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RESEARCH PAPER

A 2.45-GHz dual-diode rectenna and rectenna arrays for wireless remote supply applications

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This paper describes a compact and efficient rectenna based on a dual-diode microstrip rectifier at 2.45 GHz. This circuit has been designed and optimized using a global analysis technique which associates electromagnetic and circuit approaches. Due to the differential topology of the rectifier, neither input low-pass filter nor via-hole connections are needed. This makes the structure more compact reducing losses. Measurements of a single rectenna element show 83% efficiency over an optimal load of 1050 Ω at a power density of 0.31 mW/cm². To increase the received RF power and then increase dc power over the load, identical rectennas have been interconnected to form arrays. Two and four elements rectenna arrays, connected either in parallel or in series, have been developed. It was shown that by properly choosing the interconnection topology and the optimal output load, higher dc voltage or dc power have been obtained. The four-element series-connected array can provide experimentally up to 3.85 times output dc voltage compared to the single rectenna. The parallel-connected rectenna arrays generate approximately 2.15 and 3.75 times output dc power for two and four elements, respectively.

Keywords: rectennas, rectenna arrays, RF-to-dc conversion, efficiency, rectifiers, Schottky diode, finite difference time domain (FDTD), ISM band, frequency 2.45 GHz, electromagnetic/circuit approach, global analysis technique, microwave circuits, planar antennas, series interconnection, parallel interconnection

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I. INTRODUCTION

Nowadays, sensor nodes require battery power and the node life depends on battery power. However, problems like replacement appear when changing batteries is impractical or impossible, therefore requiring an alternative energy source. Wireless radio-frequency (RF) energy transmission is then an alternative method to avoid conventional power source imbedded inside the structure. A source antenna transmits microwaves to a receiver that is a rectenna (rectifying antenna), integrating the technology to receive and convert the RF energy into dc power. In this study, we focus on the microwaves to dc conversion at 2.45 GHz, frequency greatly used due to its low attenuation through the atmosphere, low-cost technology, and location at the center of un-licensed industrial–scientific–medical frequency band [1].

A rectenna contains a receiving antenna to collect microwave incident power and a rectifying circuit. The rectifier is often made up of a combination of Schottky diodes, an input HF filter, an output bypass capacitor, and a load resistor. The input HF filter localized between the antenna and diodes is a low-pass filter that rejects harmonics created by the non-linear diode behavior. It also acts as a matching circuit between the antenna and the rectifier [2, 3].

The microwave rectifier can take several configurations. However, the single serial [3–5] and shunt configuration [2, 6] are used in most rectifying circuits. To enhance the level of the output dc voltage, a voltage doubler configuration [2, 7, 8] can also be used. However, to supply high dc output, the rectenna array has to be able to rectify a large amount of incoming power. The rectenna array can be built by using different interconnections in series, or in parallel [2, 9–12] or most rarely in cascaded configuration [2] and each connection has its own output features.

In this paper, we propose an efficient dual-diode rectifier included on a microstrip rectenna and rectenna arrays combination at 2.45 GHz well suitable for driving smart actuators [9], wireless sensors or sensor nodes [13]. In general, the RF-to-dc rectifiers proposed in the literature contain an input HF filter [2–9] but also an output dc filter with, in the most case a shunt capacitor [2, 4, 6–9], or a microstrip low-pass filter [3], or a radial stub [5]. In addition, vias-hole connections between the rectifier and the ground plane are often used for dc path [3–9]. The proposed rectifier needs neither via-hole connections nor bypass capacitor.

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In addition, no input HF filter has been used. This makes the circuit very simple, more compact, and low cost.

The RF-to-dc rectifier has been accurately optimized using advanced design system (ADS) commercial software of Agilent Technologies. In order to take into account all the electromagnetic couplings, a global analysis technique [14] that associates momentum electromagnetic simulator (for the distributed part) and harmonic balance (for lumped linear and nonlinear elements) has been performed. Numerical simulations have also been performed using the 3D-finite difference time domain (FDTD) algorithm extended to lumped circuit elements to accurately describe and analyze the rectenna (including both antenna and rectifier circuit) in term of current distributions [15]. In addition, the total-field/scattered-field formulation has also been included to generate an arbitrary plane wave illumination.

First, four rectifiers based on two different Schottky diodes (HSMS 2860 and 2820) with the same topology have been developed and etched on low-loss Arlon 25N and low-cost FR4 substrates. Simulated and experimental results are then compared.

In a second time, rectenna arrays have been investigated. The rectenna elements are interconnected in series or in parallel. A comparison between series and parallel combinations has been performed in term of efficiencies and voltage ratio (VR) between a measured single rectenna element and the measured rectenna array based on N single rectenna elements. It was shown in [2, 16] that the optimum efficiency is obtained when identical rectenna elements and optimal resistive load are used.

