

Hybrid Rectenna and Monolithic Integrated Zero-Bias Microwave Rectifier

Jamal Zbitou, Mohamed Latrach, *Member, IEEE*, and Serge Toutain

Abstract—In this study, we have developed a hybrid sensitive rectenna (rectifier + antenna) system at 2.45 GHz. To achieve this system, we have first optimized and validated a zero-bias microwave sensitive rectifier using commercial Schottky diodes. We have then optimized and achieved a 2×2 patch antenna array, which is associated to the microwave rectifier in order to validate the rectenna system, where an RF–dc conversion efficiency of 56% has been observed experimentally. In order to minimize the rectenna dimensions, we have conducted a study using the OMMIC ED02AH 0.20- μm GaAs pseudomorphic high electron-mobility transistor process to develop and achieve a monolithic rectifier at 2.45 GHz with RF–dc conversion efficiency of 65%.

Index Terms—Monolithic microwave rectifier, rectenna, rectifier, Schottky diode, wireless power transmission.

I. INTRODUCTION

A FIRST experimental study of wireless power transmission, by microwave beams, was carried out in the early 1960s in the U.S. [1]. Since then, other research has been conducted [2], [3]. From these studies, a new method that provides some systems with a clean energy source has been developed. This is done by rectifying the microwave power, as in the case of robots and the supply of electricity to areas that are difficult to reach. In order to achieve such a result, a rectenna system (rectifier + antenna) was used. The key to improve transmission RF–dc conversion efficiency is the rectifying circuit. A rectifier is a combination of a Schottky diode, an input matching circuit, an output bypass capacitor, and a load resistor. The performances of the rectifier are determined by the nonlinear process of the Schottky diode, by the barrier losses, and by the series resistance losses [4], [5]. Thus, the input impedance matching is affected by the variation of the input power level.

In this paper, we report an optimization and an achievement of a hybrid rectifier at 2.45 GHz by using a single commercial zero-bias (ZB) diode. We also improve the detection sensitivity of this circuit at low power levels. In this investigation, we have also developed a 2×2 patch antenna array, which is associated with the validated rectifier. This permits the validation of the hybrid rectenna system.

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J. Zbitou and M. Latrach are with the RF and Microwave Group, Ecole Supérieure d'Electronique de l'Ouest, 49009 Angers, France (e-mail: mohamed.latrach@eseo.fr).

S. Toutain is with the Institut de Recherche en Electrotechnique et Electronique de Nantes Atlantique, University of Nantes, 44306 Nantes, France (e-mail: serge.toutain@polytech.univ-nantes.fr).

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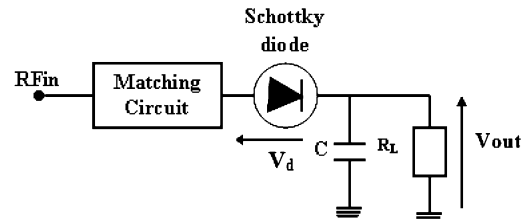


Fig. 1. Series microwave rectifier configuration.

In order to achieve an integrated rectenna system, we have developed a monolithic rectifier with good input impedance matching and an RF–dc conversion efficiency of 65%. The monolithic rectifier was designed and manufactured using the OMMIC ED02AH process.¹

II. HYBRID INTEGRATED MICROWAVE RECTIFIER

A. Simulation

The aim of this study is to achieve a low-cost ZB microwave rectifier satisfying good performances and able to have a good sensitivity at low power levels.

A comparison between the different configurations defining the microwave rectifier has been made in [6]. The obtained simulation results show that the bridge configuration is better than other topologies using a single diode in series or parallel configuration. This is due to the sufficient input voltage at the input of the bridge, which is able to overcome the junction voltage, but not enough to overcome the breakdown voltage. This voltage plays an important role in reaching the maximum conversion efficiency if the breakdown is important. Otherwise, the integration of several diodes tends to decrease the detection sensitivity, which does not fill the requirements of this study.

Hence, the configuration that we have used is the series configuration presented in Fig. 1 with a single ZB Schottky diode. Such a configuration can be easily integrated with patch antennas in order to achieve the rectenna system. This circuit is optimized and achieved by using a commercial diode HSMS2820 [7], which has been selected for unbiased large signal detectors. We have taken the package parasitic diode elements into account. The equivalent circuit of the package has been optimized and validated in [6].

