

A New Configuration of a High Output Voltage 2.45 GHz Rectifier for Wireless Power Transmission Applications

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Abstract

This work deals with the design, simulation, fabrication and experimentation of a novel 2.45 GHz rectifier for wireless power transmission applications. We have designed a voltage multiplier topology rectifier including 5 Schottky diodes known by their low threshold. This rectifier could perform a wireless power supply for many cases where the use of batteries or wires is impossible due to many limitations. The circuit was analyzed and optimized with the Harmonic Balance method provided by the Advanced Design System (ADS). Good performances are observed through the simulated results and confirmed by the fabrication tests in terms of RF-DC conversion efficiency, DC output voltage level and matching input impedance.

Keywords: wireless power transmission, rectifier, schottky diode, conversion efficiency.

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1. Introduction

The idea of wireless power transmission (WPT) has been brought to light by Nikola TESLA [1] in 1899; he discovered that energy could be transported by electromagnetic waves in free space. A WPT system contains a transmission part consisting of a DC to microwave conversion block, a transmitting antenna and a reception part also called rectenna [2-5] (Rectifying Antenna) used to convert the microwave power into exploitable energy to cover the needs in terms of power supply. The rectenna is the key element of a WPT system, it was invented in 1964 by the U.S. engineer William Brown [6] who demonstrated it by an helicopter power by electromagnetic waves transmitted from the ground and received by an attached rectenna. The block diagram of a rectenna device is illustrated in Figure 1(a), it contains a receiving antenna [7, 8] and an RF-DC conversion circuit (rectifier).

The design of a rectenna system needs, not only an optimized antenna, but also a performant RF-DC rectifier circuit consisting of one or more Schottky diodes [9], an input matching circuit and a DC output filter. To have a complete rectenna and to be able to judge the performance of the system, the rectifier must be loaded by a resistive element which represents the input impedance of the device to be powered.

The conversion efficiency is the ability to receive microwave energy and convert it into DC power. In such an application, improving conversion efficiency [10,11] is strongly required. The other key performance indicator for a rectenna is the output voltage level depending mainly on the topology used. The conversion efficiency generally depends on the input power intensity as shown in Figure 1(b). It's fixed also by the diode characteristics, which has its own breakdown voltage and forward voltage drop. If the voltage applied to the diode is lower than the forward voltage drop or higher than the breakdown voltage the diode does not show a rectification behavior and the efficiency drops down. The critical input power where the breakdown effect becomes dominant is expressed as $V_{br}^2/4R_L$ in Figure 1(b). This research proposes a novel configuration of a voltage multiplier rectifier using five HSMS2820 schottky diodes at 2.45 GHz with an important conversion efficiency in order to get done a complete miniaturized high output voltage rectenna system.

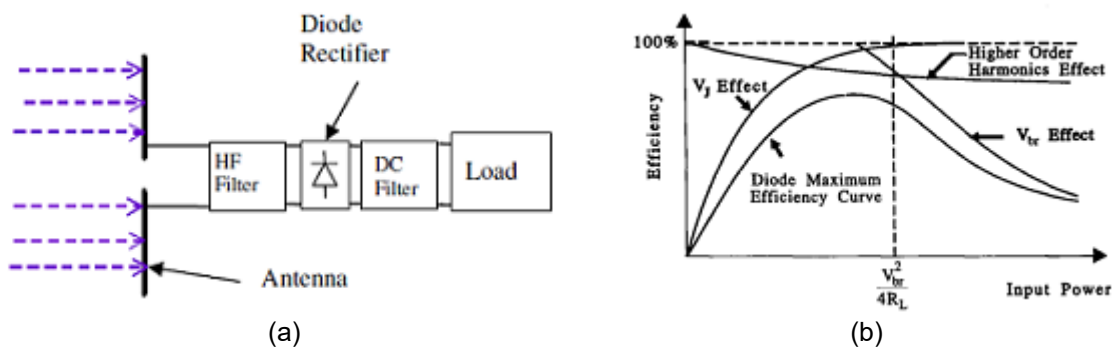


Figure 1. (a) Block diagram of rectenna circuit [12], (b) General relationship between conversion efficiency and input power [13]

