Wideband Rectenna System for Microwave Power Transfer

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

One of the fundamental devices in Microwave Power Transfer (MPT) is the rectenna or rectifying antenna, which collects the electromagnetic energy from the free space and convert it directly to a useful DC power. Although many designs of rectenna systems have been proposed, most of them operate in a narrowband frequency and/or a certain level of incident power, which limits the output DC power and the uses of the rectenna.

In this work, three novel designs of the rectenna that operate in broadband frequency and wide range of received power are developed. The design methodology for such critical characteristics for the rectenna has been discussed in details. Furthermore, the presented wideband rectennas have the best results comparing to the literature in terms of frequency bandwidth and power range, which indicates great achievement in terms of increasing the output DC power significantly as a result of decreasing the effect of the variation of the frequency and incident power and the ability of harvesting multiple frequencies simultaneously. Furthermore, the wideband rectenna can be considered as an approach to minimize the number of the used rectennas by having a single rectenna that operates in a wide frequency bandwidth and wide range of incident power. The best proposed rectenna operates from 0.5 – 5.4 GHz with 80% and 30% as maximum and minimum RF-DC conversion efficiency. In addition, it can operate within an incident power range of 3 to 25dBm at 3.4GHz.

Finally, in the literature, useful definitions of rectenna’s bandwidth and harmonics are missing. As a result, the definition of the rectenna’s bandwidth is revisited. Moreover, a new perspective for rectenna’s harmonics is introduced.

Acknowledgements

. In the name of Allah the All-Merciful, The Ever-Merciful.

First and foremost, thank for Allah who give me the strength and chance to write this thesis. Then, a lot of thanks to prof. Omar Ramahi for his always support, encouragement, and inspirational discussions. Also, I would like to thank all my great group members and friends.

Dedication

To my great parents, my loved wife Hasna, and my lovely daughter Lana. My Allah protect them.

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Chapter 1
Introduction

1.1 Thesis Objectives

The main objective for this thesis is presenting an efficient wideband rectenna system for MPT (Microwave Power Transfer), the wideband here includes the frequency bandwidth and input power range simultaneously. This objective is divided into the following branches.

1. Highlight the history of MPT and how it has been improved over decades.
2. Define the efficiency of the wideband rectenna and its cutoff frequency.
3. Explain the main elements in the rectenna system.
4. Understand the rectenna's harmonics
5. State the design procedure for an efficient wideband rectenna.
6. Introduce the methodology of designing a matching network for a wideband rectenna.
7. Discuss the challenges in designing a rectenna system.
8. Design the rectenna using ADS, HFSS and CST software.
9. Fabricate the rectenna and test it.

1.2 Thesis Contributions

The main contributions:

1. Introduce a new definition of the rectenna's frequency bandwidth.
2. Report a new perspective of the rectenna's harmonics
3. Propose efficient and simple wideband rectenna with a 6 GHz bandwidth.

In the last 20 years, the wideband rectenna system has been investigated [1-5] ; however, there is no specific definition of the rectenna's bandwidth. In this work, a new definition of the rectenna's bandwidth is introduced. This definition includes the losses associated with the diode. Also, it will guarantee an efficient design over the operating bandwidth. Furthermore, it can be used as an evaluating tool for the rectenna performance.

In order to design a wideband rectenna, this work introduces a new perspective of the rectenna's harmonics, which can be applied to the narrowband rectennas as well. Understanding the harmonics concept and how it can be controlled will help to achieve the wideband rectenna with high performance.

Moreover, modern and simple networks are implemented before the diode in order to minimize the harmonics' effect over a wideband. The ADS simulator is used to simulate the rectenna's harmonics, which proved the concept.

Finally, three novel wideband rectennas are proposed. They have promising performance when compared to the literature in terms of the frequency band and power range. One of them covers the entire frequency bandwidth of the used diode with high efficiency and wide range of incident power level.

1.3 Thesis Outline

The thesis's chapters are organized as follows:

Chapter 2 includes the history of microwave power transfer MPT and how it has been improved over decades. Furthermore, the best results and developments from previous works in terms of frequency bandwidth and/or range of incident power have been presented and discussed.

Chapter 3 explains the design of the wideband rectenna system. Moreover, a discussion of the rectenna's harmonics and the methodology to minimize its effects are presented. The simulation results, which generated from HFSS, CST, and ADS software are included and used to verify the rectenna's harmonics.