The microwave RF–dc converter has been designed and simulated by using the Advanced Design System (ADS) software,² which uses the harmonic-balance method. As presented

¹Process ED02AH, OMMIC, Limeil-Brevannes, France. [Online]. Available: <http://www.ommic.com>

²ADS, ver. 2003 A, Agilent Technol., Palo Alto, CA, 2003.

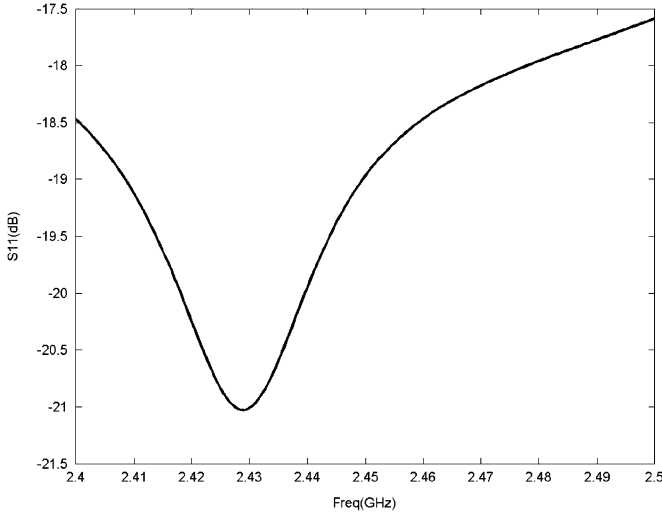


Fig. 2. Simulated input return loss versus frequency for the rectifier using one HSMS2820 Schottky diode.

in Fig. 2, the simulated circuit has a good input impedance matching around 2.45 GHz of the industrial–scientific–medical (ISM) band.

The efficiency of the microwave rectifier is defined by

$$\eta = \frac{P_{DC}}{P_{Loss} + P_{DC}} \quad (1)$$

where $P_{DC} = \frac{V_{out}^2}{R_L}$ and R_L is the load resistance, P_{DC} is the dc output power across R_L , V_{out} is the dc output voltage across R_L , and P_{Loss} is the losses power.

The conversion efficiency will be limited by conduction losses of the diode in the case where we neglect all the other losses. Thus, the approached overall efficiency can be determined by [4], [8]

$$\eta = \frac{1}{1 + \frac{V_d}{2V_{out}}} \quad (2)$$

where V_d is the voltage drop across the conducting diode.

Consequently, the simulated result, presented in Fig. 3, shows that this circuit has an RF–dc conversion efficiency, which increases above the threshold value of -20 dBm until the maximum input power is equal to 20 dBm with a maximum efficiency of 68%.

The dc equivalent circuit of the Schottky barrier diode (SBD) is a voltage source in series with the junction resistor R_j [9]. Thus, the output voltage of the rectifier can be expressed as

$$V_{out} = V_{DC} \frac{R_L}{R_L + R_j} \quad (3)$$

where V_{DC} is the dc part of the diode junction voltage and R_j is the junction resistance of the Schottky diode. R_j is obtained by differentiating the diode voltage–current characteristic and is given by [10]

$$R_j = \frac{nKT}{q(I_s + I_b)} \quad (4)$$

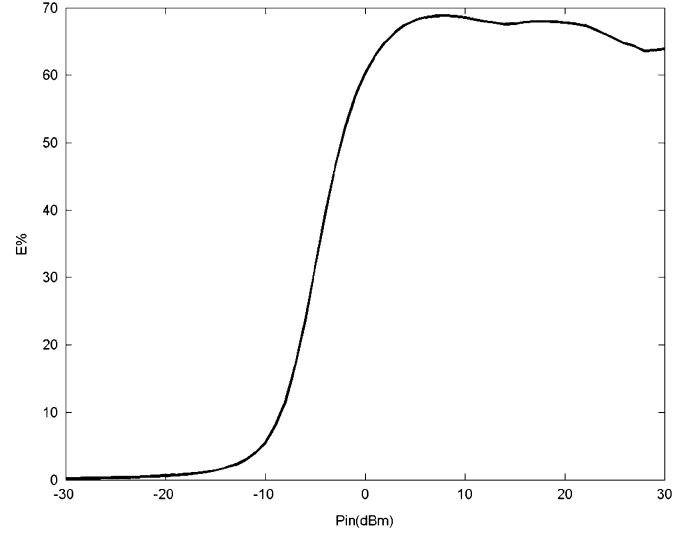


Fig. 3. Simulated RF–dc conversion efficiency versus input power for the rectifier using one HSMS2820 Schottky diode.

