



Energy and radiosciences / Énergie et radiosciences

Multiband rectenna for microwave applications

*Rectenna multi-bandes pour des applications micro-ondes*

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ARTICLE INFO

Article history:

Available online 21 December 2016

Keywords:

Electromagnetic energy harvesting
 Satellite health monitoring
 Multiband rectenna
 Cross dipole antenna array

Mots-clés :

Récupération d'énergie électromagnétique
 Rectenna multi-bandes
 Antenne
 Satellite géostationnaire

ABSTRACT

This paper reports a multiband rectenna (rectifier + antenna) suitable for the electromagnetic energy harvesting of the spill-over loss of microwave antennas placed on board of geostationary satellites. Such rectenna is used for powering autonomous wireless sensors for satellite health monitoring. The topology of the rectenna is presented. The experimental results demonstrate that the proposed compact rectenna can harvest efficiently the incident electromagnetic energy at three different frequencies that are close to the resonant frequencies of the cross-dipoles implemented in the antenna array.

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R É S U M É

Cet article présente une nouvelle rectenna (antenne + redresseur) multi-bandes utilisable pour la récupération d'énergie électromagnétique à bord de satellites géostationnaires. L'objectif est de récupérer l'énergie électromagnétique rayonnée par les antennes placées à bord du satellite. L'énergie ainsi récupérée est alors utilisée pour alimenter des capteurs autonomes sans fil. Les résultats expérimentaux montrent que cette rectenna récupère, avec une bonne efficacité, l'énergie électromagnétique à trois fréquences, qui correspondent aux fréquences de résonance de l'élément rayonnant de la rectenna.

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1. Introduction

The last decade has known a significant development of a wide range of wireless electronic devices such as RFID systems and wireless sensors networks. For many critical applications (e.g., space, aeronautic, and medical applications), the sensors used to monitor physical and structural quantities should be wireless and energetically autonomous. The energy, under its different forms (kinetic, thermal, solar, radio waves...) can be used to power these sensors. In this work, the use of the radio waves as energy source for autonomous power sensors is addressed. The autonomy of the wireless sensors can

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<http://dx.doi.org/10.1016/j.crhy.2016.12.002>

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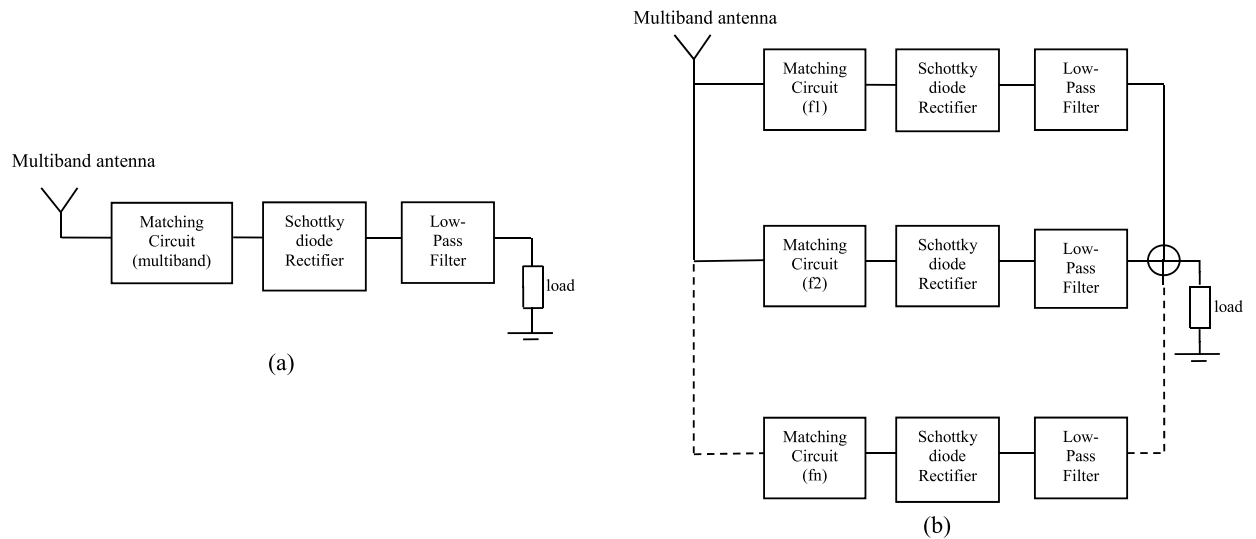


Fig. 1. Topologies for multiband rectennas: (a) rectenna with one RF band-pass filter for a broadband/multiband RF matching, and (b) rectenna combining the harvested DC powers at each frequency.