2. Voltage multiplier RF-DC rectifier

The proposed microwave RF-DC converter has been designed and simulated by using the Advanced Design System (ADS) software on an FR4 substrate. The kind of Schottky diode used determines critically the performance of the whole circuit. The choice is generally based on the frequency range related to the desired application, and in order to have the optimum conversion efficiency and output voltage level. For WPT applications, the Schottky diodes are widely employed by reason of their low threshold and their fast switching speed. It uses a Metal / Semiconductor junction. Figure 2(a) shows the equivalent circuit of a Schottky diode, which has a series resistance R_s , a junction capacitance C_j , a junction resistance R_j , a package inductance L_p , and a package capacitance C_p . Its forward-bias turn-on voltage V_{bi} and breakdown voltage V_B .

2.1. Theoretical study

The closed form expressions for the rectifying efficiency of the diode is derived with the following assumptions:

- The voltage V applied between node A and C consists of the dc term and the fundamental frequency only.
- The current due to the junction capacitance is negligible when the diode is forward biased.
- The forward voltage drop across the intrinsic diode junction is constant during the forward bias period.

The first assumption is reasonable considering that the magnitude of the higher order harmonics is usually small compared to those of the dc and fundamental components. The second assumption is based on the fact that the change of V_d in Figure 2(a) is small during the forward-bias period. Under these assumptions, the voltage waveform of V and V_d can be expressed as follows [13]:

$$V = -V_0 + V_1 \cos(\omega t) \quad (1)$$

$$V_d = \begin{cases} -V_{d0} + V_{d1} \cos(\omega t - \phi) & \text{if diode is off} \\ V_f & \text{if diode is on} \end{cases} \quad (2)$$

The voltage V_0 in (1) is the output dc voltage and the voltage V_1 is the Peak voltage of an incident microwave. V_{d0} and V_{d1} are the dc and the fundamental frequency components of diode junction voltage V_d , respectively, when the diode is off. V_f is the forward voltage drop of the diode when the diode is on. V_0 is known by specifying the output dc power. The efficiency is calculated by relating the other variables such as V_1 , V_{d0} , V_{d1} , and ϕ to the known variable of V_0 . By applying Kirchhoff's voltage law along the dc-pass loop shown as a dotted line in Figure 2(a), the dc voltage ($-V_{d,dc}$) of V_d is related to the dc component of V according to [13]:

$$V_0 = \frac{V_{d,dc}}{1+r} \quad (3)$$

Where $r=R_s/R_L$ and R_L is the dc load resistance as shown in Figure 2(a). V_d introduced here is the average value of the waveform V_d , and V_{d0} in (2) is the dc component of the waveform V_d in turn-off period. Therefore, $V_{d,dc}$ is derived by taking an average of V_d over one full period as [13]:

$$V_{d,dc} = V_{d0} \left(1 - \frac{\theta_{off}}{\pi}\right) + \frac{V_{d1}}{\pi} \sin \theta_{off} - V_f \frac{\theta_{off}}{\pi} \quad (4)$$