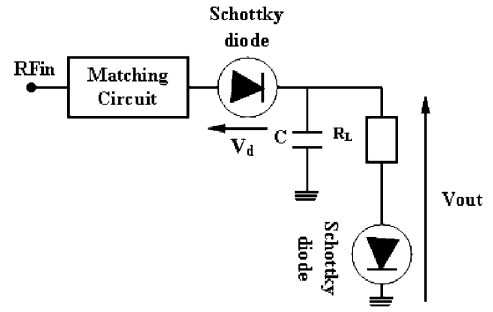


Fig. 4. Series microwave rectifier detection sensitivity improvement configuration.

where n is the diode ideality factor, K is the Boltzmann's constant, q is the electronic charge, I_s is the diode saturation current, I_b is the external bias current, and T is the temperature of the diode in degrees Kelvin. At low power levels, the saturation current is very small and, for ZB diode, external bias current is zero. Therefore, as presented in (4), the value of R_j is higher than R_L . For the HSMS2820 diode, it is approximately $1.7 \text{ M}\Omega$ at ambient temperature, which tends to decrease the value of V_{out} , as mentioned in (3). As input power increases, some circulating rectified current will cause a drop down in the value of R_j , and this phenomena will increase the value of the dc output voltage.

According to (3), an increase of V_{out} at low power levels can be obtained when a variable resistance, which fluctuates as R_j , is connected in series with R_L . The value of this variable resistor must vary with the rectified current.

Thus, to improve the detection sensitivity, we have employed (as shown in Fig. 4) a technique using, in the dc portion of the rectifier, the same Schottky diode in series with R_L . In this case, the rectified current produced by the first diode constitutes the external bias current of the second diode. Consequently, the second diode will act as a variable resistor due to its current dependence in the junction resistance, as shown by (4).

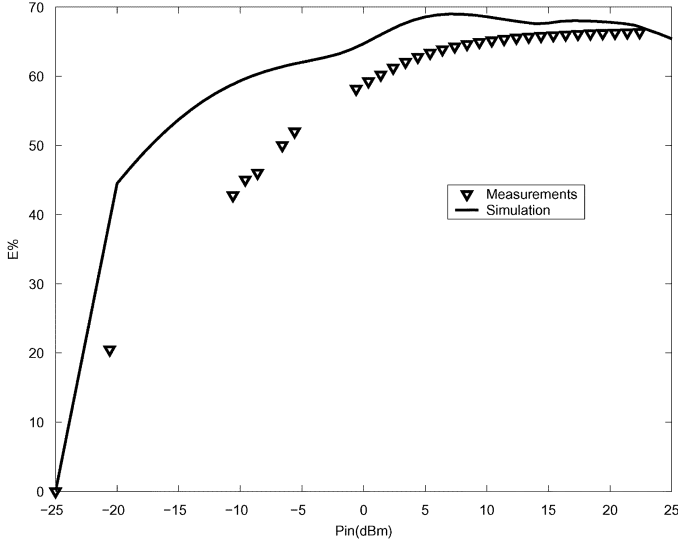


Fig. 5. RF-dc conversion efficiency versus input power for the rectifier using two HSMS2820 Schottky diodes.