Chapter 4 presents discussions and comparisons of the measurements' results with the simulations' results.

Chapter 5 provides a conclusion and suggestions for the future.

Chapter 2
Literature Review

2.1 Introduction

The MPT is an approach of transferring the power from one point to another wirelessly at microwave frequency band. It is considered a part of the WPT (Wireless Power Transfer) systems. According to the literature, Figure 1.1 illustrates the general block diagram of the MPT system. It contains RF-signal generator, power amplifier, transmitting antenna, free space as a transmission medium, receiving antenna, RF filter, rectifier circuit, DC pass filter, and the DC-load. This work concentrates on the rectenna, which contoured in a box in Figure 1.1. Until the date of this thesis, many designs of the rectenna systems have been proposed. In general, these rectennas suffer low output DC power, high sensitivity of variation in power received, and/or high cost, which can be minimized by the wide band rectenna. Also, the maximum operating bandwidth of nearly all of the proposed rectenna systems did not exceed 1GHz. As a result, this work presents a rectenna system with bandwidth of 6GHz. This chapter introduces the basic history of improvements of MPT systems from the beginning to the date of this thesis.

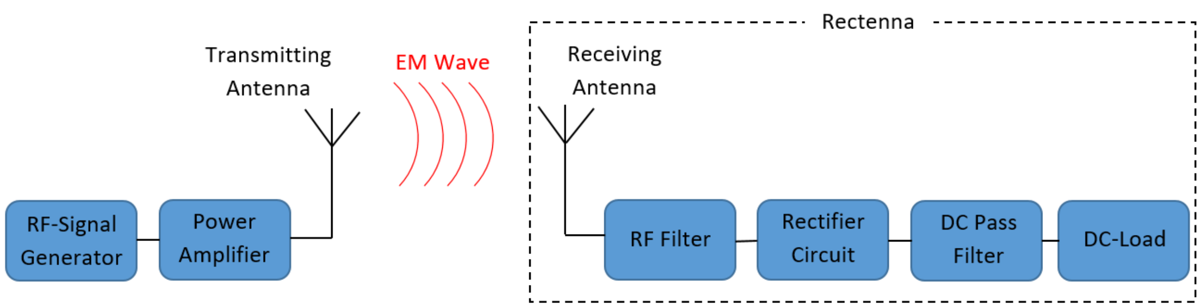


Figure 1.1. Block diagram of MPT system

2.2 Early History

The concept of WPT started with Nikola Tesla in 1899, when he successfully transmitted the power wirelessly. He designed a system to operate at 150 KHz, which required a large antenna because of the associated long wavelength. Tesla used a large coil feed with a 300 KW. He successfully received 100 KV at the receiving end [6]. Tesla could light 200 lamps placed 26 miles away from the transmitter [7]. All recorded experiments after Nikola Tesla's experiment were focusing on long wavelength and high transmission power, hundreds of watts with a wide beam. On the other hand, Heinrich Hertz who demonstrated electromagnetic waves in free space, did the first obvious experiment of short wavelength 0.6 meter. He transferred and received microwave power for the first time; however, the poor power generation of the oscillator in the short wavelength range was too low. In the 1930s, two effective methodologies of generating microwave power appeared: Klystron tube and cavity magnetron [6].

In May 1963, Brown used the first oscillator, which worked upon the principle of microwave cavity magnetron and produced a large amount of power with high efficiency in the microwave frequency range. The oscillator was able to produce an electromagnetic wave with 400 watts with efficiency equal to 80% at 3 GHz [8]. Brown used this oscillator to generate the electromagnetic signal and rectify it on the receiving end, where he used thermionic diodes to rectify the electromagnetic wave, which was received by a horn antenna with a 0.6 meter aperture and was replaced 5.48 meters away [9, 10]. In the transmission, an ellipsoidal reflector with a diameter of 2.9 meter was used. As a result of this experiment, Brown achieved 26% an overall efficiency [9]. After this experiment, Brawn realized that it was important to increase the AC to DC conversion efficiency and overcome the low directivity of the receiving antenna in order to increase the overall efficiency. After several meetings, Brown decided to transfer electromagnetic wave with low power in order to use a semiconductor diode in the rectifier, which could overcome the previous challenges [6].

