating frequency (f_0) the length of each dipole (L_d) is in the range of the half wavelength ($L_d \sim \lambda/2$) and the distance between the center of the opposite dipoles (L_2) is in the range of wavelength ($L_2 \sim \lambda$). Another operating/resonant frequency is $f_2 \sim 2f_0$. At this frequency $L_d \sim \lambda$ and $L_2 \sim 2\lambda$. There is another resonant frequency at approximately $f_1 \sim 1.5f_0$. At this frequency $L_d \sim 0.7\lambda$ and $L_2 \sim 1.5\lambda$. Note that the relationships $f_1 \sim 1.5f_0$ and $f_2 \sim 2f_0$ are not exact because the 4CDAA is very compact and a non-negligible electromagnetic coupling between the four cross dipoles exists. Fig. 2 shows the simulated results for: (i) the radiation pattern of 4CDAA at the 3 resonant frequencies (12 GHz, 17 GHz and 20 GHz), (ii) the simulated gain (over Oz axis) and input impedance (viewed at the diode input port) as a function of the frequency for the same 4CDAA. The simulation results in the frequency band of 13–16 GHz were not yet available where this paper was prepared was submitted. The optimized 4CDAA exhibits the following simulated gain: $G=11$ dBi at 12 GHz, $G=11.9$ dBi at 17 GHz and $G=12.4$ dBi at 20 GHz as it can be observed from Fig. 2 c). The simulated input impedance is shown in the Fig. 2 d).

A generic electrical model for the diode exists in the ADS software. It was customized with the following parameters [6][7]: ohmic resistance $R_s = 20\Omega$, junction capacitance $C_{j0} = 0.14$ pF, saturation current $I_s = 5 \mu A$, forward voltage $V_f = 0.34V$, reverse breakdown voltage $B_v = 2V$ and the current at reverse breakdown voltage $I_{bv} = 0.1mA$. The ADS simulation model is represented in Fig. 3. The PCB located on the bottom side of the PCB was simulated by using standard printed PCB lines and via holes founded in the ADS library. The harmonic balance port was charged by the input impedance viewed at the input port of the diode.

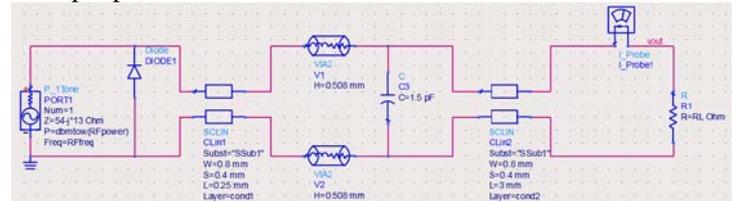


Fig. 3. ADS electrical circuit model.

The first simulations results obtained from this model demonstrates that the maximum DC power is obtained at the frequency of 12 GHz . Nevertheless we observed that ADS harmonic balance engine exhibited numerical convergence problem in this case and an important sensitivity of the DC power delivered to the load (RL) as function of the length of the printed PCB line. Thus we decided to manufacture a prototype and to keep as compact as possible the PCB layout of the bottom side in order to avoid any uncontrolled coupling between the 4CDAAs (bottom side) and the PCB layout of the bottom side.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental setup shown in the Fig. 4 was used to characterize the rectenna. 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 linearly polarized E-field. 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 derived from the measured DC voltage as long as the load is known. The measured loss due to the coaxial cable and connectors between the antenna and the signal generator was close to 3 dB in the operating frequency band. Two different transmitting horn antennas were used: one for covering the 12GHz – 16 GHz frequency band and another one to cover the 16GHz – 22 GHz frequency band.

The efficiency η (in %) of the rectenna can be computed by using the following expression [8]:

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

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 wavelength of the illuminating electromagnetic wave.