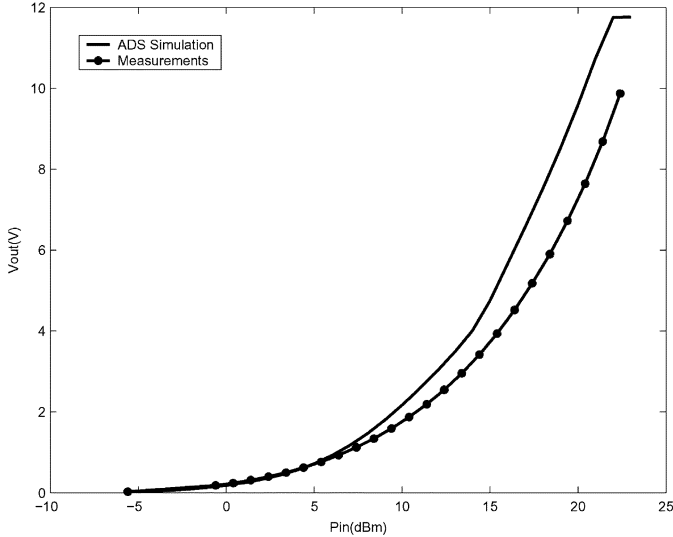


Fig. 6. Output voltage versus input power for the rectifier using one single HSMS2820 Schottky diode.

The global load (R_L in series with the diode) of this rectifier (Fig. 4) thus constitutes a variable resistor with a rectified current corresponding to the value of R_j at very low power levels and to the value of R_L at very high power levels. The choice of this configuration (Fig. 4) is justified because it is a ZB structure, which is not expensive and is very simple to achieve.

The use of this technique (Fig. 4) allows to increase the detection sensitivity to a level of -25 dBm (Fig. 5) by simultaneously improving the conversion efficiency, which is theoretically equal to 45% at -20 dBm. By comparison, only 5% was obtained at -10 dBm (Fig. 3) with the single Schottky diode.

B. Design and Measurements

The fabrication of the microwave hybrid rectifier is done by using the FR4 as a substrate (relative permittivity $\epsilon_r = 4.4$, loss tangent = 0.02, thickness = 1.58 mm). Fig. 6 shows the variations of the output voltage versus the input

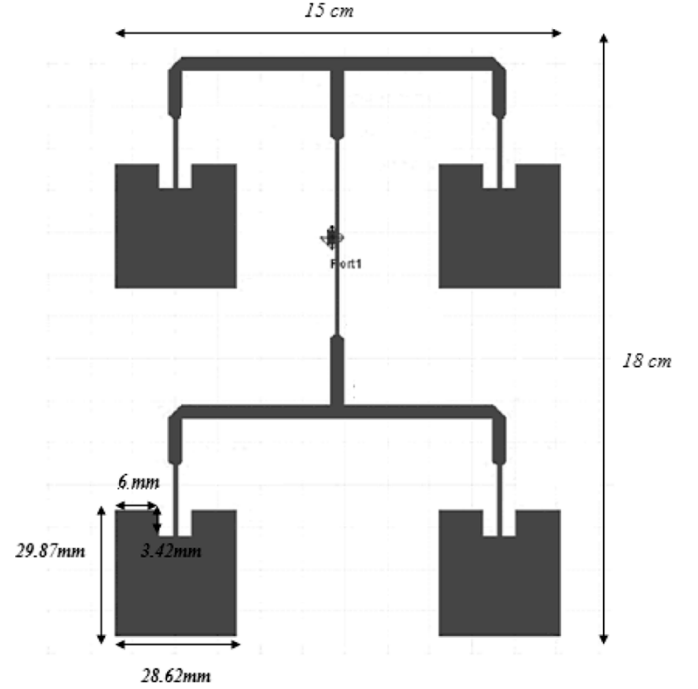


Fig. 7. Final 2×2 patch antenna array layout.

power for the RF-dc converter using one single Schottky diode: it starts to detect at -5 dBm. The simulation and measurement results are in good agreement.

This agreement in the obtained results is due to the fact that the parasitic elements of the Schottky diode package are taken into account and are due to the good choice of the load resistance, which maintains the matching of the input impedance [6], [11]. To improve the detection sensitivity, we have achieved the rectifier by using two identical Schottky diodes HSMS2820. The obtained simulation and experimental results of the conversion efficiency versus the input power (Fig. 5) permits the validation of the technique improving the threshold detection value to -25 dBm, and a measured efficiency of 20% at -20 dBm. This value is lower than the simulated one.

This first study permits the validation of a low-cost sensitive rectifier associated to a good RF-dc conversion, which can be easily integrated with a microstrip antenna, in order to achieve a wide-band power rectenna system.