be achieved mainly by two techniques: (i) wireless power transfer and (ii) energy harvesting. These are two important concepts of “energy in radiosciences”; the first one consists in transmitting an electromagnetic energy generated by a dedicated/intentional transmitter and converting this energy into DC on the wireless sensor node by using a rectenna (coming from *rectifier antenna*), and the second one consists in harvesting the energy of the existing/surrounding radio waves by using a rectenna. In geostationary telecommunication satellites, high-gain microwave antennas are mounted on the external panels of the satellite for communication broadcasting. The radiofrequency (RF) power radiated by such antennas is in the range of 100 W. Consequently, an important amount of electromagnetic energy is available around the satellite and illuminates the (antenna) panels. 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 K_u -band, and 127 V/m in K-band [1]. Thus, electromagnetic energy harvesting was identified as a realistic solution to power autonomous wireless sensors deployed along the surface of the panels for structure health monitoring [1]. The rectenna (antenna + rectifier circuit) plays a crucial role in receiving and converting RF power into DC power. It consists of two main blocks: the first block is the antenna used to capture RF energy and converts it into an RF signal; the second block is the rectifier that converts this RF signal into a DC voltage used to power an autonomous wireless sensor. This paper presents recent results obtained in K_u and K bands through using an innovative rectenna topology reported in [2] and developed in [3] and [4], which is composed of four-printed-cross-dipole antenna arrays and uses a single low-cost Schottky diode [5]. Rectennas using a cross-dipole antenna were also reported in [1,6], while a rectenna using a two-cross-dipole array was reported in [7]. The rectenna topology and the design methodology are presented in Section 2. The experimental results are reported in Section 3 and show that very good performances can be achieved in three frequency bands by using a single rectenna. The proposed compact topology is an extension of the rectenna using two cross dipoles antenna array reported in [7].

2. Rectenna topology and design

In order to implement a multiband rectenna, two topologies can be considered. They are shown in Fig. 1. They consist of a multiband antenna that captures the ambient electromagnetic energy and converts it into a RF signal. This RF signal is then transferred to the rectifier via an impedance matching circuit/band pass filter for maximizing the transfer of power and minimizing the return loss at operating frequencies. The rectifier (e.g., a Schottky diode) is another key element of a rectenna and must be chosen carefully. Its role is to rectify the RF signal and a low-pass filter is then used in order to suppress the fundamental frequency component and its harmonics. The sensing device (typically a resistor) is modeled as a load impedance to be powered. As shown in Fig. 1a, the first possible topology uses only one rectifier for addressing all the targeted frequencies. As a drawback, this topology generally requires a multiband/broadband matching network that can be very challenging to design/implement in practice. A rectenna based on this topology is reported in [8,9]. Another solution is shown in Fig. 1b. A specific rectifier is used with its own impedance matching circuit at each targeted frequency. Then all the obtained DC powers are combined for powering the load (i.e. the sensing device). The rectenna proposed in [10] is based on this topology. For compactness purposes, the topology shown in Fig. 1a is adopted here. Moreover, by adopting this topology, a non-resonant matching technique is used. Matching is carried out by controlling the impedances of the antenna and of the rectifier. From a theoretically point of view, another topology can be proposed: it consists in using a specific rectenna (with a narrow-band/single-band antenna) for each frequency band and then combining the harvested DC powers. Nevertheless, this solution leads to a very large design.

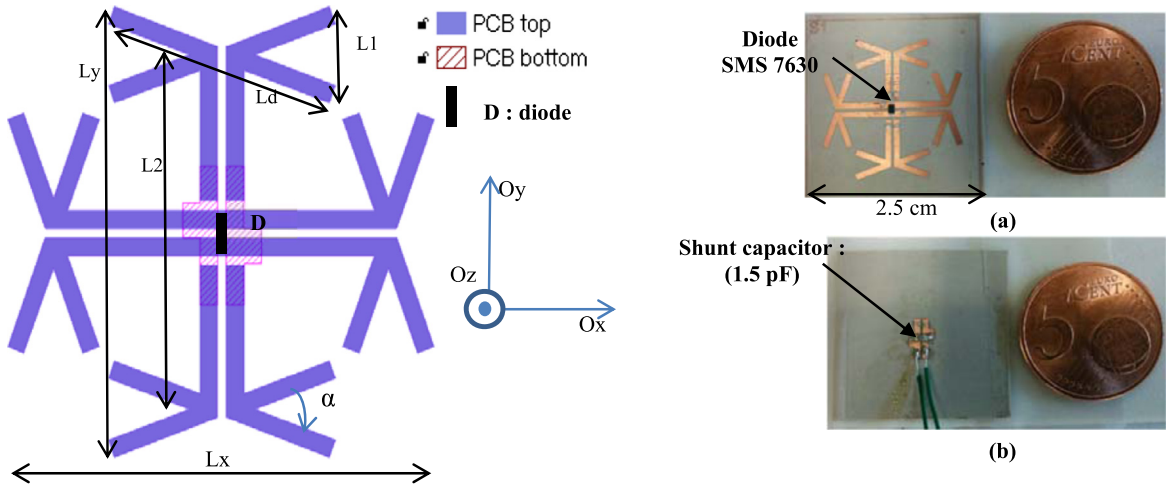


Fig. 2. (a) Top view (not to scale) of the layout of the 4CDAA rectenna, and (b) photos of the top and bottom sides of the manufactured rectenna. The wires shown here were used to connect a variable resistance in order to reach the optimal load impedance.

The proposed topology is composed of a four-cross-dipole antenna array (4CDAA) and of a silicon Schottky diode—Skyworks SMS7630—[5] mounted in shunt configuration. In order to select the topology of our antenna, several requirements were taken into account: (i) the rectenna should be as compact as possible (we note that the size of our design is determined mainly from the size of its antenna), (ii) the gain should be as high as possible in order to increase the rectenna's efficiency, (iii) the antenna should have a multiband behavior. As we will show later, the 4CDAA topology represents a good trade-off between the previously mentioned criteria. The best way to feed the 4CDAA is to use Coplanar Strip Lines (CPS). Thus the use of a single diode in a shunt configuration seems to be the best solution to implement the rectifier. Then the rectifier is comprised of (i) a silicon SMS7630 diode mounted in shunt configuration, (ii) a shunt capacitor to implement the DC low-pass filter, (iii) the CPS lines and via-holes used to interconnect the lumped components (diode and capacitance). From an electrical point of view, the rectifier views the input impedance of the CDAA as shunt impedance.