II. DUAL-DIODE MICROWAVE RECTIFIER

A) Description of the structure

The RF-to-dc microwave rectifying circuit shown in Fig. 1 contains two Schottky diodes (D_1 and D_2) mounted with a differential topology. It contains a 50-Ω characteristic impedance microstrip feed line. At point P_o, the RF input power is divided into two equal entities that are rectified by diodes D_1 and D_2. These two diodes have the same impedance at 2.45 GHz and behave identically. The rectifier contains also two folded quarter wavelength open stubs, connected to points P_1 and P_2, which act as short circuits at 2.45 GHz and therefore isolate the resistive load R_L during the measurement step. The distance L between stubs (connected to points P_1 and P_2) and diodes D_1 and D_2 has been optimized to tune out the reactances of the diodes and increase their efficiencies. In addition, due to the differential measurement of the output dc voltage over the load ($V_{DC} = V_1 - V_2$), no via-hole connection is necessary. Both diodes exhibit high impedances at 4.9 GHz. At this frequency, the distance between each diode and the point P_o is equal to a quarter wavelength resulting in a small impedance at the input of the circuit (P_o). The point P_o behaves like a short circuit at this frequency. Note that the HSMS 286x series is designed to operate from 915 MHz to 5.8 GHz and this circuit has been designed at 2.45 GHz. However, the same rectifier topology can be developed and optimized at other frequencies using when possible another specific Schottky diodes well dedicated in the frequency band of interest.

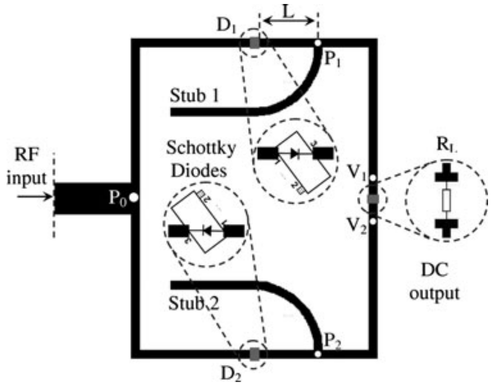

Fig. 1. Layout of the dual-diode rectifier at 2.45 GHz.

B) Numerical simulations

In this study, four dual-diode microwave rectifiers (Table 1) have been developed and compared. Circuits 1 and 2 are etched on Arlon 25N substrate ($\epsilon_r = 3.38$, thickness = 1.524 mm, tan $\delta = 0.0025$). Otherwise, circuits 3 and 4 are printed on low-cost FR4 substrate ($\epsilon_r = 4.4$, thickness = 1.58 mm, tan $\delta = 0.02$). To compare numerical results over a large amount of RF power, the HSMS 2860 and 2820 Schottky diodes in a SOT 23 package are used. Their models are done in [17]. These two diodes are, respectively, characterized by a breakdown voltage B_V of 7 and 15 V. The rectifiers have the same topology and have been optimized for an RF input power of 10 mW (circuits 1 and 3) and 20 mW (circuits 2 and 4). The dedicated optimal loads are listed in Table 1.

The simulated return loss (S_{11}) of the rectifiers versus RF frequency is shown in Fig. 2. Simulations are made using ADS software with 10 or 20 mW RF input power. Results

Table 1. Parameters of the RF-to-dc rectifiers.

Circuit	Diode type	Substrate	Optimal load (Ω)
1	HSMS 2860	Arlon 25N	500
2	HSMS 2820	Arlon 25N	1050
3	HSMS 2860	FR4	750
4	HSMS 2820	FR4	1100

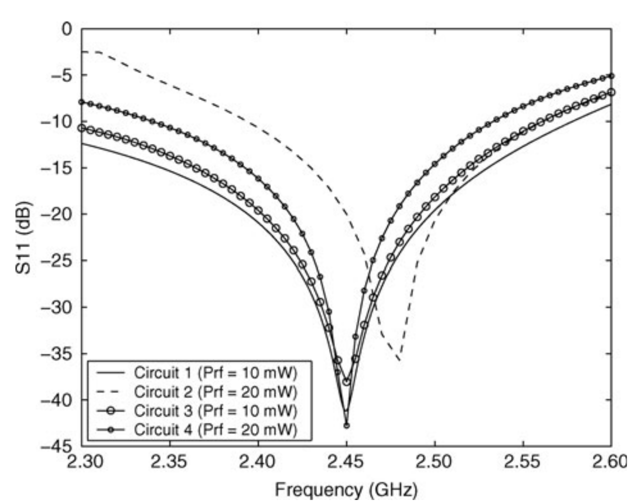

Fig. 2. Return loss of the RF-to-dc rectifiers versus RF frequency (ADS simulation).