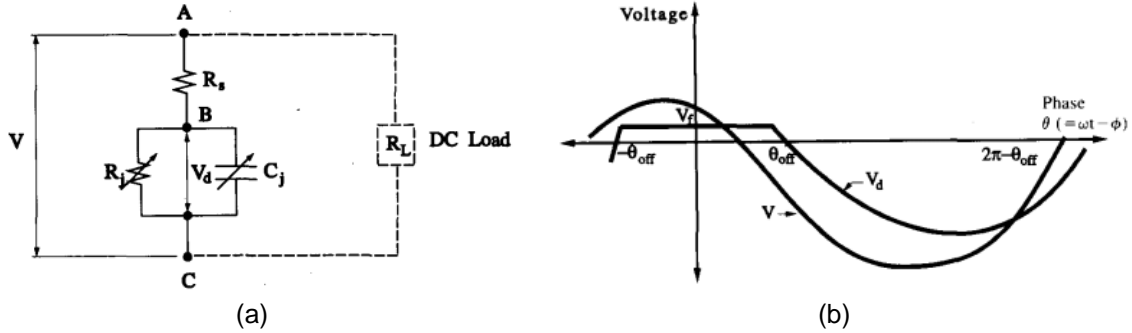


Figure 2. (a) Equivalent circuit model of the Schottky diode, (b) Simplified time-domain waveform of voltage V and V_d . V_d is the voltage between intrinsic diode. V is the voltage between A and C of Figure 2(a). Variable θ is defined as $\theta=\omega t-\phi$ [13].

Where θ_{off} is the phase angle where the diode is turned off as shown in Figure 2(b). The phase θ is defined as $\theta=\omega t-\phi$. Since the switching of the diode occurs when V_d is equal to the forward voltage drop V_f of the diode, θ_{off} is calculated by [13]:

$$\cos \theta_{off} = \frac{V_f + V_{d0}}{V_{d1}} \quad (5)$$

On the other hand, the equation for the current flowing through R_s is written as follows when the diode is off [13]:

$$R_s = \frac{d(C_j V_d)}{dt} = V - V_d \quad (6)$$

Since C_j is a monotonic increasing function of V_d , C_j can be expanded as follows [13]:

$$C_j = C_0 + C_1 \cos(\omega t - \phi) + C_2 \cos(2\omega t - 2\phi) + \quad (7)$$

Substituting C_j into (6) with a Fourier series of (7) and neglecting the terms higher than the second harmonic, the equation becomes

$$\omega R_s (C_1 V_{d0} - C_0 V_{d1}) \sin(\omega t - \phi) = V_{d0} - V_0 + (V_1 \cos \phi - V_{d1}) \cos(\omega t - \phi) - V_1 \sin \phi \sin(\omega t - \phi). \quad (8)$$

Since the above equation should hold during the off period of the diode, each term should separately zero:

$$V_{d0} = V_0 \quad (9a)$$

$$V_{d1} = V_1 \cos \phi \quad (9b)$$

$$V_1 \sin \phi = \omega R_s (C_0 V_{d1} - C_1 V_{d0} + C_2 V_{d1}) \quad (9c)$$

The phase delay is obtained from (9) as follows:

$$\phi = \arctan \left[\omega R_s \left(C_0 - \frac{C_1 \cos \theta_{off}}{1+v_f} + C_2 \right) \right] = \arctan(\omega R_s C_{eff}) \quad (10)$$

Where $v_f = V_f/V_0$. From (3), (4), (5) and (9a), the relationship between θ_{off} and r is derived as

$$\frac{\pi r}{1+v_f} = \tan \theta_{off} - \theta_{off} \quad (11)$$

θ_{off} is determined by the ratio of R_s to R_L and the ratio of the forward voltage drop V_f to the dc output voltage V_0 . V_f is solved with the I-V relation of the diode:

$$I_s \left(\exp \left(\frac{eV_f}{nkT} \right) - 1 \right) = \frac{-V_0 + V_1 - V_f}{R_s} \quad (12)$$

V_1 in (12) is a function of θ_{off} and therefore V_f cannot be solved without first knowing θ_{off} . However, since the left term is of exponential form V_f does not vary significantly from the cut-in voltage of the diode. Therefore, θ_{off} is solved from (11) substituting V_f with a typical value of the cut-in voltage of the diode. Once θ_{off} is solved from a given V_0 , R_s and R_L , the efficiency and the input impedance can be calculated from the time domain waveform V and V_d . These waveforms are expressed as a function of θ_{off} , diode parameters, and V_0 or V_1 .