The PCB layout and a photo of the manufactured rectenna are shown in Fig. 2. 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 the PCB. A metallic plate is added on the bottom side in order to enhance the antenna gain. This compact topology (its size is fixed by the size of the antenna array) is an extension of the rectenna using the two-cross-dipole antenna array 2CDAA reported in [7]. Moreover, a non-resonant matching technique is used here. Instead of using a dedicated matching circuit that acts as a (resonant) band-pass filter, we try here to implement directly the (conjugate) matching requirements by properly controlling the input impedances of the 4CDAA and of the rectifier. Then, the matching circuit is virtually suppressed and leads to a more compact structure. The main goal is to achieve the best impedance matching at the resonant frequencies of the 4CDAA.

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-dipole arrays printed on the top of the PCB. Each cross dipole is an array with two dipoles in cross configuration, as shown in Fig. 2. The substrate used is the Rogers RT/Duroïd 6002 (substrate thickness: 0.508 mm, relative dielectric permittivity: 2.94 and dielectric loss tangent: 0.0012) [11].

3. Design of the rectenna

Some specific technical requirements for space applications must be fulfilled for designing an efficient rectenna: (i) the rectenna topology has to be as simple as possible; (ii) all the components in the rectenna (dielectric substrate, diode, capacitors, etc.) must be qualified for space applications, ready to be qualified or at least with performances suitable for space requirements; (iii) the operating frequencies must be chosen from the electromagnetic environment existing on board of satellite antenna panels. An analysis of the electromagnetic energy available on the panels at different frequencies is reported in [1].

3.1. Design of the antenna

Intensive full-wave electromagnetic simulations were performed by using Ansys HFSS software in order to design the 4CDAA structure. The diode was replaced by a voltage port, while the shunt capacitor and the load were modeled as lumped RLC boundaries as shown in Fig. 3. The antenna was initially simulated and optimized for 12 GHz, but it also displays a good impedance matching at two other frequencies, which corresponds to the higher resonant modes of the 4CDAA. The simulated return loss shows a multi-band behavior (12 GHz, 17.6 GHz and 20.2 GHz). Fig. 4 displays the simulated results regarding the return loss and the input impedance versus frequency.

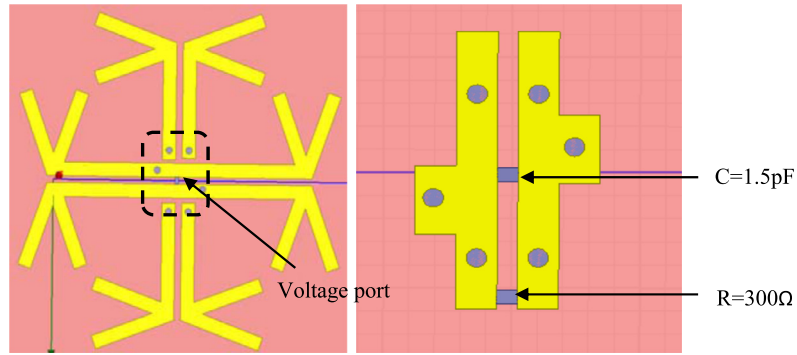


Fig. 3. The antenna with its voltage port and the lumped RLC boundaries.

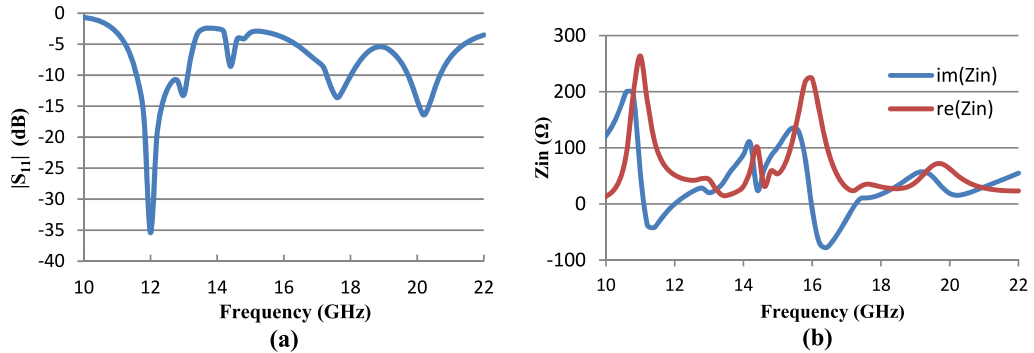


Fig. 4. (a) S11 viewed at the input port of the diode vs. frequency; (b) input impedance viewed at the input port of the diode vs. frequency.

The highest gain of such an array can be estimated by using the following expression:

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

where n is the number of dipoles ($n = 8$ in our case) and G_d is the gain of each (lossless) dipole. This gain can be increased when a 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 gain should be considered as an upper limit for any practical 4CDAA design.

There are no accurate closed-form expressions for designing such arrays, but some rules and methodology can be applied in order to start the design. The length of each dipole (L_d in Fig. 2) should be approximately half wavelength and the distance between the center of two opposite cross dipoles (L_2 in Fig. 2) should be an integer multiple of half wavelength. The angle between the dipoles (α in Fig. 2) impacts the polarization of the radiated field and the maximum achievable gain. CoPlanar Strip (CPS) lines are used to feed each cross dipole.