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clearly show that circuits 1–4 are correctly matched and have a return loss lower than – 20 dB at 2.45 GHz. However, circuit 2 has a minimum of the return loss shifted throughout higher frequencies. Note that the conception of the rectifier is here based on the optimization of its RF-to-dc conversion efficiency at 2.45 GHz. This constraint involves a correct matching at the input of the rectifier but not necessarily a minimum of the return loss at this frequency.

Figure 3 shows the simulated return loss (S_{11}) of the rectifiers versus RF input power from 0.1 to 1000 mW at 2.45 GHz using ADS software. Results show that the circuits have a good matching level on the RF input power for which they have been optimized but, as previously mentioned, these values do not correspond to the minimum of the return loss. Return loss is lower than −40 dB at 10 mW for circuits 1 and 3 and lower than −20 dB at 20 mW for circuits 2 and 4.

In Table 2, we present the harmonic levels at the input and output of the circuits. All results are normalized with the input RF power at 2.45 GHz. The 4.9 GHz second harmonic is always strongly attenuated at the input of the rectifiers. This is due to the short circuit at point P_0 at this frequency. The 7.35 GHz third-order harmonic is sufficiently attenuated for circuits 2 and 4 (both based on HSMS 2820 diodes). However, circuits 1 and 3 (based on HSMS 2860 diodes) exhibit an attenuation of −20 dB. This can significantly affect the efficiency of the rectifier and then, the overall efficiency of the rectenna. At the output of the circuit, the 2.45 GHz RF component is greatly attenuated. The resistive load is then correctly RF isolated.

Figure 4 shows the simulated RF-to-dc conversion efficiencies of rectifiers when input power varies from 0.1 to 1000 mW at 2.45 GHz. The RF-to-dc conversion efficiency (η) is generally defined as follows:

$$\eta = \frac{P_{DC}}{P_{RF}} = \frac{V_{DC}^2}{R_L \times P_{RF}} \quad (1)$$

where P_{RF} is the maximum input RF power toward the rectifier, P_{DC} is the output dc power and V_{DC} is the output dc voltage over the resistive load.

The results show that circuits 1 and 3 have maximum efficiencies (75 and 68%, respectively) higher than those obtained with circuits 2 and 4 (68 and 63%, respectively). The efficiencies of rectifiers 1 and 3 roughly decrease from 40 and 32 mW respectively, whereas the efficiencies of rectifiers 2 and 4 decrease from 500 mW. This is due to the breakdown voltage (B_V) of diodes which limits the amount of incoming RF input power [18]. The rectifier contains two diodes in series. In this case, the maximum RF power that can be converted is defined as follows:

$$P_{RF}^{max} = \frac{B_V^2}{2 \times R_L} \quad (2)$$

We can also notice that the efficiencies of circuits 2 and 4, both based on HSMS 2820 diodes, slightly vary between 30 and 500 mW. At 2.45 GHz, the diode impedance has been computed as a function of RF input power (Fig. 5) and, unlike the HSMS 2860, the real and imaginary parts of the HSMS 2820 diode vary slowly when the input power increases. This slightly affects the matching of the rectifiers, and then explains the smooth variation of the efficiency.

Circuits 3 and 4, etched on FR4 substrate, exhibit efficiencies lower than those obtained for circuits 1 and 2. The FR4 has a loss tangent higher (tan $\delta = 0.02$) than the Arlon 25N substrate (tan $\delta = 0.0025$). This directly affects the conversion efficiency of the rectifier.

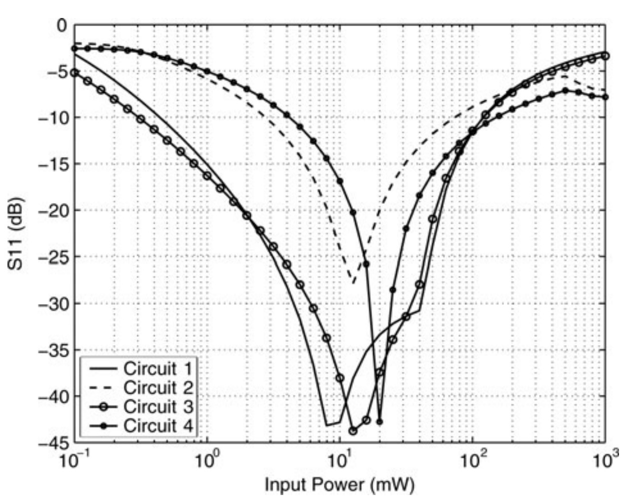

Fig. 3. Return loss of the RF-to-dc rectifiers versus RF power at 2.45 GHz (ADS simulation).

Table 2. Input and output harmonics levels.