For the efficiency, it's defined by the following equation:

$$Efficiency = \frac{P_{DC}}{P_{loss} + P_{DC}} \quad (13)$$

2.2. Design, Optimization and Simulation Results

The number of Schottky diodes and the way how they are distributed in the circuit have a remarkable importance. Several types of diode topologies are available in the literature: The series one [14] where the diode is connected in series between the matching circuit and the output filter, the advantage of this topology is mainly related to its realization and design. It is well matched to microstrip lines. Furthermore, the characterization and modeling of the diode in series are easier than those in parallel. The second type is the parallel topology [15] where the diode is placed in parallel between the two HF and DC filters, with the anode or cathode connected to the ground plane. The diode is therefore polarized by the generated DC voltage. Finally, the voltage doubler topology [16] has a series capacitance and two Schottky diodes, in this topology and in DC operation, the two diodes are in series with the load, and the output voltage can therefore be doubled.

In this work, and to obtain a maximum rectification behavior, a voltage multiplier topology is adopted in the designed circuit. We have used a combination of 4 HSMS 2820 Schottky diodes operating at the frequency of 2.45 GHz. The topology is shown in Figure 3(a). We have employed (as shown in Figure 3(b)) a technique using the same Schottky diode in series with the load impedance [17] to improve the detection sensitivity. So that the rectified current produced by the diodes constitutes the external bias current of the inserted diode. Consequently, this diode will act as a variable resistor due to its current dependence in the junction resistance, as shown by:

$$R_j = nKT / q (I_s - I_b) \quad (14)$$

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.

The design of the rectifier circuit is performed by using the Harmonic Balance (HB) simulator, from the Advanced Design System (ADS) software [18]. The LSSP (Large Signal S-Parameters) simulator is also used to check the matching input impedance versus the input power of the conversion circuit. To ensure a good matching input impedance at the resonant frequency, we have used microstrip lines with different lengths and in different positions, these

lines have been optimized using the optimization function integrated in ADS. The simulated reflection coefficient of this rectifier is shown in Figure 4. It is clear that the proposed design provides a good matching input impedance with a good return loss.

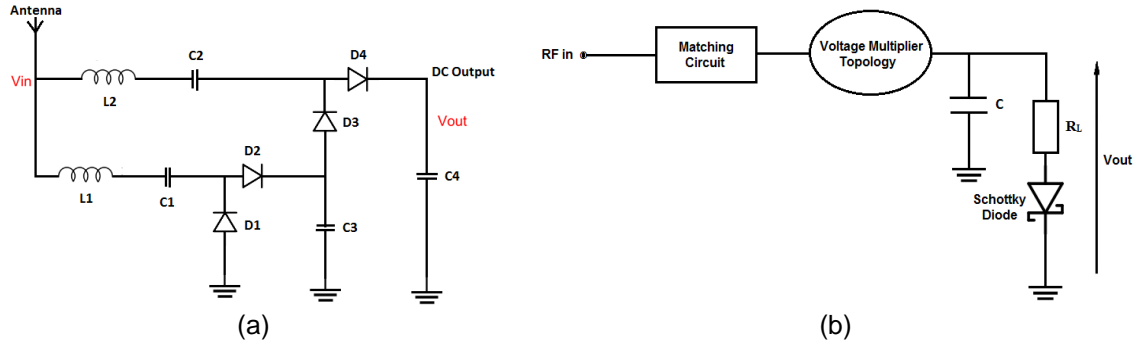


Figure 3. (a) The proposed rectifier topology, (b) Microwave rectifier detection sensitivity improvement configuration.

