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Rectifier Circuit Designs for RF Energy Harvesting applications

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ABSTRACT: RF energy scavenging, commonly referred to as RF energy harvesting, is the capability of collecting ambient RF energy from antennas to supply power to electronic devices. The rectifier circuit is the key component of wireless energy harvesting system. Therefore, the development of efficient and compact rectifier circuit has become recently a vital research topic. This paper presents a state of the art and review of the recent designs of microstrip rectifier circuit used for RF energy harvesting applications at 2.45 GHz and 5.8GHz.

Keywords : RF energy harvesting system, rectenna, microstrip rectifier circuit, diode, low pass filter.

1 INTRODUCTION

Wireless power transfer and RF energy harvesting are an alternative technology that can reduce the dependency of the most wireless devices on non-autonomous power source. They have received great attention and known a successful impact in many real life applications since the last several decades, due to their fulfillment of remote power to electronic and electrical devices involving low power consumption, located in unreachable area or needing expensive maintenance costs [1][2]. Rectenna is the most main element in RF energy harvesting system to harvest the wireless energy from the RF sources. The components of the rectenna system have traditionally been focused at 2.45 GHz. To decrease the aperture sizes without sacrificing component efficiency, the frequency of ISM band centered at 5.8 GHz has been investigated [3]. The general block diagram of a rectenna is depicted in fig 1. This passive element contains a receiving antenna that collects and captures the radiated microwave energy from the transmitting antenna, and the rectifying circuit that converts these incoming energy into DC power. Usually, printed dipole and circular polarized microstrip patch antennas are the most used in rectenna system [4].

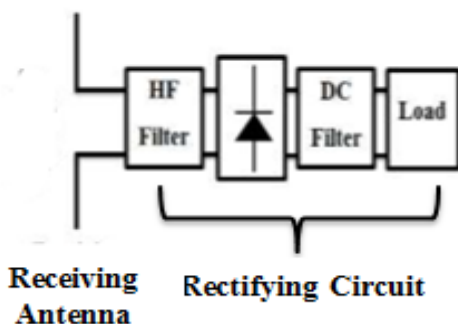


fig 1 : The general block diagram of a rectenna

As highlighted in fig.1, the rectifying circuit consists of a HF filter, rectifier (diode), DC filter and a load. The input HF filter preserve the antenna from the high order harmonics generated by the diode due to its nonlinear characteristics, and ensures the adaptation between the receiving antenna and the rectifying circuit. The diode rectifies the RF signal (AC current) and converts it into a DC signal. The output DC filter blocks all the high order harmonic frequencies produced by the rectifier in order to protect the load. These last one is a resistive element that presents the input impedance of the device to be powered.

In the recent years, the challenge in designing a rectifier circuit is to ensure a compromise between a high output voltage and good power conversion efficiency for low input power applications. Thus, the main design methodology is: First, selection of an adequate energy harvesting circuit topology. Next, choose of an appropriate diode. Then, conception of a matching network (bandpass filter) and low pass filter. Finally, optimization and simulation of the overall circuit design using the EM simulation software.

This review paper is organized as follows. First, the rectifier circuit theoretical background is introduced in section 2. In section 3, the related works and comparison of reviewed designs are presented. Finally, some propositions are suggested for our own design.

2 RECTIFIER CIRCUIT BACKGROUND

2.1 Topologies

The microwave rectifier can take several topologies depending on the configuration of the diodes used for rectification. The serial and shunt topologies are the most used in the literature. Furthermore, in order to improve the output DC voltage, the voltage doubler or voltage multiplier topology can also be used[5]. These conventional rectifier circuit topologies are illustrated in fig 2.