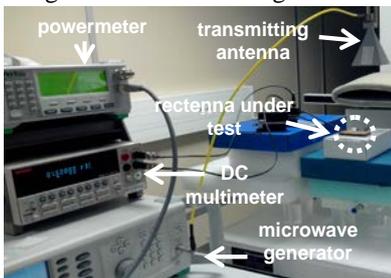


Fig. 4. Experimental setup used to characterize the tri-band rectenna

The power density ($\mu\text{W}/\text{cm}^2$) 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_i injected to the input of the transmitting horn antenna of gain G_i and positioned at the distance d from the rectenna, as follows:

$$S = \frac{E^2}{120 \cdot \pi} \cdot 100 = \frac{30 \cdot P_i \cdot G_i}{d^2 \cdot 120 \cdot \pi} \cdot 100 \quad (3)$$

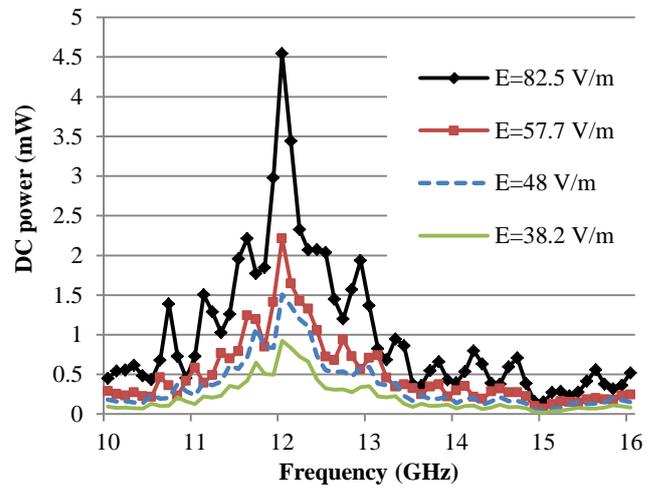


Fig. 5. Measured DC power at the input port of a resistive load ($RL=300\Omega$) as function of frequency and for various E-field amplitudes

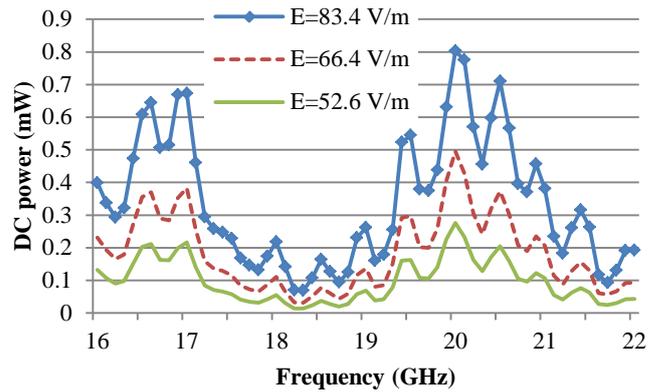


Fig. 6. Measured DC power at the input port of a resistive load ($RL=300\Omega$) as function of the frequency and for various E-field amplitudes.

The E-field and the power density illuminating the rectenna can be computed as function of the G_i and d by using eq. (3). Fig. 5 shows the measured harvested DC power at the input port of a resistive load ($RL=300\Omega$) in the frequency band 12GHz – 16GHz for various amplitudes of the E-field (the first transmitting horn antenna with $G_i=19$ dBi at 12 GHz was used). The E-field values were computed by using eq. (3). The maximum DC power was measured at 12 GHz as represented in Fig. 5.

Fig. 6 displays the measured DC power as function of frequency on a load of $RL=300\Omega$ in the frequency band 16GHz – 22 GHz as function of E-field (the second transmitting horn antenna with $G_i=19.5$ dBi positioned at the distance $d=22$ cm was used). The E-field amplitudes were computed by using eq. (3). The measurement results shown in Fig. 6 demonstrate also a multi-band behavior. Beside of its main operating frequency (12 GHz) the proposed rectenna harvests efficiently the RF power at 20 GHz. One can see also an important amount of the DC power for the frequencies of 17 GHz and 16.6 GHz. The optimal load was also determined (results not shown here). The maximum DC power was obtained for a load impedance RL of 300Ω .