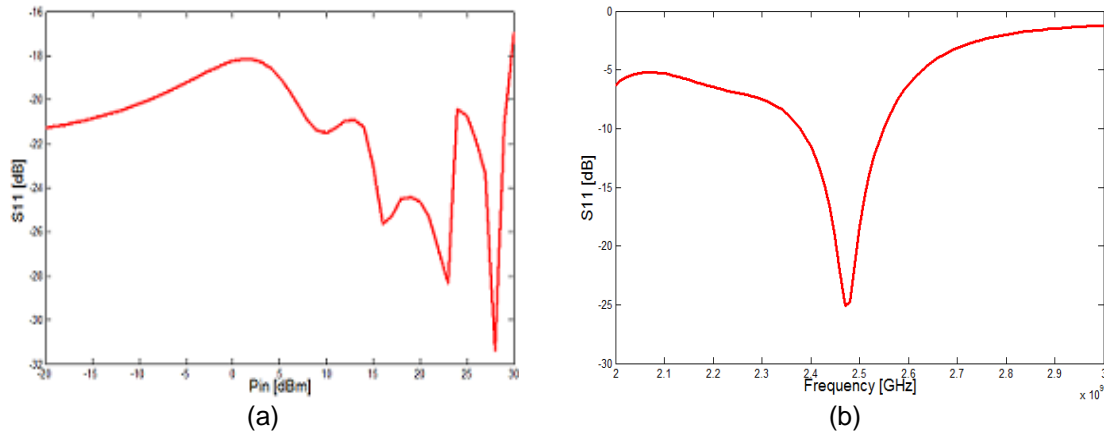


Figure 4. (a) Simulated S11 versus input power, (b) Simulated S11 versus frequency.

The efficiency (η) of the microwave rectifier is defined by:

$$\eta = P_{dc} / P_r = V_{dc}^2 / P_r R_L \tag{15}$$

Where P_{DC} is the dc power produced at the load resistance (R_L) of the rectifier and P_r is the power received at the antenna of rectenna or any other source of microwave energy. P_r is calculated from the Friis transmission equation which gives the amount of power an antenna received under ideal conditions from another antenna. The Power from isotropic antenna falls off as R^2 , so that the power density (p) would be:

$$p = p_t / 4 \pi R^2 \tag{16}$$

Multiplying by the gain of the transmitting antenna gives a real antenna pattern

$$p = (p_t / 4 \pi R^2) G_t \tag{17}$$

If receiving antenna has an effective aperture of A_{eff} the power received by this antenna (P_r) is

$$P_r = p \cdot A_{\text{eff}} \quad (18)$$

Thus,

$$P_r = (p_t / 4 \pi R^2) G_t A_{\text{eff}} \quad (19)$$

The effective aperture of an antenna can be written as:

$$A_{\text{eff}} = (\lambda^2/4\pi) \cdot G \quad (20)$$

So, we conclude that the Friis transmission equation could be expressed as follow:

$$P_r = P_t \cdot G_t \cdot G_r \cdot (\lambda/4\pi R)^2 \quad (21)$$

Where P_t is the power of the transmitter, λ is the wavelength used, R is the distance separating the transmitter and the receiver, G_t and G_r are the transmitter and receiver antenna gain, respectively. In designing a rectifier circuit, the value of the load resistance is critical due to its influence on the performance of the rectenna mainly the efficiency and the output voltage level. After a parametric study performed by using ADS, the optimal load value that gives satisfying results is equal to 2KOhm.

The conversion efficiency reaches a value of 69% for a maximum input power of 25dBm. The circuit starts to detect at a low power level and efficiency increase as the input power level increase. The other parameter to take into account for the evaluation of the rectifier performance is the output voltage. The structure presents an important output voltage level.