We target here a linear polarization, but other polarizations (e.g., circular polarization) can be obtained by controlling the angle α between the crossed dipoles and the relative phase at the input of each cross dipole. Depending on the system requirements, the microwave antennas of the broadcasting satellites may operate using circular or linear polarization [1]. Linear polarization is adopted here because the (in-house) experimental setup used for rectenna characterization has been built up by using a linearly polarized horn antenna. The diode is mounted at the center of the array, as shown in Fig. 2. Six metallic via holes were used to connect the top and the bottom sides 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.

At the first operating frequency ($f_0 = 12$ GHz), the length of each dipole (L_d) is close to the half wavelength ($L_d \sim \lambda/2$), and the distance between the center of the opposite dipoles (L_2) is close to the wavelength ($L_2 \sim \lambda$). The second operating/resonant frequency is $f_1 \sim 1.5f_0$. At this frequency, $L_d \sim 0.7\lambda$ and $L_2 \sim 1.5\lambda$. The third operating/resonant frequency is $f_2 \sim 2f_0$. At this frequency, $L_d \sim \lambda$ and $L_2 \sim 2\lambda$. Fig. 5 shows the simulated radiation patterns (gain) of 4CDAA at the three resonant (operating) frequencies 12 GHz, 17.6 GHz and 20.2 GHz. Fig. 6 shows the surface current density on the rectenna. From a theoretical point of view, at the third frequency (20.2 GHz), the radiation pattern is expected to be null along the Oz axis. This is not the case because L_d is not exactly equal to λ and also because an electromagnetic coupling exists between the cross dipoles. The designed 4CDAA exhibits the following simulated gain (values obtained for $\theta = \varphi = 0^\circ$): 11.7 dBi at 12 GHz, 11.7 dBi at 17.6 GHz and 12.7 dBi at 20.2 GHz. As expected, the simulated gains for the 4CDAA are much higher than the theoretical gain of a single dipole (2.15 dBi for an ideal half-wavelength dipole).

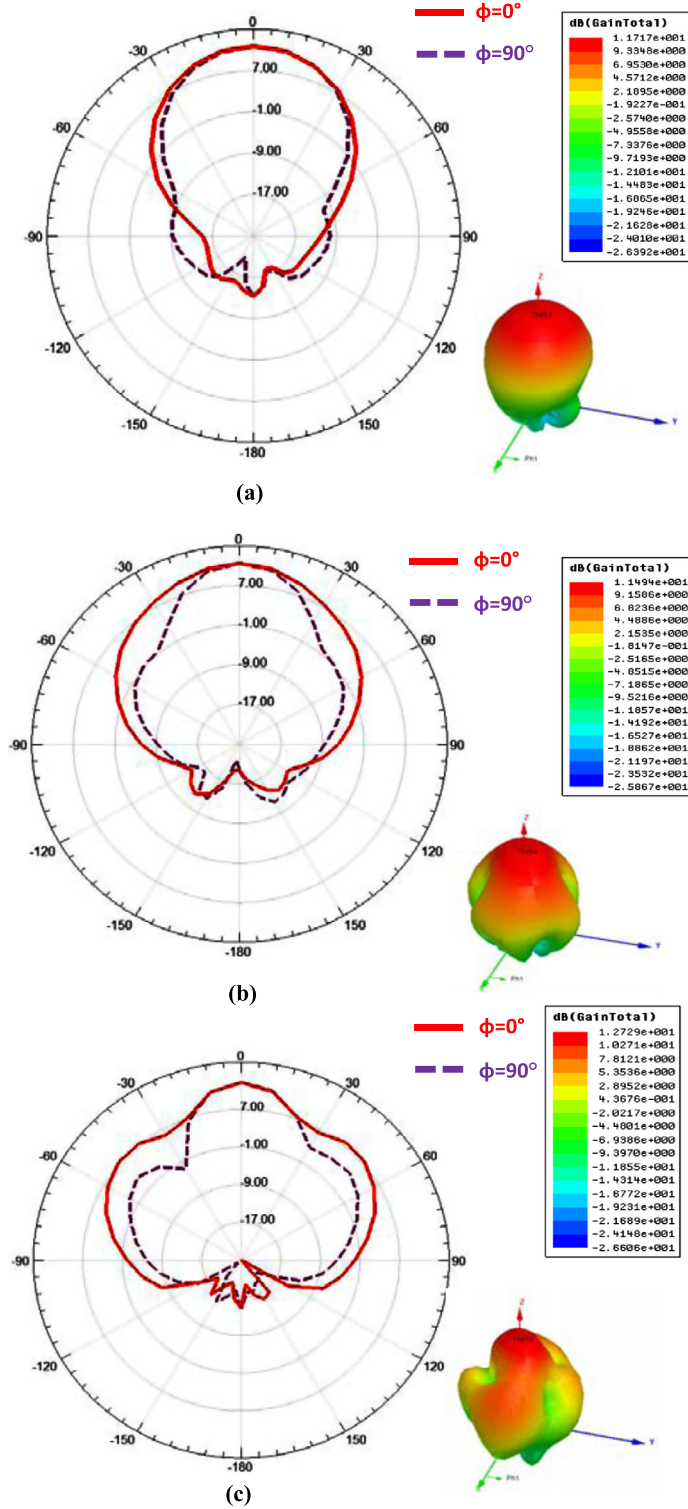


Fig. 5. Simulated (HFSS) radiation pattern (gain) in the xOz plane ($\phi = 0^\circ$, continuous line) and in the yOz plane ($\phi = 90^\circ$, dashed line) of the 4CDA at the frequencies of (a) 12 GHz, (b) 17.6 GHz, and (c) 20.2 GHz.