In addition, Brown and George worked on a project which aimed to keep a helicopter airborne using 28 rectennas. Although they achieved a good amount of DC output, 4 watts with 50% AC to DC conversion efficiency, it was not enough to feed the helicopter's motor. The small power capability of the rectifier diodes was the main reason for the low DC output [6, 10].

In 1964, the first helicopter airborne using rectennas was demonstrated. The helicopter was airborne around 50 feet from the ground for ten hours. The rectennas contained more than 4000 semiconductor diodes, in an area of 4 sq. ft., which were connected together to form an array with a weight of 2.27

Kg. The array had 230 watts as DC output, which was an excellent amount to feed the helicopter's motor [11, 12].

In 1968, Brown developed the first free flying helicopter with rectennas that used Schottky diodes in the rectification. The movement to the Schottky diode technology was because of the high-power capability, small size and light weight for this type of diode. For instance, comparing this type of a Schottky diode to the previous semiconductor diode (point contact diode), the mass of the platform can be decreased five times for the same level of DC output power [10].

Figure 2.1. Brown and the successful experiment of the airborne helicopter using MPT [6]

In 1971, some testing on gallium arsenide diodes were done. It provides ten times higher power capability comparing to the HPA diode [6].

In 1974, Brown inserted LPF for the rectenna design, which placed before the diode in order to illuminate the unwanted effects of harmonic components. Furthermore, GaAs Schottky used in a half wave rectifier for the first time in rectenna design [6, 10]. Comparing this diode to the previous diodes, it can provide higher power capability, smaller size, and better conversion efficiency.

In 1975, Brown designed large rectenna (263 square ft) contains 4590 rectennas elements in order to receive the electromagnetic wave and extract a DC power up to 30 kW with 82% AC to DC conversion efficiency. The distance between the transmitter and receiver was one mile; LPF, half wave rectifier and Schottky diode have been used in the design [10].

In 1968 the concept of solar power satellite or SPS using photovoltaic cells was introduced [13]. This concept depends in the fact that the solar energy significantly decreases while passing the atmosphere due to absorption and scattering. SPS can overcome this limitation by receiving the solar energy outside the atmosphere using photovoltaic devices and convert it into microwave energy; then send it in a narrow beam toward the receiving antenna which replaced on the earth. The receiving antenna connected directly to the rectifier circuit which forms a rectenna system in order to convert the receiving microwave energy into DC power [14].

Another application of rectenna systems is radio-frequency identification RFID, which used CMOS technology in order to achieve best performance for low power detection. In RFID, CMOS technology overcome the limitation of extremely low receiving power because of lower parasitic value [15]. The flexibility of RFID, which can be sewn or attached to human body or clothes in order to track or identify the tag is an advantage of it. For energy harvesting, a passive tag has been used, which reflected the power back toward the transmitter; then using this reflected wave in purpose of identification or tracking of the tag. The required distance between the transmitter and tag of passive RFID is one of the most challenging and limitations for such an application, which depends on different parameters such as the required power for the chip in order to do the expected operation [16]. Furthermore, low-profile antennas are widely use in RFID tags because of the light weight and small size.

2.3 Recent Development in Wideband Rectenna

Numerous research discussed the rectenna system; however, most of them are focusing on a narrow bandwidth [17-19]. The rectenna's bandwidth depends on the antenna or/and rectifier circuit. In terms of the antenna, there are many designs that can operate in wideband frequency [20-22]. On the other hand, the bandwidth of the rectifier circuit depends on the diode, matching network, and DC load resistor. Usually, the diode operates in wide frequency and power range [23]. Furthermore, many techniques for wideband matching have been developed [1-3, 19]. The effect of the DC load resistor is investigated in this work.

The diode considers as a nonlinear device which has an input impedance varying with the input power level in a nonlinear fashion. Also, it depends on the operating frequency and DC load resistor [24]. As a result, the most challenging point while designing a rectenna system is providing high RF-DC efficiency for wide range of input power and/or wide band of frequency as the following papers discussed.