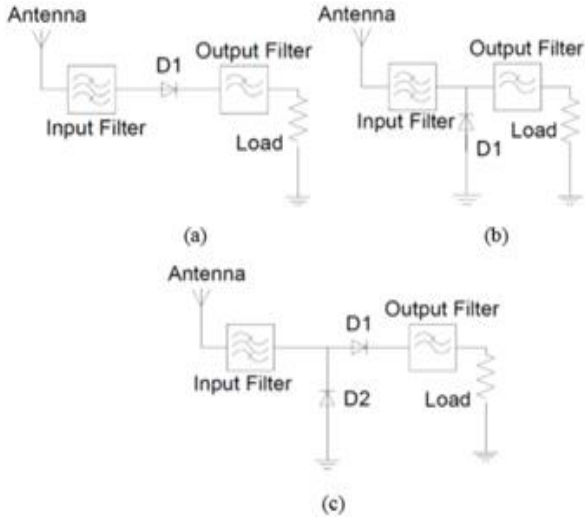


fig 2 : The conventional rectenna topologies: (a) series; (b) shunt; (c) single stage voltage doubler

In the serial topology, the single diode is placed between the RF filter and the DC filter. In the shunt topology, the diode is connected in parallel between the filters. The diode is self-biased by the DC voltage that it generates. The single stage voltage multiplier circuit or voltage doubler topology can be seen as the combination of the two preceding topologies. It consists of two diodes, one mounted in serial and the other in parallel, to produce a larger output voltage.

In effect, the mono diode topologies are mainly preferable because of their ease of implementation, their high efficiency, their small size and their low cost. They offer the theoretical advantage of minimizing the losses in the diodes [6]. However, the output voltage levels for both topologies are low. The voltage doubler topology provides a high output voltage, but a low RF-DC conversion efficiency compared to the mono diode topology.

The simulations performed in [7] prove that the voltage doubler circuit is more suitable for high input power levels applications (>20 dBm). The serial topology presents a good RF-DC conversion efficiency for low input power levels applications (around -10 dBm and 20 dBm).

Each of these topologies has its advantages and limitations. The choice of the suitable rectifier circuit topology is generally depends on the voltage required at the output, the available input power and the size constraint.

2.2 Diode

In designing a rectifier circuit with high RF-to-DC conversion efficiency, the choice of a proper diode is one of the most important factors since the diode is the main source of loss and its performance and character-

istic determine the overall performance of the circuit [1]. Zero bias Schottky diodes are usually used for high frequency rectifiers because of their high switching capacity, low barrier (high saturation current), low junction capacitance and low voltage threshold than the common PN diodes. In fact, the low threshold allows for more efficient operation at low powers, and the low junction capacitance increases the maximum frequency at which the diode can operate [8]. Fig 3 shows the equivalent electrical circuit of a Schottky diode.

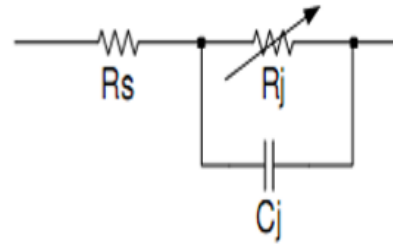


fig 3 : The equivalent electrical circuit of a Schottky diode

With C_j the junction capacitance in Farad, R_s the series resistance in Ω (This resistance is due to the inability of charges to easily move through the crystal lattice structure, It models the losses by joule effect of the diode, and R_j the junction resistance in Ω . The variable junction resistor models the fact that the diode is either conducting or blocked.

The Schottky diodes have two main classes. The first class is the n-type silicon with a high- barrier and low values of R_s . The second class is the p-type silicon characterized by low barrier and high R_s . For low input power levels applications, the p-type Schottky diode is recommended since it provides a higher output voltage compared to the n-type [10]. The most used commercial Schottky diodes are HSMS-285X (n-type) and HSMS-286X (p-type) [9]. The simulations performed in [6] shows that HSMS-285x has the largest efficiencies at the lowest powers. This characteristic is due to its low turn-on voltage. However, it is unable to function well at larger powers because of its small reverse breakdown voltage.