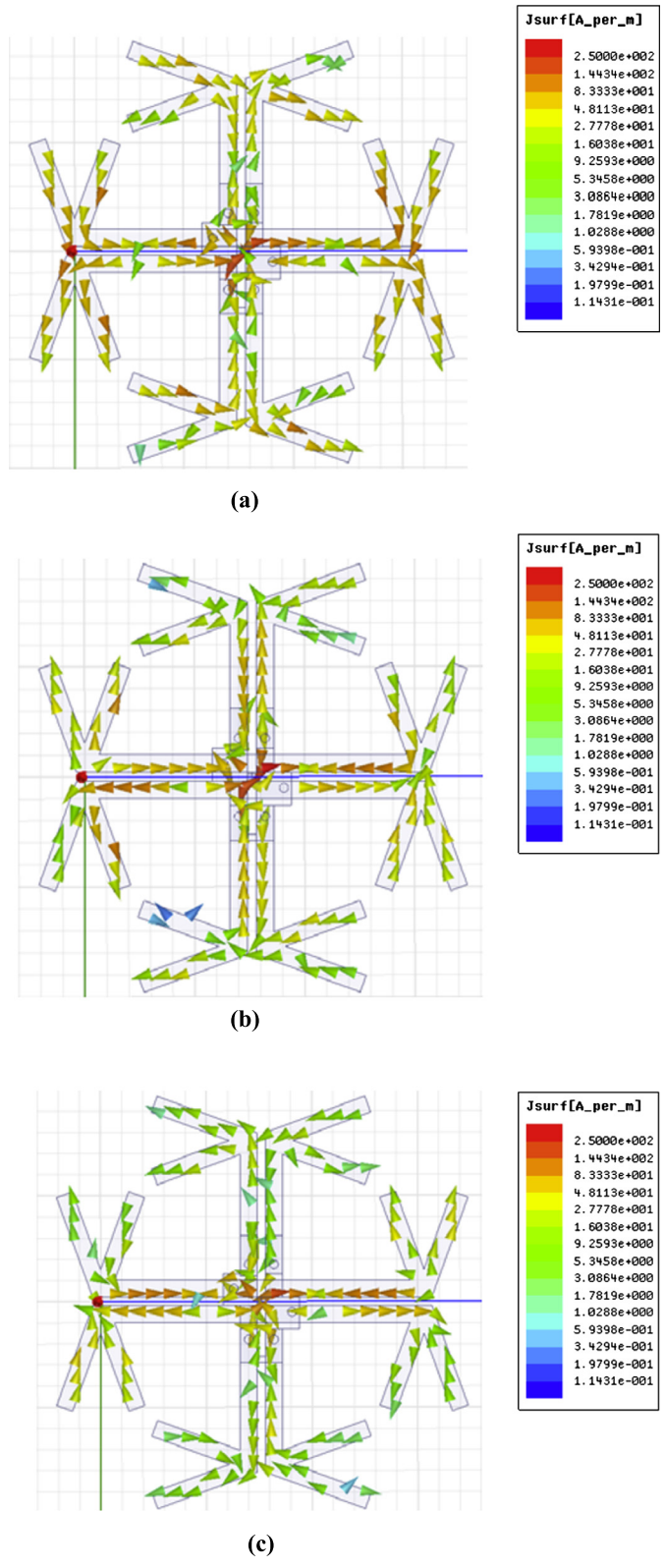


Fig. 6. Surface current density on the 4CDA at (a) 12 GHz, (b) 17.6 GHz, and (c) 20.2 GHz.

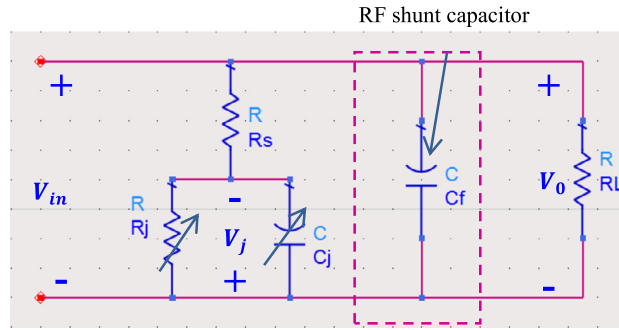


Fig. 7. Equivalent circuit of the diode.

Table 1
Schottky diode parameters.