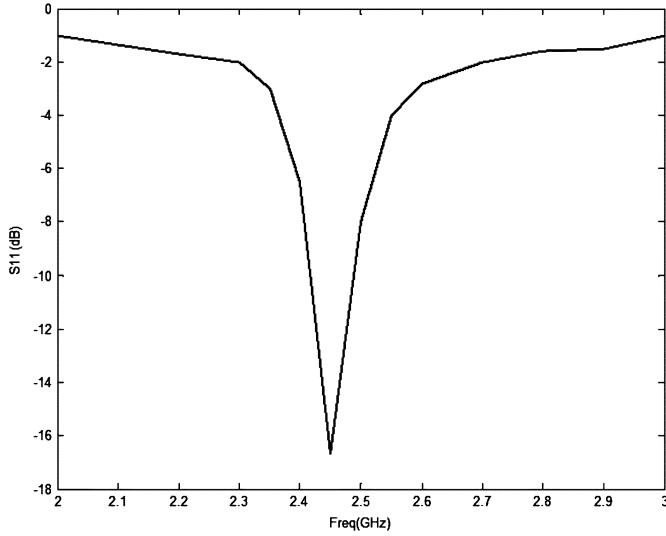
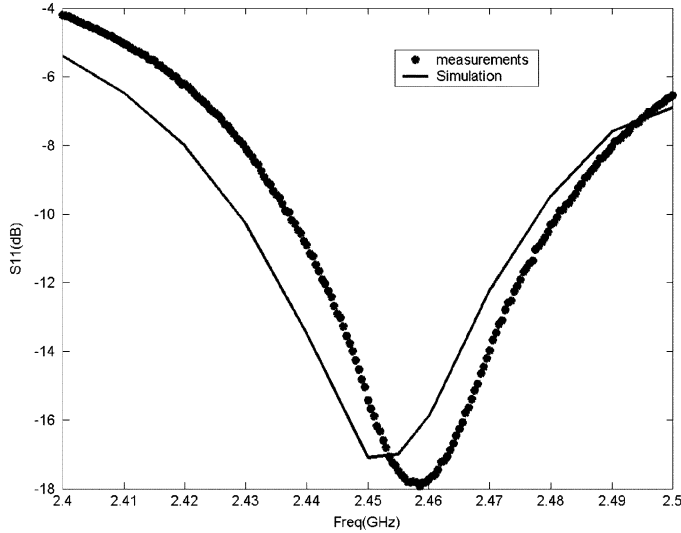
III. MICROWAVE HYBRID RECTENNA DESIGN

A. 2×2 Patch Antenna Array Study

1) *Design and Simulation:* To increase the received power level at the input of the rectifier, and to be able to test and validate the rectenna system, we have done a study to achieve a 2×2 patch antenna array at 2.45 GHz by using the FR4 substrate ($\epsilon_r = 4.4$, thickness = 1.58 mm, loss tangent = 0.02). Each element of the antenna array is fed by using $(\lambda/4)$ transformer microstrip lines. The optimization of the patch array is done by using Designer software from the Ansoft Corporation.³

The layout of the final validated antenna structure is presented in Fig. 7, where the dimensions of each patch element are

³Designer, ver. 2.0, Ansoft Corporation, Pittsburgh, PA, 2004.

Fig. 8. Simulated S_{11} of the patch antenna array.Fig. 9. Simulated and measured S_{11} of the patch antenna array.

28.62 mm \times 29.87 mm, those of the array are 15 cm \times 18 cm, and the simulated gain is equal to 7 dBi. As shown in Fig. 8, the resonant frequency is equal to 2.45 GHz with a return loss of 17 dB.

2) *Test and Measurements:* As presented in Fig. 9, the simulated and measured return losses of the achieved patch array are in good agreement with an experimental return loss of 16 dB at 2.45 GHz. The measured gain of the patch array, by using the three antenna method [12], is equal to 6.8 dBi.

B. Rectenna Test and Validation

After the validation of the microwave sensitive rectifier (Fig. 4) and the 2×2 patch antenna array (Fig. 7), we have used the measurement system presented in Fig. 10. This experimental system includes an RF generator associated to a wavelength dipole antenna array with a gain of 11 dBi, which will transmit the microwave energy to the rectenna system. The wireless transmission distance d is equal to 1 m, and the gain of the receiver antenna is 6.8 dBi.