2.3 Energy conversion efficiency

The main characteristics that should be optimized when designing rectifier circuit are the DC output voltage and the RF-DC conversion efficiency. This last one refers to the ratio of the PDC power recovered at the output of the rectifier and the PRF power injected at the input of the rectifier using a microwave source. It is determined using the formula (1) :

$$\eta (\%) = 100 \cdot \frac{P_{DC}}{P_{RF}} \quad (1)$$

The PDC power is calculated as follows:

$$P_{DC} = \frac{V_{DC}^2}{R_L} \quad (2)$$

With R_L is the load resistance, and V_{DC} is the maximum DC voltage across the diode, limited by the reverse breakdown voltage V_{br} by:

$$V_{DC} = \frac{V_{br}}{2} \quad (3)$$

The PRF power is calculated using the FRIIS transmission equation (4):

$$P_{RF} = P_e G_e G_r \left(\frac{\lambda}{4\pi r} \right)^2 \quad (4)$$

It gives the received RF power as a function of the transmitted power P_e , the maximum gains of the transmitting G_e and receiving antennas G_r and the losses in the free space which depend on the frequency and the distance r between the two antennas .

In fact, a variety of loss mechanisms make it difficult to achieve high RF-DC conversion efficiency, especially in nonlinear devices such as the diodes [8]. The maximum energy conversion efficiency of the rectifier circuit is limited by impedance matching, device parasitics, and harmonic generation. It generally depends on the microwave input power, the optimum connected load, the own junction voltage and breakdown voltage of the diode. The efficiency becomes quite low when the power is small or the load is not matched. When the input voltage to the diode is lower than the junction voltage or is higher than the breakdown voltage the diode does not show a rectifying characteristic[6]. Fig 4 illustrates the general relationship between the efficiency and losses in microwave energy conversion circuits as a function of input power[1].

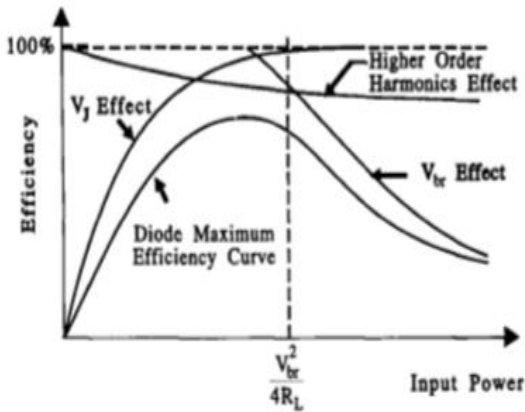


fig 4 : General Relationship between the efficiency and losses in microwave energy conversion circuits as a function of input power

At low input power region, the efficiency is small because the voltage swing at the diode is below or comparable with the diode turn-on threshold voltage (V_T Effect). As the power continues to increase, the efficiency increases and levels off with the generation of higher order harmonics. At high input power region, the efficiency sharply decreases because the voltage swing at the diode exceeds the breakdown voltage (V_{br} Effect) of the diode [8]. The critical input power where the breakdown effect becomes dominant is expressed as $\frac{V_{br}^2}{4R_L}$.

In addition, the RF-DC conversion efficiency strongly depends on the characteristics and internal parameters ($V_{br}, V_T, R_s, C_j, V_j$) of the used diode, as well as the value R_L of the load. The simulations performed in [6][8] prove that :

- As the turn-on threshold voltage V_T is decreased, the energy conversion efficiency at a given power increases. So a low turn-on threshold is required for efficient and low input power applications.
- When the series resistance R_s increases, the energy conversion efficiency decreases. So a low value of R_s means that it is low losses in the diode and therefore a high efficiency.
- As the junction tension V_j is decreased, the RF-DC conversion efficiency increases.
- As the junction capacitance C_j , is decreased, the RF-DC conversion efficiency increases. C_j limits the maximum frequency for which a diode can operate.
- When the resistance of the load R_L is low, the efficiency is high. Hence, an optimization must be done to determine the optimum R_L .

2.4 Impedance matching network

When the rectifier circuit is not properly matched to the receiving antenna, a part of the incident power from the antenna will be reflected back to the environment and not absorbed. Then the available power for rectification is automatically reduced. Thus, it is necessary to design an impedance matching network in order to match correctly the input impedance between the circuit and the receiving antenna [11]. The most frequently used matching networks are the L network, π network, and T network. The choice of the suitable adaptation network depends on the objective sought. If it is to simply make a single-band adaptation, the L-network is sufficient. If other functions are added to the adaptation

such as the harmonic rejection (Band-pass HF filter). T or π networks will be favored in this case. π type matching circuit attains wider bandwidth than L type matching network[7].