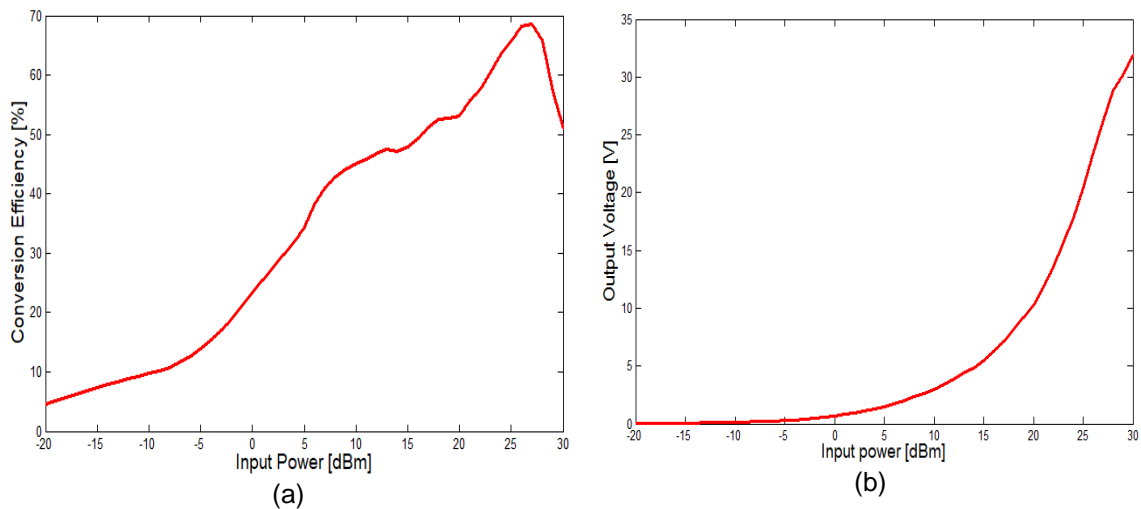


Figure 5. (a) Simulated rectifier efficiency versus input power, (b) Simulated output voltage versus input power of the rectifier.

2.3. Achievement and measurement

A prototype rectifier circuit was built and evaluated to validate simulation results. The measurements were performed by using the setup illustrated in Figure 6. The circuit was fabricated on an FR4 substrate with dielectric constant of 4.4 and having a thickness of 1.6mm. Due to equipment limitations, a maximum input power of 24 dBm was applied and a results analysis was done to extract the rectifier performance indicators.

The measured reflection coefficient of the rectifier within the operating frequency band is shown in Figure 7(a) and a good agreement in terms of input impedance matching is observed. Figure 7(b) shows the variation of the efficiency versus the input power. As expected, there is a strong correspondence to the simulated results. The measured output voltage

reaches a high value of 18V for an input power of 24 dBm, this important output voltage could be used to deal with many problems of power supply in different applications.

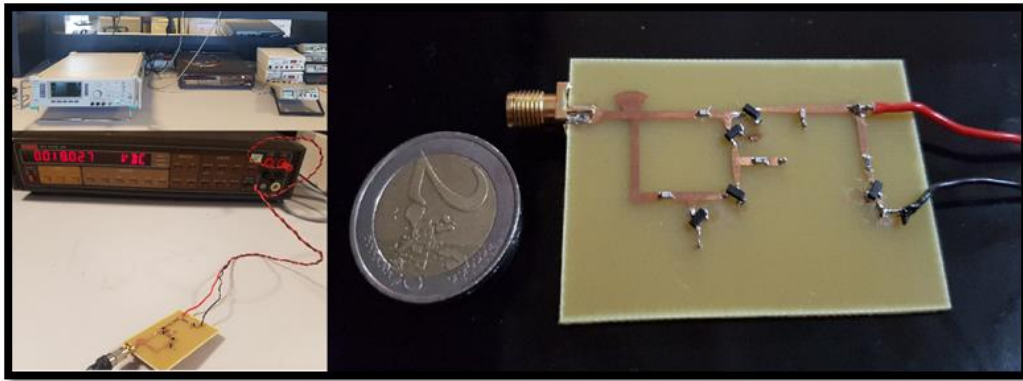


Figure 6. Fabricated voltage multiplier rectifier.