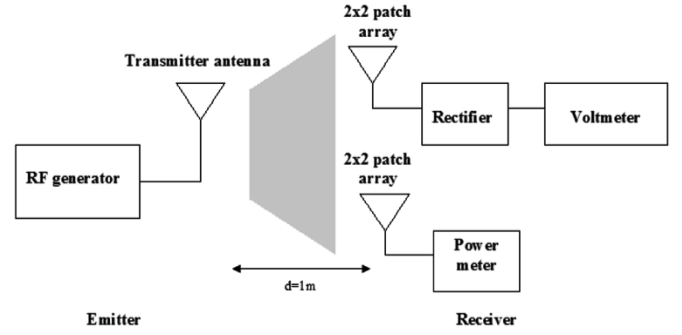


Fig. 10. Rectenna measurements system.

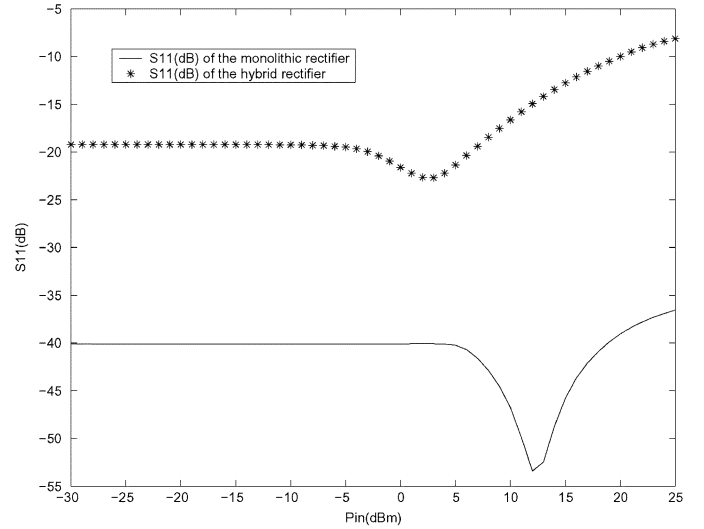


Fig. 11. Simulated input return losses versus the input power for the hybrid and monolithic rectifier.

For a supplied power of 20 dBm by the generator at 2.45 GHz, we measured an RF–dc conversion efficiency of 56% for the rectifying system at the reception level, and a global conversion efficiency of 19% between the emitter and output of the rectenna (Fig. 10). Furthermore, the sensitivity of the rectenna can be improved by increasing the gain of the antenna, e.g., by using an array of more elements or electromagnetic-bandgap (EBG) or left-handed (LH) materials [13].

Among the possible applications of this rectenna, let us quote the biasing of active components to increase the life cycle of electronic systems.

To be able to minimize the rectenna dimensions and achieve an integrated circuit, in the next study, we have used the ED02AH OMMIC process to develop a monolithic rectifier.

IV. MICROWAVE MONOLITHIC RECTIFIER

A. Design and Simulation

The idea of this second study is to develop a miniaturized RF–dc converter at 2.45 GHz in the ISM band, which can be integrated afterwards into a rectenna system.

This study is performed by using the process ED02AH derived from OMMIC. This technology presents the possibility of modifying and optimizing the geometric dimensions of the Schottky diode used for the rectifying operation. This study is

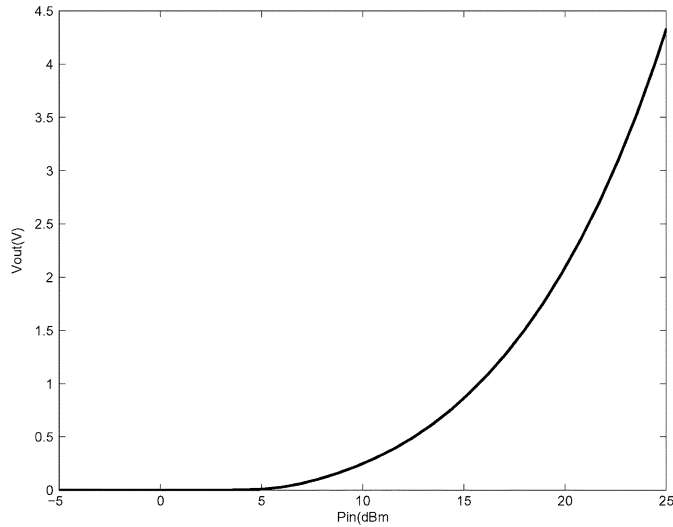


Fig. 12. Simulated output voltage versus input power of the monolithic rectifier.