An adaptation circuit can be composed of lumped elements such as capacitors and inductors or distributed elements such as stubs and microstrip lines[11]. However, at high frequencies, the distributed technology is the most applied [12]. In fact, at microwave frequencies, the lumped components perform poorly due to parasitic reactance. In order to pass from the lumped elements to the distributed elements, we can use the microstrip lines and stubs in open circuit or in short circuit. An open circuit stub in microstrip technology is equivalent to a parallel-mounted capacitor, and a short-circuit stub is equivalent to a parallel inductor [13].

2.5 DC filter

The DC filter is a low-pass filter that is the most often composed of capacitors placed in parallel with the load resistance. The filtering capacitor is the part of the rectifier that will block the fundamental signal and the harmonics downstream of the diode. The cutoff frequency must be lower than that of the fundamental signal. The value of the filtering capacitor is determined from the following equation:

$$C = \frac{1}{2\pi fc} \quad (5)$$

In general, the design of microstrip low pass filters involves two main steps. The first one is to select an appropriate low pass prototype (lumped-element filter design). The choice of the type of response, including passband ripple and the number of reactive elements (filter order), will depend on the required specifications [24]. Chebyshev and Butterworth are the most popular low pass prototypes in microstrip filters design. Chebychev filter tolerates a slight ripple in the bandwidth, but has a better rejection than the Butterworth filter. The next step is to find an appropriate microstrip realization that approximates the lumped element filter. The low pass filter is widely implemented with stubs (shunt, radial) or stepped impedance lines [13].

3 RELATED WORKS

In the literature, many kinds of Microstrip rectifier circuit designs at 5.8 GHz and 2.45 GHz for RF energy harvesting system have been proposed. This section presents a brief review of the recent designs.

3.1 Circuits at 2.45GHz

The paper [19] reported a RF-DC rectifier circuit based on modified bridge rectifier with four Schottky diodes. A maximum efficiency of 52 % and an output DC voltage of 3.64 V have been reached over an optimal resistive load of 1050 Ω at the input power of 10 dBm. The presented circuit device doesn't need neither input HF filter nor bypass capacitor.

In [20], a RF-to-DC rectifier circuit has been optimized at 2.45 GHz for an input power of 100 mW. the proposed circuit is based on a commercial zero bias Schottky diode HSMS-2850 ,and it is designed at the back side of the antenna in order to reduce the size of the rectenna .The output DC voltage and overall efficiency are respectively higher than 1.1 V and 56% over a resistive load of 2500 Ω .

In [21] ,the authors have developed a microwave rectifier circuit ,which consisted of a short-ended T-microstrip line matching network, a Schottky diode HSMS-2820, and an output low pass filter. The circuit provided a high conversion efficiency of 65.8% and a DC output voltage of 7.02V at 20dBm input power for an optimum load resistor of 750 Ω .

The paper [22] proposed a microwave double voltage rectifier with two Schottky diodes HSMS2820. A maximum efficiency of 71.5% and a DC voltage output of 10.75 V are reached at 22dBm of input power. The optimal load resistance was around 810 Ω .

A RF-DC rectifying circuit based on a Schottky diode HSMS2820, with a series topology, have been developed in [23]. It provided an important value of output voltage of 11.23V at 20 dBm of input power .The optimal load resistance was around 2 k Ω .

Table 1 shows the results comparison of the presented rectifier circuits at 2.45 GHz. It can be noticed that the rectifier circuit proposed in [23], has presented the best performances with a high output voltage of 11.23V, with just one rectification diode. This circuit is judged to be compact, low cost and efficient.

Table 1: Comparison between the rectifier circuit designs at 2.45GHz

Ref	Topology	Schottky Diode	Input power	η (%)	V _o (V)	R _L (Ω)
[19]	modified bridge rectifier	–	10 dBm	52	3.6	1050
[20]	–	HSMS-2850	100 mW	56 %	1.1	2500
[21]	–	HSMS-2820	20 dBm	65.8	7.02	750
[22]	double	HSMS-	22	71.	10.	

	voltage rectifier	2820	dBm	5	75	810
[23]	series	HSMS-2820	20 dBm	–	11.23	2000

3.2 Circuits at 5.8 GHz

The authors in [2], have developed a microstrip rectifier that combined series and shunt configurations. It constituted of an input matching circuit (low pass filter, two Schottky diodes HSMS2852 and HSMS2850, and an output filter (three fan shaped stubs).An output DC voltage of 2.2 V and a RF-to-DC conversion efficiency of more than 70% were achieved with an optimum load resistance of 6 k Ω for 0 dBm microwave incident power level.