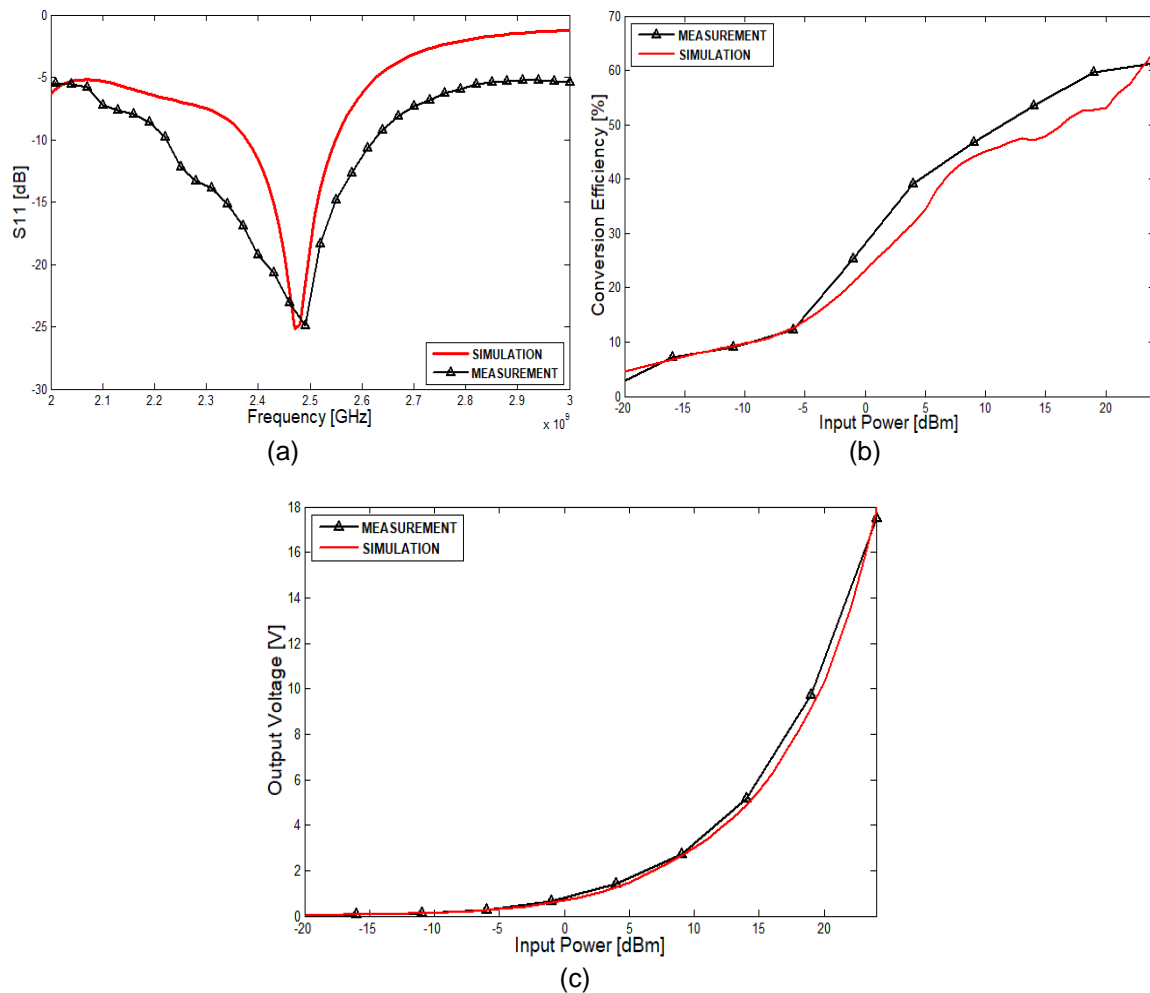


Figure 7. Simulated and measured results of the rectifier (a) S₁₁ versus Frequency (b) Conversion Efficiency versus Input power (c) Output voltage versus input power.

3. Conclusion

In this paper, a novel voltage multiplier rectifier working at the ISM band (Industrial Scientific Medical band) has been presented. We have used to achieve this circuit five HSMS2820 Schottky diodes implemented on an FR4 substrate and by using optimized microstrip lines to interconnect the different components. The rectifier is loaded by a 2KOhm resistive element to replace the device to be powered. Measured results seems to be in total agreement with the simulated ones performed by the Advanced Design System solver.

This structure has a good matching input impedance and important conversion efficiency with an input power varying between -20dBm to 24dBm and the structure start to detect at a low power level. A high output voltage was observed (18V) giving the opportunity to solve many problems of power supply in different cases.

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