In Ref. [1] spiral rectenna array with dual-circular polarization was introduced. The array consists of 64 elements and operating from 2 to 18 GHz with input power level range from 0.01 to 100 μW/cm² and AC to DC power conversion efficiency from 0.1% to 20%. This ranges of frequency and power level is great achievement and considered as the best for following reasons. Firstly, the μW range of power can be harvested, which is the range of ambient electromagnetic waves such as Wi-Fi, radio, and mobile phone networks. Secondly, the losses of the diode that associated with the low power range is high, basically because of the relatively high threshold voltage of the diode comparing to the incident power level. Thirdly, the diode’s input impedance is largely depends on the operation frequency which leads to difficulty in designing a rectenna for this huge frequency bandwidth. Furthermore, each single operating frequency has it is own harmonics, which lead to interferences between the operation and harmonics' bands.

In Ref. [2] a novel rectenna which operating from 0.9 to 2.45 GHz and convert input power range from -30 to +30 dbm into DC was presented. The challenging in such a power range level is providing rectifier circuit converts the receiving electromagnetic signal into DC with high efficiency. For instance, some diodes are providing best performance in low power level while other types of diodes are best to use in high incident power. On the other hand, some rectifier topology providing better efficiency with high incident power more than low incident power such as the bridge rectifier. As a result, the basic idea behind this rectenna design is consisting of three rectifier circuits; each circuit response on converting certain input power level to DC; by designing a switch circuit to direct the incident wave to the proper rectifier. So firstly for low incident power a single series-mounted diode was used, the recorded AC to DC efficiency of power range of -20 to 0 dbm is approximately

15 to 50%. Secondly, for higher incident power in range of 0 to 20dbm, a single shunt-mounted diode has been used with maximum AC to DC conversion efficiency equal to 70%. The third stage which consists of a bridge rectifier could achieve 70% as AC to DC conversion efficiency for high incident power.

In Ref. [3] a dual-polarized cross-dipole antenna is connected to a novel full wave rectifier, which used to harvest wide range of incident power -35 to -10 dBm. In -35dBm and -10dBm the maximum RF-DC conversion efficiency is 5% and 55% respectively. Furthermore, the proposed rectenna operating from 1.8 to 2.5 GHz with maximum and minimum RF-DC conversion efficiency of 55% and 35% respectively at -10dBm. The antenna and the ground plane are embedded with slot in order to reject the second and third harmonics. These slots are used to replace the regular filter between the antenna and the rectifier.

In Ref. [4] two triangular monopole antennas operating from 0.85 to 1.94GHz with an omidirectinal radiation pattern and dual polarization property are proposed. Voltage doubler rectifier is used; however, the author did not record the rectifier efficiency and bandwidth. When the incident power is almost 7 dBm, the rectenna has RF-DC power conversion efficiency of 60.4% and 17% at 0.98GHz and 1.8GHz respectively.

In Ref. [5] the author introduced a rectifier circuit operating from 0.78GHz to 1.43GHz with maximum and minimum RF-DC power conversion 81% and 50% respectively at 14dBm. Although the most proposed rectifiers for the broad band rectenna are voltage doubler or full wave topologies, in this reference, a shunt topology is introduced. LPF is inserted between the antenna and the diode for matching, and an inductor is implemented after the diode to choke the RF and pass the DC power to the resistor load. The design achieved a good result, however it requires a large substrate because of the LPF's size.

Table 2.1 shows the best recorded results for wideband rectennas up to date. Also, it compares the achieved measurement results in this work. The table start with the narrower rectenna's bandwidth to the wider.

The input and output matching networks are playing a leading role in rejecting the harmonics from reaching the antenna and the load. Blocking the harmonics from reaching the antenna is necessary in order to improve the RF-DC efficiency [1, 25], which is a result of avoiding the reradiation of the harmonics [1]. Two different ways have been used throughout the literature for this task. The first one is inserting a filter between the antenna and the diode [5, 19, 26, 27], and the second method is embedding the filter on the antenna [3, 14, 25, 28, 29]. In addition, a matching network is inserted after the diode to tune the diode capacitance and block the harmonics from reaching the DC load resistor. For wideband rectenna, adding an inductor after the diode is proposed as a solution [1, 2, 5, 30]. This methodology is used here with further explanation, besides choosing the right rectifier topology and the other rectenna's elements such as the diode and DC load resistor to enhance the frequency bandwidth and the incident power range.