Circuit (GHz)	Input harmonic levels (dB) 4.9	7.35	9.8	Output harmonic levels (dB) 2.45	4.9	7.35	9.8
1	−75	−20	−70	−85	−24	−80	−27
2	−100	−40	−120	−68	−40	−115	−35
3	−100	−20	−105	−100	−27	−105	−35
4	−88	−28	−85	−66	−28	−83	−43

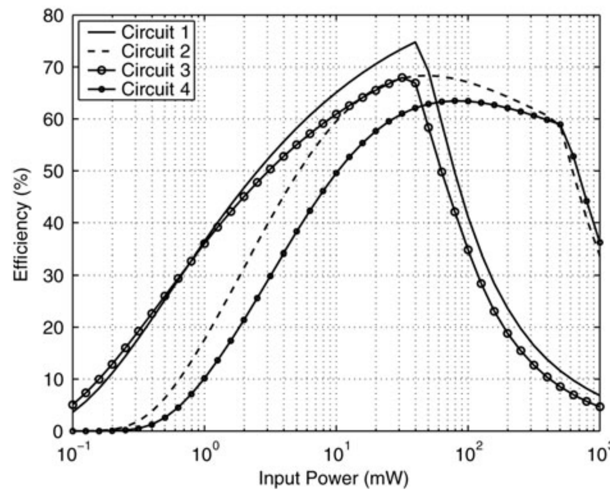

Fig. 4. Efficiencies of the RF-to-dc rectifiers (ADS simulation).

C) Experimental characterization of the rectifiers

Rectifiers etched on Arlon 25N substrate (circuits 1 and 2) have been realized and experimentally characterized to compare the results with ADS simulations.

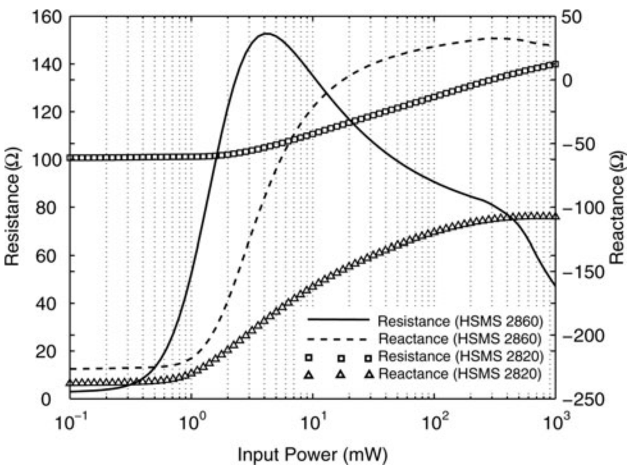

Fig. 5. Impedance of the HSMS 2820 and 2860 diodes (ADS simulation).

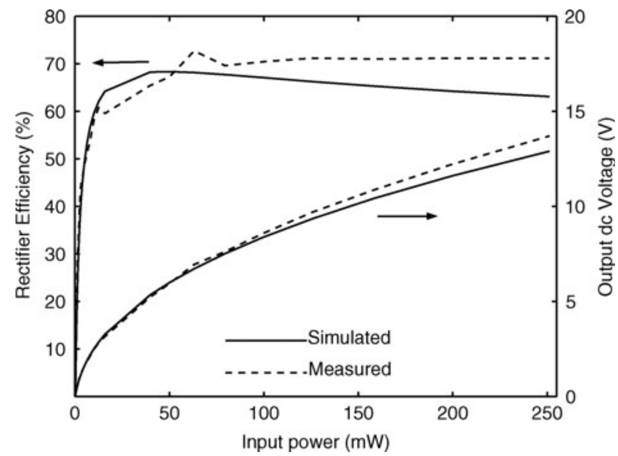

Fig. 7. Characterization of circuit 2 – simulation and measurements.

Figure 6 shows the output dc voltage and conversion efficiency of circuit 1 when input RF power varies between 0 and 10 mW. At 10 mW RF input power, simulated and measured efficiencies are, respectively, 65 and 58% while the output voltage is 1.7 V over an optimal load of 500 Ω. Simulations agree well with the measured results. However, some differences appear between simulated and measured efficiencies (7–10%). These differences can be mainly explained by the dispersion between the electrical characteristics of the Schottky diodes used in the experiment and the values given by the electrical model provided by ADS. The differences are also due to the tolerances during the fabrication process and the errors during measurements. In addition, the frequency domain simulations performed by harmonic balance (ADS) have a limited accuracy to simulate nonlinear circuits like rectifiers including one or several diodes.

Figure 7 shows the output dc voltage and RF-to-dc conversion efficiency of circuit 2 when input power varies from 0 to 250 mW. The measured efficiency varies slightly between 50 and 250 mW ($\eta = 67$–72%). DC voltages of 12.9 and 13.7 V have been, respectively, obtained by simulation and measurement across a 1050 Ω optimal resistive load at 250 mW RF input power.