Parameter	Value
Ohmic resistance (R_s)	20 Ω
Junction capacitance (C_{j0})	0.14 pF
Saturation current (I_s)	5 μ A
Forward voltage (V_f)	0.34 V
Reverse breakdown voltage (B_v)	2 V

3.2. Rectifier

The diode is the key element of the rectifier. The choice of an appropriate diode is crucial and must be done carefully in the design of a high-efficient rectifying circuit. This is because the diode is the main source of losses and its performance impacts significantly the performances of rectennas. The equivalent circuit of the diode/rectifier is shown in Fig. 7. It consists of the series resistance (R_s), a nonlinear junction resistance (R_j) derived from the I - V characteristic of the diode and a nonlinear junction capacitance (C_j). Due to the self-biasing nature of the shunt connected diode, C_j depends on the bias voltage across the diode as follows [12,13].

$$C_j = C_{j0} \sqrt{\frac{V_f}{V_0 + V_f}} \tag{2}$$

where C_{j0} is the zero-bias junction capacitance of the diode and V_0 denotes the DC output voltage. Following [12], an ideal DC pass-band filter is assumed here. Three key parameters of the diode impact the RF-to-DC conversion efficiency. The series resistance (R_s) limits the efficiency through the dissipation losses, the zero-bias junction capacitance (C_{j0}) affects the harmonic currents through the diode and the breakdown voltage (V_{BR}) limits the power handling capability of the rectifier.

The diode used in this design is the silicon Schottky diode SMS7630 from Skyworks. Its main parameters are reported in Table 1 (see [14,15]).

4. Experimental results and discussion

The experimental setup used in order to characterize the rectenna is shown in Fig. 8. A microwave signal provided by an Anritsu MG3694B generator is injected at the input of a horn antenna using a coaxial cable. During the measurement, the rectenna was aligned in order to match the (linear) polarization of the transmitting horn antenna. The horn antenna is placed at a distance d above the rectenna and allows illuminating the rectenna with a linearly polarized electric field. An automatic acquisition routine is implemented in Labview software from National Instruments to speed-up the acquisition process. The harvested DC voltage is 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 losses due to the coaxial cable and connectors placed between the signal generator and the horn antenna are around 3 dB in the operating frequency band (12 GHz). Two different transmitting horn antennas are used here: the first one covers the 12 GHz–16 GHz frequency band and the second one covers the 16 GHz–22 GHz frequency band.

The efficiency η (in %) of the rectenna can be computed as follows [16]:

$$\eta(\%) = \frac{P_{DC}}{S A_{eff}} \cdot 100 = \frac{4\pi P_{DC}}{S G_R \lambda^2} \cdot 100 \tag{3}$$

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.

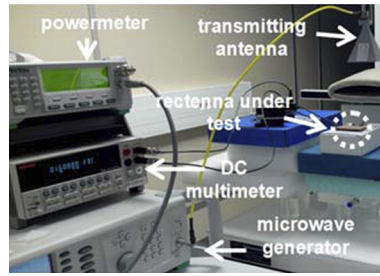


Fig. 8. Experimental setup used to characterize the multiband rectenna.

Table 2

Comparison of the rectennas' performances.

Ref.	Operating frequency	Diode	Incident power density/RF power at the rectifier's input	Dimensions	Maximum conversion efficiency
[12]	35 GHz	Skyworks DMK6606	20.79 dBm, $R_L = 400 \Omega$ 17 dBm, $R_L = 100 \Omega$	NC ^a	39%
[17]	2.45 GHz–5.8 GHz	Macom MA4E1317	2.38 mW/cm ² –8.77 mW/cm ²	NC ^a	84.4%–82.7%
[18]	24 GHz	Macom MA4E1317	10 mW/cm ²	Length: 55 mm $1.9\lambda_0$	24%
[19]	35 GHz	Macom MA4E1317	30 mW/cm ²	Length: 23.55 mm $2.7\lambda_0$	35%
[20]	25.7 GHz	Macom MA4E2502L	8 dBm	$21.9 \times 15 \text{ mm}^2$ $2.4\lambda_0^2$	16%
[21]	5.8 GHz	Macom MA4E1317	12 mW/cm ²	NC ^a	76%
This work	12 GHz–17 GHz–20 GHz	Skyworks SMS7630	1.8 mW/cm ²	$25 \times 25 \text{ mm}^2$ λ_0^2 at 12 GHz	41%

^a Not communicated.

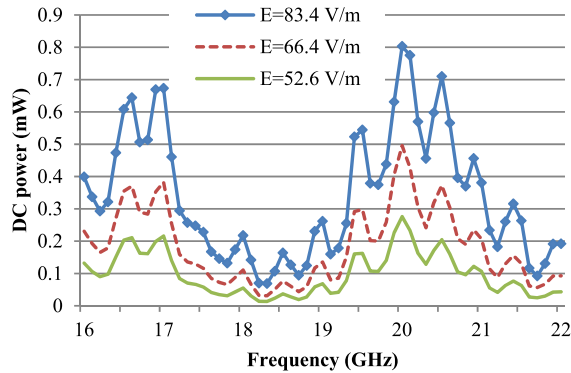


Fig. 9. Measured DC power at the input port of a resistive load ($R_L = 300 \Omega$) as a function of frequency and for various amplitudes of the electric field.

From equation (3), power density ($\mu\text{W}/\text{cm}^2$) can be computed as a function of the electric field's 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:

$$S = \frac{E^2}{120\pi} \cdot 100 = \frac{30P_t G_t}{d^2 120\pi} \cdot 100 \quad (4)$$

The electric field and the power density illuminating the rectenna can be computed as a function of G_t and d by using Eq. (3). Fig. 9 shows the measured harvested DC power at the input port of a resistive load ($R_L = 300 \Omega$) in the frequency band 10 GHz–16 GHz for various amplitudes of the electric field (the gain G_t of the first transmitting horn antenna at 12 GHz is 19 dBi). The maximum DC power was measured at 12 GHz, as shown in Fig. 9.