The harvested DC power for $RL=300\Omega$ as function of E-field illuminating the 4CDAA at the frequency of 12 GHz is reported on Fig. 7. From a practical point a view at least 1 mW of DC power is required to supply an autonomous wireless sensors for satellite health application. Typically such a wireless sensor is composed of a sensor (DC power consumption in the range of few μW), a DC-to-DC convertor, a power management unit and a low-power wireless transceiver (DC power consumption in the range of the mW). However the electromagnetic energy illuminating the antenna panels is almost constant and the DC circuitry (including the power management unit) should be minimal [1]. As represented in Fig. 7 the rectenna can provide a DC power of 1mW or higher when it is illuminated by an electric field amplitude higher than 38 V/m. The efficiency of 4CDAA rectenna is computed by using eq. (2). Fig. 8 represents the RF-to-DC conversion efficiency as function of the E-field illuminating the rectenna under test.

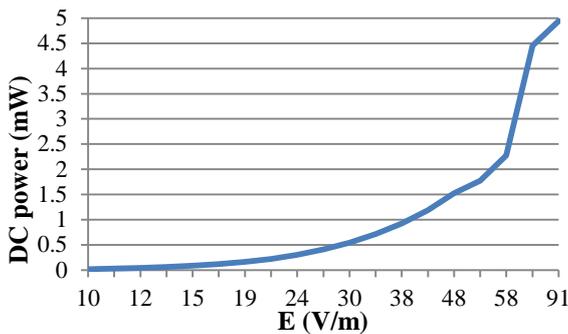


Fig. 7. Measured DC power at the input of a load ($RL=300\Omega$) as a function of the illuminating E-field amplitude at 12 GHz

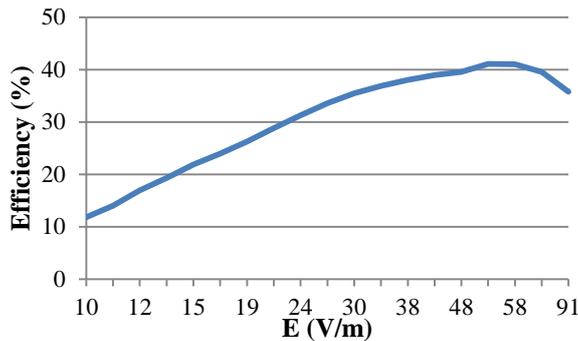


Fig. 8. Rectenna efficiency at 12 GHz as a function of illuminating E-field amplitude for $RL=300\Omega$.

The maximum achieved efficiency is approximately 41% at 12 GHz (first resonant frequency for 4CDAA) for an illuminating E-field amplitude ranging between 51 V/m and 58 V/m. The maximum achieved efficiency at the second resonant frequency ($f=17$ GHz) is approximately 12% while at 20 GHz (the third resonant frequency) the maximum efficiency is 16.3%. The reported efficiencies are limited by: (i) the ohmic resistance of the selected low-cost silicon diode, (ii) the adopted non-resonant matching technique, (iii) the lack of accurate simulation models of the selected diode. The overall performances of the 4CDAA rectenna can be further improved by optimizing PCB layout on the bottom side which

has a major impact on the impedance matching between the rectifier and the antenna located on the top side of the PCB. Works are under run and more results will be presented at the conference. Despite of the adopted non-resonant matching technique and of the inherent inaccuracy of the simulation model an efficiency greater than 25% can be obtained at the first resonant frequency by using a low cost silicon Schottky diode (SMS7630) when the E-field amplitude exceeds 19 V/m. The rectenna is very compact as shown in Fig. 1. Its size is 2.5 cm x 2.5 cm that is square wavelength at 12 GHz. Moreover this rectenna exhibits a tri-band behaviour explained mainly by the multiple resonant frequencies of the cross dipoles antenna array.

IV. CONCLUSION

A compact rectenna (overall size is approximately square wavelength at 12 GHz) based on the use of an original four cross dipoles antenna array was designed, manufactured and measured. The experimental results demonstrate that a DC power greater than 1 mW can be harvested in the Ku band (12 GHz) for electric field amplitude higher than 38 V/m. This DC power is sufficient to power a wireless sensor (including the sensor, the power management unit and the wireless transceiver) for satellite health monitoring application. A maximum RF-to-DC conversion efficiency of 41% was obtained for a load of 300Ω and an incident electric field of 51 V/m. Moreover this rectenna exhibits a multi-band behavior at frequencies that corresponds to the multiple resonant frequencies of the cross dipoles antenna array.

ACKNOWLEDGEMENT

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

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