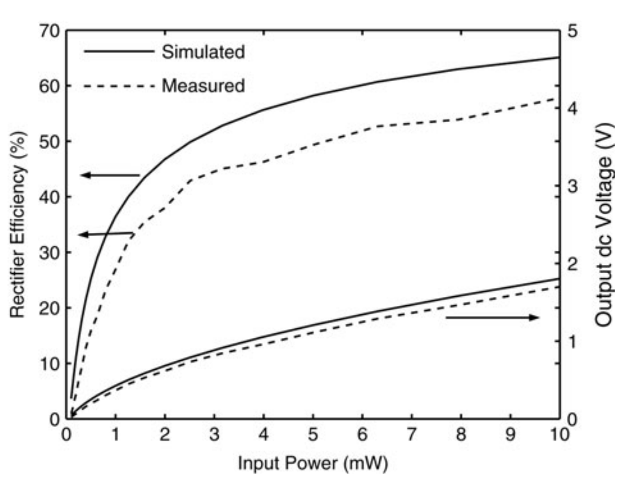

Fig. 6. Characterization of circuit 1–simulation and measurements.

III. RECTENNA ARRAY

When a large dc output (voltage and/or power) is necessary, rectenna arrays are then needed. We focus here on the rectenna arrays with two different interconnections: series and parallel connections (Fig. 8). Rectenna arrays have been realized from the single dual-diode rectifier previously described. Four rectenna arrays containing 2 and 4 single rectenna elements were developed and experimentally characterized in an anechoic chamber at 2.45 GHz.

The single rectenna element has been printed on Arlon 25 N substrate with $\epsilon_r = 3.38$ and 1.524 mm thickness. It contains a linearly polarized rectangular patch antenna with notches designed at 2.45 GHz. A 4.7 dB gain and a minimum return loss of −20 dB have been measured. The effective area at its broadside ($\theta = 0°$) is 35.23 cm². The rectenna contains two HSMS 2860 Schottky diodes in a SOT 23 package. As well described in [15], the length of the feeding line (L_4) between antenna and the input of the rectifier has been accurately adjusted using numerical FDTD

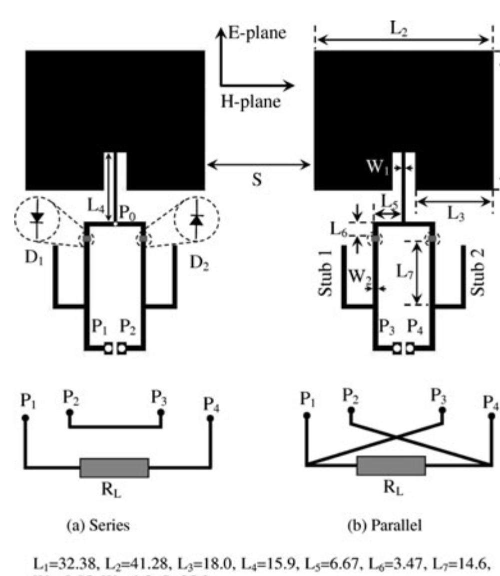

Fig. 8. Layout of the two-elements rectenna array (dimensions in millimeters): (a) series and (b) parallel.

simulations in order to match the antenna and the rectifier, and then obtain optimized performances. The 7.35 GHz third-order harmonic at the input of the rectifier has been reduced (−30 dB attenuation) due to the mismatch between the antenna and the rectifier at this frequency. Therefore, the single rectenna exhibits 83% measured efficiency on an optimal load of 1050Ω when the power density is 0.31 mW/cm² (P_{RF} = 11 mW).

The two-element rectenna array layout with series and parallel interconnections is shown in Fig. 8. The receiving antennas are positioned collinearly along the *H*-plane. For a spacing between patches larger than 0.10 λ_o, it was shown that the *H*-plane arrangement exhibits a smaller coupling compared to the *E*-plane arrangement [19]. Here, a spacing of 25 mm (λ_o/5) was chosen between patches, resulting in a mutual coupling less than −25 dB. The radiating elements are then correctly isolated.

The overall efficiency has been measured when the resistive load and the power density striking the rectenna panel successively vary. The Friis transmission equation, including effective aperture of the receiving antenna allows to compute the effective received RF power toward the rectifier [9]. Experimental characterizations have been performed using a dedicated measurement setup presented in [20]. Rectenna array is localized in the far field transmitting antenna region ($2D^2/\lambda > 53$ cm) at a distance of 70 cm from a linearly polarized horn antenna (G_{trans} = 12 dB) and is illuminated at its broadside. On the transmitter side, a 30 dB gain power amplifier at 2.45 GHz has been connected to a RF signal generator. The output dc voltage across R_L has been measured by a voltmeter.