Fig. 10 displays the measured DC power on a load of $R_L = 300 \Omega$ in the frequency band 16 GHz–22 GHz as a function of the electric field (the gain G_t of the transmitting horn antenna at 12 GHz is 19.5 dBi). The measurement results shown in Fig. 10 demonstrate also a multi-band behavior. The proposed rectenna harvests efficiently the RF power at 17 GHz and 20 GHz. The optimal load was also determined, and Fig. 11 shows the DC power as a function of the load for an electric field of 48 V/m at 12 GHz. A standard potentiometer (0–10 k Ω) was used as a load impedance. The results shows that the

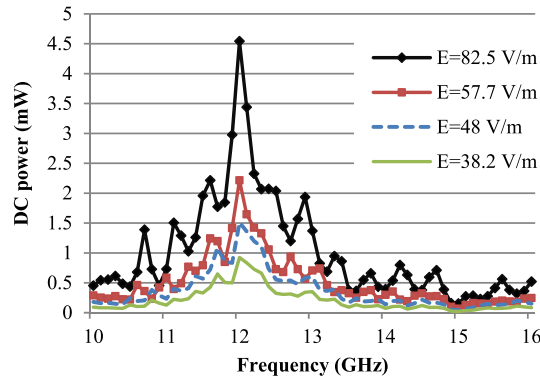


Fig. 10. Measured DC power at the input port of a resistive load ($R_L = 300 \Omega$) as a function of the frequency for various amplitudes of the electric field.

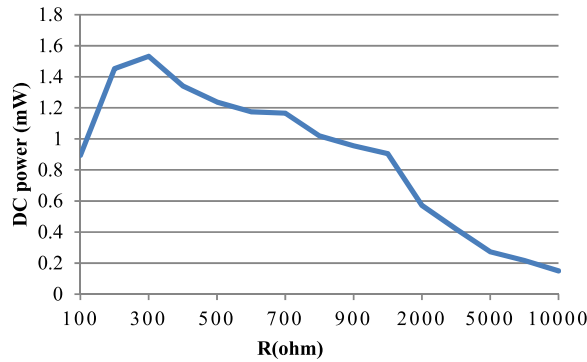


Fig. 11. Measured DC power as a function of the resistance of the load for an electric field of 48 V/m.

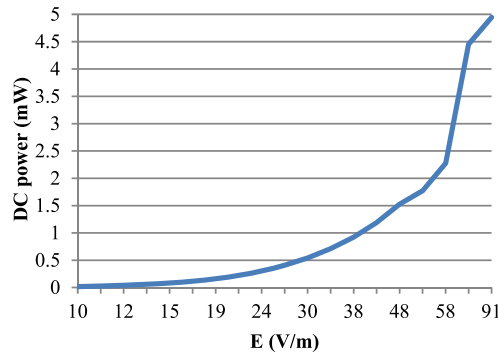


Fig. 12. Measured DC power at the input of a load ($R_L = 300 \Omega$) as a function of the illuminating electric field amplitude at 12 GHz.

DC power decreases (i.e. the efficiency decreases) when the load impedance increases. The highest DC power is obtained when $R = 300 \Omega$.

The harvested DC power for electric field = 300Ω as a function of the electric field illuminating the 4CDAA at the frequency of 12 GHz is reported in Fig. 12. From a practical point a view, at least 1 mW of DC power is required to supply an autonomous wireless sensor for satellite health application. Typically, such a wireless sensor is comprised of a sensor (DC power consumption in the range of few μW), a DC-to-DC converter, a power management unit, and a wireless low-power 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 shown in Fig. 12, the rectenna can provide a DC power of 1 mW 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. 13 represents the RF-to-DC conversion efficiency as a function of the electric field illuminating the rectenna under test.

The highest efficiency is approximately 41% at 12 GHz for an illuminating electric field amplitude ranging between 51 V/m and 83 V/m. Table 2 compares the main performances of this rectenna with other state-of-art multiband rectennas. At the second resonant frequency ($f_1 = 17.6$ GHz), the highest efficiency is approximately 12% while an efficiency of about

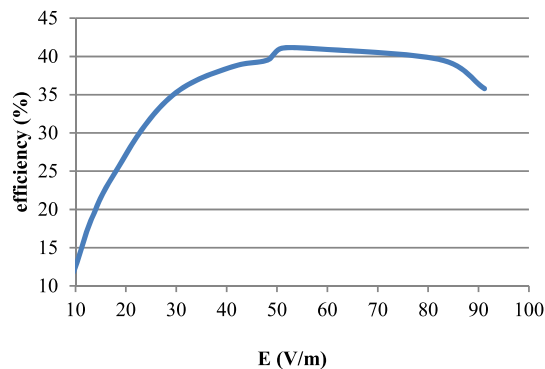


Fig. 13. Rectenna efficiency at 12 GHz as a function of the illuminating electric field amplitude for $R_L = 300 \Omega$.

20% is obtained at 20 GHz. The main sources of power loss are: (i) the ohmic resistance of the selected low-cost silicon diode and (ii) the eventual mismatch between the antenna and the rectifier (due to the adopted non-resonant matching technique and to the lack of accurate simulation models of the selected diode). The overall performances of the 4CDAA rectenna can be further improved by optimizing the 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. Efficiencies greater than 25% can be obtained at the first resonant frequency by using a low-cost silicon Schottky diode (SMS7630) when the electric field amplitude exceeds 19 V/m. The rectenna is very compact, as shown in Fig. 2. Its size is $2.5 \text{ cm} \times 2.5 \text{ cm}$. Moreover, this rectenna exhibits a tri-band feature, which is obtained from the multiple resonant frequencies of the cross-dipole antenna array.