In [5], a RF-to-DC rectifier circuit with a modified doubler voltage topology was developed for low incident power .The rectifier circuit consisted of an impedance matching network (a T-junction with short end), two Schottky diode HSMS-2862, and three parallel capacitors of 200 pF of each one ,have used as a DC low pass filter and placed in parallel with the resistance R. The rectifier exhibited an output DC voltage of more than 2.53V, 2.1 V and 0.61 V when the input power was around 0 dBm,-2dBm and -10 dBm with the optimum load of 7.5 K Ω .

In [1], a RF-DC rectifier circuit has been proposed using microstrip lines technology, with a voltage multiplier topology including four schottky diodes HSMS2820 and another diode in series with the load resistance (160 Ω) in order to improve the sensitivity. This diode was acted as a variable resistor due to its current dependence in the junction resistance. The conversion efficiency and the output voltage reached respectively the values of 47% and 12V for an input power of 30 dBm.

In [15], the authors have implemented a rectifier circuit with a Greinacher Voltage Doubler topology, using Schottky diode HSMS- 285C.The matching circuit consisted of inductors and capacitors lumped together. A load of 1500 ohm was used. The proposed rectifier circuit yielded a maximum output voltage of 3.34 V and a conversion efficiency of 74.38% when the input power was around 10 dBm.

The rectifier circuit proposed in[16] ,was integrated on the back side of the antenna substrate in order to minimize the profile of the rectenna.The Schottky diode HSMS-286c double tube was used in series to increase the output DC voltage. The DC pass filter consists of a 100 pF choke and a section of microstrip line. A maximum efficiency of 66.2 % and an output DC voltage of 6.33 V have been measured with a 900 Ω load at the input power of 18 dBm.

Table 2 summarizes the performances of these present- ed rectifier circuit designs.

Table 2: Comparison between the rectifier circuit designs at 5.8GHz

Ref	Topology	Schottky Diode	Input power	η (%)	V _o (V)	R _L (Ω)
[2]	series-shunt	HSMS-2852,HS MS-2850	0 dBm	70	2.2	6000
[5]	modified doubler voltage	HSMS-2862	0 dBm	–	2.5	7500
[1]	voltage multiplier	Five of HSMS-2820	30 dBm	47	12	160
[15]	Greinacher Voltage Doubler	HSMS-285C	10 dBm	74	3.34	1500
[16]	–	HSMS-286C	18 dBm	66.2	6.33	900

We can deduce that the rectifier circuit proposed in [2] has achieved a good efficiency of 70%, but a very low output DC voltage of 2.2 V at 0 dBm .It is need to be further improved.

3.3 Synthesis

Based on the review gained in the previous sections ,it has been found that the main challenge in designing a rectifier circuit is to insure a compromise between a high output voltage ,good power conversion efficiency, small size and low cost ,especially for low input power applications. To achieve this purpose, some suggestions may be useful:

- If the RF energy harvesting application required a larger voltage, the use of voltage doubler and voltage multiplier configurations can increase enormously the DC output voltage.
- If the size constraint is paramount, the use of series topology is preferred.
- Integration of rectifier circuit on the back side of the antenna substrate can minimize the profile and the size.
- It is recommended to use schottky diode HSMS-285x at 2.45GHz and HSMS-286x at 5.8GHz.
- Optimization of the rectifier circuit using harmonic balance analysis and ADS simulator.

4 CONCLUSION

In this study, we have performed a roundup of rectifier circuit, by approaching its different topologies and the critical points to consider in order to design a compact and efficient rectifier circuit. Furthermore, we have reviewed the recent and advanced designs developed in microstrip technology at 5.8GHz and 2.45 GHz, for RF energy harvesting applications at low input power. As a perspective, conception, simulation and implementation of our own rectifier circuit.

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