A) Parallel interconnection

Theoretically, in the case of parallel-connected rectennas, the optimal resistive load is divided by the number of single rectenna elements (N) and the dc voltage is the same as a single rectenna. This means that the dc power (and then the dc current) is multiplied by the number of array elements assuming that the rectennas have the same efficiency, that they are illuminated by the same power density and are also correctly isolated to provide the same dc outputs. It has been previously shown in [16] that an imbalance between the characteristics of the single rectenna degrades the performances and the dc output of the rectenna array.

Figure 9 shows the parallel-connected array efficiencies as a function of the resistive load. Measurements have been done considering two power densities: 0.027 and 0.28 mW/cm². For the two-element array, efficiencies are optimal for a resistive load of 525 Ω (instead of 1050 Ω) and 265 Ω for the four-element rectenna panel. These results show that measurements are in good agreement with the theoretical prediction.

The measured dc voltage and efficiency as a function of power density (0–0.31 mW/cm²) is shown in Fig. 10. The effective aperture of a rectenna panel is then obtained by multiplying the effective aperture of a unit cell element by the number of elements. Therefore, we assume that the rectenna elements have the same properties and are isolated. The measured dc output of the single rectenna (N = 1) is plotted as a reference and optimal loads are connected in all cases. For N = 2, the dc voltage is close to that provided by the single element and the measured efficiency is about 88% at 0.28 mW/cm² (P_{RF} = 20 mW). The four-element array

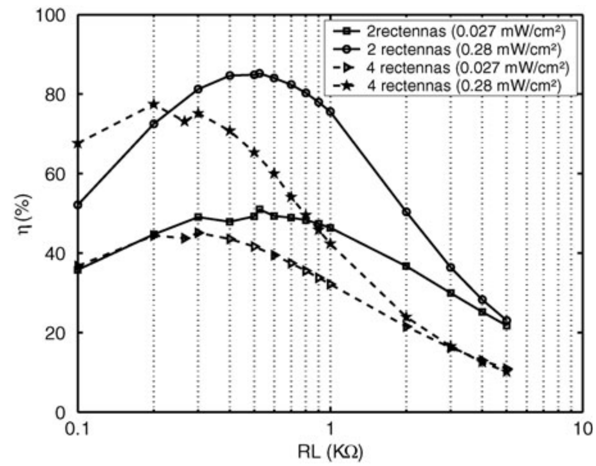

Fig. 9. Measured efficiency against resistive load – parallel interconnection.

provides 3 V output dc voltage across a 265 Ω optimal load when the power density is 0.31 mW/cm² (P_{RF} = 43.7 mW). It exhibits a maximum efficiency of 78%.

B) Series interconnection

When a single-rectenna element cannot provide a large dc voltage, the development of series-connected arrays can be an alternative solution. In this case, the optimal load (R_L) and the output voltage are multiplied by the number of elements (N). Assuming the previous hypothesis concerning the small mutual coupling between radiating elements and the same properties for each single rectenna, the efficiency should remain constant when the number of elements increases.

To find the optimal loads experimentally, measurements of the efficiency as a function of the output load were performed and results are shown in Fig. 11. Measurements have been performed for the same power densities: 0.027 and 0.28 mW/cm². For the two-element array, results show that the efficiency is optimal when the output load is close to 2.1 kΩ and it increases when the number of elements increases. An optimal load of 4.2 kΩ has been measured for a panel of four rectennas. Measurements agree well with theoretical predictions and confirm the previous hypothesis. The spacing

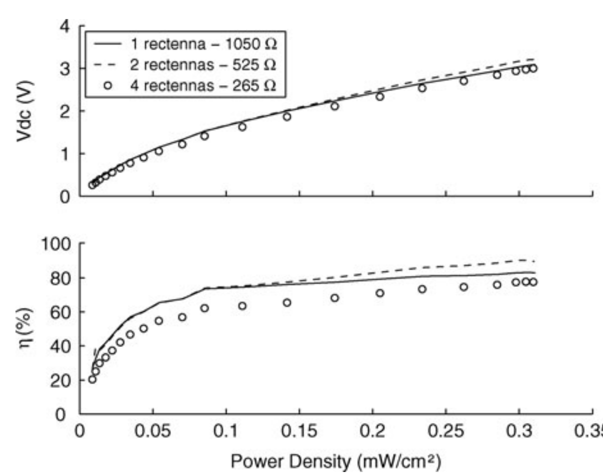

Fig. 10. Measured dc voltage efficiency against power density – parallel interconnection.