5. Conclusion

A compact rectenna 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 K_u band (12 GHz) for an electric field amplitude higher than 38 V/m. This DC power is sufficient to power a wireless sensor (including the sensor, the sensing device, the power management unit and the wireless transceiver) for satellite health monitoring applications. 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., this rectenna exhibits a multi-band behavior at frequencies that correspond to the available multiple resonant frequencies of the cross-dipole antenna array.

Acknowledgements

The authors acknowledge the support of French Space Agency within the framework of several R&T contracts (R&T 2012 R-S12/MT-0002-012 and R&T 2015 R-S15/MT-0002-012).

References

- [1] A. Takacs, H. Aubert, S. Fredon, L. Despoisse, H. Blondeaux, Microwave power harvesting for satellite health monitoring, *IEEE Trans. Microw. Theory Tech.* 62 (4) (2014) 1090–1098.
- [2] A. Okba, S. Charlot, P-F. Calmon, A. Takacs, H. Aubert, Cross dipole rectenna for satellite health monitoring, in: *URSI Conference*, Nantes, France, March 2016.
- [3] A. Okba, S. Charlot, P-F. Calmon, A. Takacs, H. Aubert, Multiband rectenna for microwave applications, in: *IEEE Wireless Power Transfer Conference*, Aveiro, Portugal 5–6 May 2016.
- [4] A. Okba, S. Charlot, P-F. Calmon, A. Takacs, H. Aubert, Cross dipoles rectenna for microwave applications, in: *European Microwave Conference*, London, UK, 3–7 October 2016.
- [5] http://www.skyworksinco.com/Product/511/SMS7630_Series.
- [6] H. Sun, Y.-X. Guo, M. He, Z. Zhong, Design of a high-efficiency 2.45-GHz rectenna for low-input-power energy harvesting, *IEEE Antennas Wirel. Propag. Lett.* 11 (2012) 929–932.
- [7] A. Takacs, H. Aubert, A. Luca, S. Charlot, S. Fredon, L. Despoisse, Rectenna design for K band application, in: *2014 European Microwave Conference*, Rome, Italy, 5–10 October 2014.
- [8] V. Kuhn, C. Lahuec, F. Seguin, C. Person, A multi-band stacked RF energy harvester with RF-to-DC efficiency up to 84%, *IEEE Trans. Microw. Theory Tech.* 63 (5) (2015) 1768–1778.
- [9] K. Niotaki, S. Kim, S. Jeong, A. Collado, A. Georgiadis, M.M. Tentzeris, A compact dual-band rectenna using slot-loaded dual band folded dipole antenna, *IEEE Antennas Wirel. Propag. Lett.* 12 (2013) 1634–1637.
- [10] C. Song, Y. Huang, J. Zhou, J. Zhang, S. Yuan, P. Carter, A high-efficiency broadband rectenna for ambient wireless energy harvesting, *IEEE Trans. Antennas Propag.* 101 (8) (2015) 3486–3495.
- [11] RT/duroid® 6002 high frequency laminates, Rogers Corporation, Chandler, AZ, USA, 2013. Online available: <http://www.rogerscorp.com/documents/609/acm/RT-duroid-6002-laminate-datasheet.pdf>.
- [12] T.-W.Y. Chang, K. Chang, Theoretical and experimental development of 10 and 35 GHz rectennas, *IEEE Trans. Microw. Theory Tech.* 40 (12) (1992) 2359–2366.

- [13] J. Guo, X. Zhu, An improved analytical model for RF-DC conversion efficiency in microwave rectifiers, in: IEEE MTT-S International Conference, Montreal, QC, Canada, 17–22 June 2012.
- [14] http://www.skyworksinc.com/uploads/documents/Surface_Mount_Schottky_Diodes_200041AB.pdf.
- [15] Skyworks application notes 'mixer and detector diodes', <http://www.skyworksinc.com/uploads/documents/200826A.pdf>.
- [16] Z. Popovic, E.A. Falkenstein, D. Costinett, R. Zane, Low-power far-field wireless powering for wireless sensors, Proc. IEEE 101 (6) (2013) 1397–1407.
- [17] Y.-H. Suh, K. Chang, High-efficiency dual-frequency rectenna for 2.45- and 5.8-GHz wireless power transmission, IEEE Trans. Microw. Theory Tech. 50 (7) (2002) 1784–1789.
- [18] 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 Syst. I, Regul. Pap. 61 (12) (2014) 3358–3366.
- [19] Y.-J. Ren, M.-Y. Li, K. Chang, 35 GHz rectifying antenna for wireless power transmission, Electron. Lett. 43 (11) (2007) 602–603.
- [20] A. Collado, A. Georgiadis, 24 GHz substrate integrated waveguide (SIW) rectenna for energy harvesting and wireless power transmission, in: IEEE MTT-S International Conference, Seattle, WA, USA, 2–7 June 2013.
- [21] Y.-J. Ren, K. Chang, 5.8-GHz circularly polarized dual-diode rectenna and rectenna array for microwave power transmission, IEEE Trans. Microw. Theory Tech. 54 (4) (2006) 1495–1502.