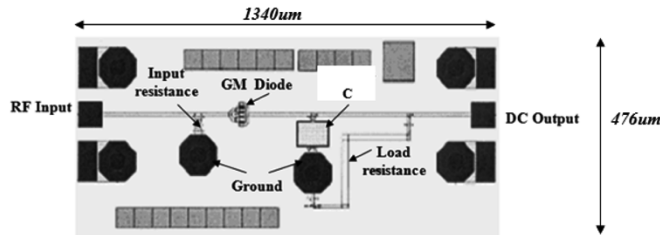


Fig. 13. Monolithic rectifier layout.

also done to achieve a good input impedance matching for a wide-band power variation by using ADS software, as presented in Fig. 11, where we find a difference between the hybrid and monolithic rectifier input impedance matching. It is worth mentioning that the return loss of the monolithic rectenna is close to 40 dB for all powers, which is better than the hybrid rectifier.

Thus, that the monolithic technology allows a better matching of the rectifier design, and this matching is not affected by the variation of the input power level. As shown in Fig. 12, the rectifier starts to detect at 5 dBm.

B. Measurements

After the theoretical study of the rectifier by simulation, we have generated the layout that was optimized to have a low fabrication cost and to respect the layout rules. To take into account the layout modifications, we have again simulated and optimized the rectifier circuit. The layout of the achieved circuit is presented in Fig. 13; the die size is $1340 \mu\text{m} \times 476 \mu\text{m}$. The diode is a $0.2\text{-}\mu\text{m}$ GM GaAs Schottky diode created by connecting the drain and source of a GaAs $2 \times 15 \mu\text{m}$ pseudomorphic high electron-mobility transistor (pHEMT). The RF port of the rectifier is matched to 50Ω , corresponding to the antenna impedance of the rectenna, using a microstrip line and the resistor (input resistor). At the output of the diode, the RF suppression was achieved by a bypass capacitor C.

To test the achieved monolithic rectifier, we have used the experimental setup system presented in Fig. 14. To evaluate the

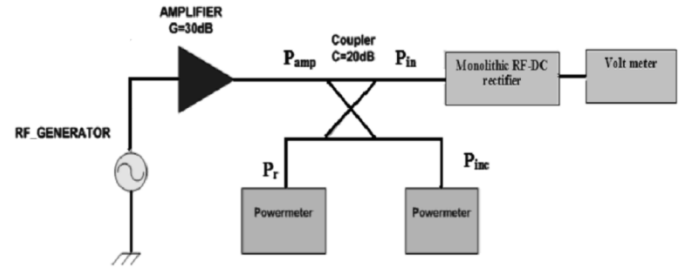


Fig. 14. Experimental setup for the microwave monolithic rectifier.

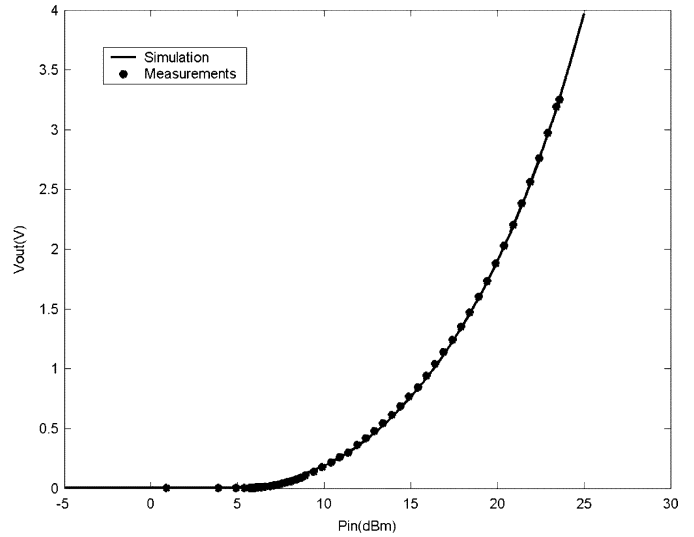


Fig. 15. Measurement and simulation comparison results of the output voltage versus input power for the monolithic rectifier.