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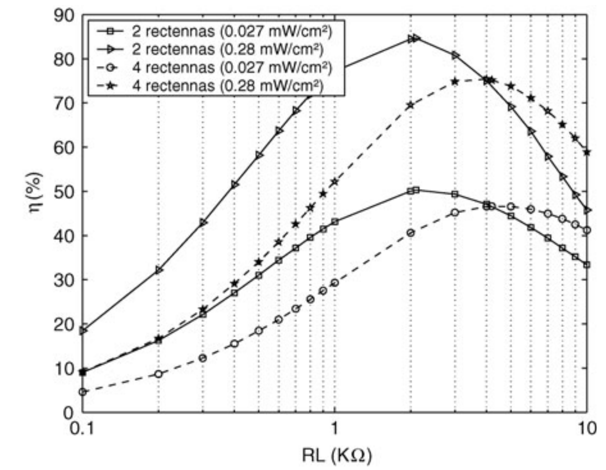

Fig. 11. Measured efficiency against resistive load – series interconnection.

between each element has been finely adjusted to have a very small coupling. Therefore, we can consider that each element behaves like an independent dc power source.

Figure 12 presents the measured dc voltage and efficiency of series-connected arrays ($N = 2$ and 4) in the power density range of 0–0.31 mW/cm². The measured output voltage and efficiency of the single-rectenna element are plotted as a reference. The two-element rectenna array provides 6.43 V over a 2.1 kΩ optimal load when the power density is 0.31 mW/cm² ($P_{RF} = 21.9$ mW). It exhibits an efficiency of 88%. Under the same power density, when $N = 4$ ($P_{RF} = 43.7$ mW), the dc voltage reaches about 11.9 V over a 4.2 kΩ resistive load. The maximum measured efficiency is about 78%.

C) Output VR of the interconnected rectenna arrays

The output VR is defined as the ratio of the dc voltage between the array of rectennas and the single-element rectenna. Figure 13 compares the VR in the case of $N = 1$, 2, and 4. In the power density range (0–0.31 mW/cm²), the series-connected arrays, with two and four elements, respectively, provide approximately 2.07 and 3.84 times output voltage. However, the parallel-connected arrays generate approximately 1.04 ($N = 2$) and 0.97 ($N = 4$) times output voltage whatever the power density striking the rectenna. These results match the theoretical predictions well.

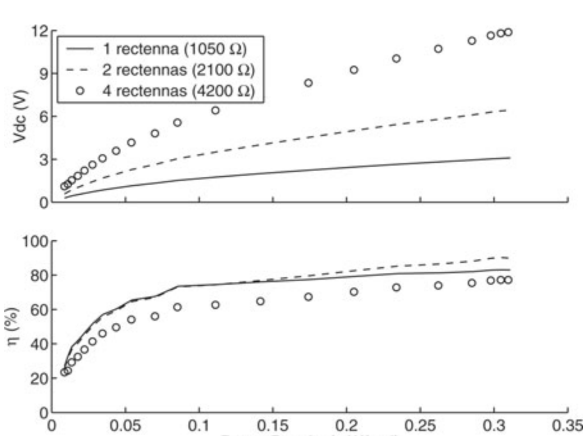

Fig. 12. Measured dc voltage and efficiency against power density – series interconnection.

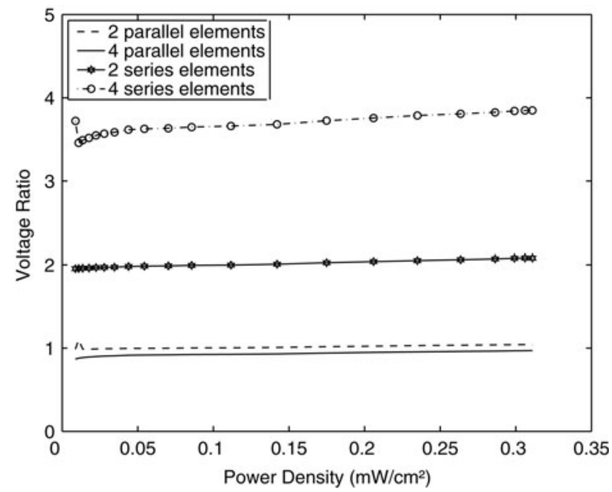

Fig. 13. Measured voltage ratio (VR) of the single rectenna element and the interconnected rectenna array.

IV. CONCLUSION

In this paper, a 2.45 GHz efficient dual-diode rectenna and rectenna arrays have been developed. The proposed circuits are simple and compact as they are avoiding the use of input HF filter and via-hole connections. In order to compare and evaluate the performances of a single rectenna element etched on various substrates and using different diodes, two Schottky diodes (HSMS 2860 and 2820) and two substrates (low-loss ARLON 25N and low-cost FR4) were used and results compared. The proposed single rectenna on Arlon 25N can provide a maximum efficiency of 83% under a power density of 0.31 mW/cm².

Rectenna arrays have been investigated and experimentally characterized. A combination of two and four identical rectenna elements were interconnected either in series or in parallel. Measured results are in good agreement with theoretical predictions, showing that the rectenna elements are equally illuminated, have the same characteristics and are correctly isolated. It has been shown that the choice of the topology of interconnection and the output load can significantly improve the dc power and/or voltage across the load. It is obvious that series connection can give a higher output voltage than the parallel connection but both array interconnections exhibit efficiencies above 78% at a power density of 0.31 mW/cm². These results can be useful for wireless power transmission applications. The developed rectifier and rectenna arrays are particularly suitable to power remote supply of wireless and low consumption sensors, sensor nodes and actuators.

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REFERENCES

[1] Brown, W.C.: The history of power transmission by radio waves. IEEE Trans. Microw. Theory Tech., MTT-32 (9) (1984), 1230–1242.

[2] Ren, Y.J.; Chang, K.: 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.

[3] Douyere, A.; Lan Sun Luk, J.D.; Alicalapa, F.: High efficiency microwave rectenna circuit: modeling and design. Electron. Lett., **44** (24) (2008), 1409–1410.

[4] Zbitou, J.; Latrach, M.; Toutain, S.: Hybrid rectenna and monolithic integrated zero-bias microwave rectifier. IEEE Trans. Microw. Theory Tech., **54** (1) (2006), 147–152.

[5] Akkermans, J.A.G.; van Beurden, M.C.; Doodeman, G.J.N.; Visser, H.J.: Analytical models for low-power rectenna design. IEEE Antennas Wirel. Propag. Lett., **4** (2005), 187–190.

[6] Strassner, B.; Chang, K.: 5.8-GHz circularly polarized rectifying antenna for wireless microwave power transmission. IEEE Trans. Microw. Theory Tech., **50** (8) (2002), 1870–1876.

[7] Heikkinen, J.; Kivikoski, M.: Low-profile circularly polarized rectifying antenna for wireless power transmission at 5.8 GHz. IEEE Microw. Wirel. Compon. Lett., **14** (4) (2004), 162–164.

[8] Heikkinen, J.; Kivikoski, M.: A novel dual-frequency circularly polarized rectenna. IEEE Antennas Wirel. Propag. Lett., **2** (2003), 330–333.

[9] Epp, L.W.; Khan, A.R.; Smith, H.K.; Smith, R.P.: A compact dual-polarized 8.51-GHz rectenna for high-voltage (50 V) actuator applications. IEEE Trans. Microw. Theory Tech., **48** (1) (2000), 111–120.

[10] Bharj, S.S.; Camisa, R.; Grober, S.; Wozniak, F.; Pendleton, E.: High efficiency C-band 1000 element rectenna array for microwave powered applications, in IEEE MTT-S Int. Microw. Symp. Digest, Albuquerque, NM, June 1992, 301–301.

[11] Hagerty, J.A.; Popovic, Z.: An experimental and theoretical characterization of a broad-band arbitrarily-polarized rectenna array. IEEE MTT-S Int. Microwave Symp. Dig., **3** (2001), 1855–1858.

[12] Shinohara, N.; Matsumoto, H.: Experimental study of large rectenna array for microwave energy transmission. IEEE Trans. Microw. Theory Tech., **46** (3) (1998), 261–268.

[13] Farinholt, K.M.; Park, G.; Farrar, C.R.: RF energy transmission for low-power wireless impedance sensor node. IEEE Sens. J., **9** (7) (2009), 793–800.

[14] Takhedmit, H.; Merabet, B.; Cirio, L.; Allard, B.; Costa, F.; Vollaire, C.; Picon, O.: Design of a 2.45 GHz rectenna using a global analysis technique in Proc. of the 3rd European Conf. on Antennas and Propagation, EuCAP 2009, Berlin, Germany, 23–27, March 2009. 2321–2325.

[15] Takhedmit, H. et al.: Efficient 2.45 GHz rectenna design including harmonic rejecting rectifier device. Electron. Lett., **46** (12) (2010), 811–812.

[16] Shinohara, N.; Matsumoto, H.: Dependence of dc output of a rectenna array on the method of interconnection of its array elements. Scr. Tech. Electron. Commun. Japan, **125** (1) (1998), 9–17.

[17] HSMS-286x, HSMS-282x series. Surface Mount Microwave Schottky Detector Diodes. Available: http://www.avagotech.com/

[18] Yoo, T.-W.; Chang, K.: Theoretical and experimental development of 10 and 35 GHz rectennas. IEEE Trans. Microw. Theory Tech., **40** (6) (1992), 1259–1266.

[19] Balanis, C.A.: Antenna Theory: Analysis and Design, 3rd ed., John Wiley & Sons, Inc., 2005.

[20] Takhedmit, H. et al.: A 2.45 GHz low cost and efficient rectenna, in Proc. of the 4th European Conf. on Antennas and Propagation, EuCAP 2010, Barcelona, Spain, 12–16 April 2010, pp. 1–5.

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