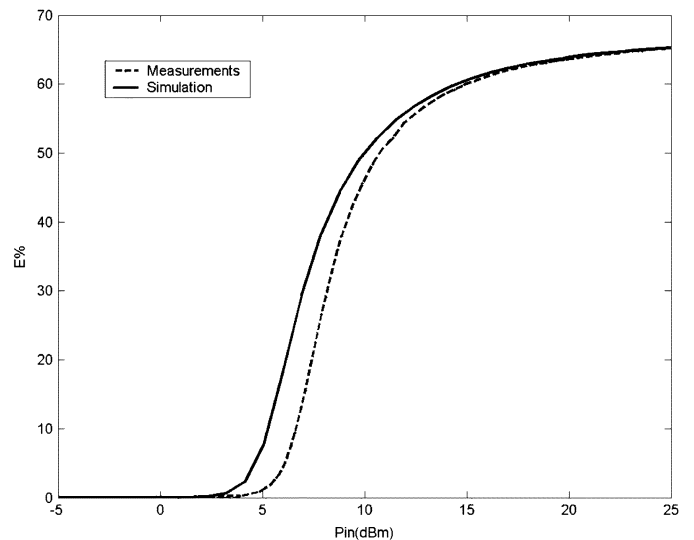


Fig. 16. Measurement and simulation comparison results of the conversion efficiency versus the input power for the monolithic rectifier.

performance in power of the circuit, we have associated an amplifier of 30 dB of gain to the RF generator.

The measured rectifier at 2.45 GHz proves good performances in input impedance matching, and we also have good agreement between simulations and measurements (Figs. 15 and 16). As presented in Fig. 16, the monolithic rectifier has a

maximum conversion efficiency of 65% for an input power of 25 dBm, confirming the theoretical prediction.

V. CONCLUSION

This study has validated a low-cost ZB hybrid microwave sensitive rectenna having an RF–dc conversion efficiency of 56%. This is due to the good choice of the commercial Schottky diodes, and the new technique using as load a nonbias diode in series with the conventional resistance. After the validation of this hybrid circuit, we have been interested in the reduction of the circuit dimensions. As a consequence, we have developed a monolithic microwave rectifier at 2.45 GHz. The dimensions of the circuit are $1340\ \mu\text{m} \times 476\ \mu\text{m}$. It has been designed for high levels of power. The maximum input power is validated to be equal to 30 dBm, which is related to the technology used for design and fabrication: with 65% of the RF–dc conversion efficiency. In the future, we are going to design and develop a wide-band monolithic rectenna structure for wireless power transmission by associating the monolithic rectifier to a patch antenna using bonding wire technology.

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Jamal Zbitou was born in Fes, Morocco, in June 1976. He received the B.S. degree in electronics and computer engineering from the Scientific and Technique University of Fes, Fes, Morocco, in 2000, the M.A. degree in electronics from the Polytechnic Engineering Institute, University of Nantes, Nantes, France, in 2001, and the Ph.D. degree in electronics from the University of Nantes, Nantes, France, in 2005.

He is involved in the design of hybrid, monolithic active, and passive microwave electronic circuits.



Mohamed Latrach (M'03) was born in Douar Ksiba, Sless, Morocco, in 1958. He received the Ph.D. degree in electronics from the University of Limoges, Limoges, France, in 1990.

He is currently a Professor of microwave engineering with the Ecole Supérieure d'Electronique de l'Ouest (ESEO), Angers, France, where his research involves RF and microwaves. His field of interest is the design of hybrid, monolithic active, and passive microwave circuits, metamaterials, LH materials, antennas and their applications in wireless communications, and wireless power transmission.



Serge Toutain was born in 1948. He received the Engineer degree from the Ecole Nationale de Radio-Electricité Appliquée (ENREA), Paris, France, in 1970, and the Ph.D. degree from the University of Lille, Lille, France, in 1976.

From 1984 to 1998, he was Head of the Microwave Department, Telecom Bretagne. In 1998, he joined the University of Nantes, Nantes, France, where he is currently a Full Professor. His main research interests are telecommunications, design of passive and active microwave devices, antennas, and propagation.