Ref	Bandwidth in GHz	Power in dBm	Maximum Efficiency	Minimum Efficiency	Rectifier Topology	DC Load Resistor
[31] (2016)	0.47-0.86	10	69%*	60%	Voltage doubler	12.2 kΩ
[32] (2017)	0.47-0.88	-1	75%	65%*	Voltage doubler	5 kΩ
[5] (2014)	0.78-1.43	14	81%	50%	Shunt	510 Ω
[3] (2015)	1.8-2.5	10	55%	25%*	Full wave	14.4 kΩ
[33] (2013)	1.7-2.5	-	75%	35%*	Full wave	300 Ω
[4] (2016)	0.85-1.94	7.21	60%	17%*	Voltage doubler	100 Ω
This Work	1.5-4.5	16	55%	30%	Series	50 Ω
This Work	0.5-4.2	16	47%	30%	Voltage doubler	1 kΩ

Table 2.1 State of art of the wideband rectenna system starting from the narrower to the wider frequency (* from draw)

Chapter 3
Rectenna Design and Simulation

3.1 Introduction

This chapter presents a detailed study of the wideband rectenna elements and how to integrate them efficiently in order to maximize the bandwidth and RF-DC conversion efficiency. Figure 3.1 illustrates the block diagram of the proposed wideband rectenna. This chapter is divided into five main sections. The first section states the rectenna efficiency equations, which is important to evaluate the rectenna's performance. The second section presents a new definition of the rectenna bandwidth which is missing in the literature. The third section discusses the receiving antenna and its properties. The fourth section highlights the main parts in the rectifier circuit, which are the diode, the matching network, and the load impedance; and how to integrate these three elements efficiently in order to achieve a wideband rectenna system. Furthermore, the fourth section includes a new concept of the rectenna's harmonics, which are supported by simulation results using ADS software in order to achieve an efficient rectenna design over a wideband. The last section proposes three wideband rectenna systems, working on the same concept but with different properties.

By implementing the techniques in this thesis, I was able to design three novel wideband rectennas. They consider as the best comparing to the literature as shown in Table 2.1. The rectenna could operate for 6GHz bandwidth with good efficiency; 6GHz is the bandwidth of the used diode.

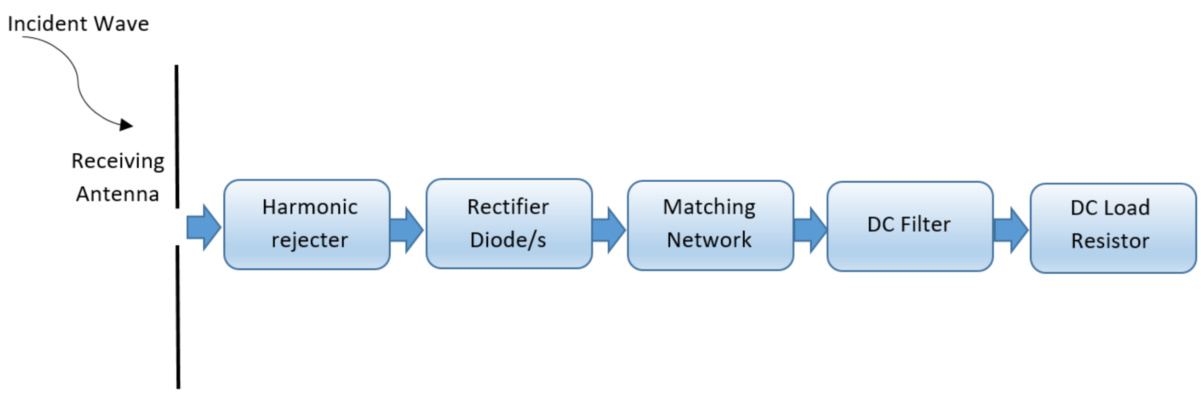


Figure 3.1. The proposed block diagram of the wideband rectenna

3.2 Rectenna efficiency

One of the important concepts to evaluate the rectenna performance is its efficiency. The rectenna efficiency gives the first impression on the merit of the design. The RF to DC conversion efficiency is the total efficiency of the rectenna system which can be expressed as

$$\eta = \frac{P_{out}}{P_{recived}} \tag{1}$$

Where P_{out} is the DC output power which can be calculated by (2), and $P_{recived}$ is the power received by the antenna which can be found from Friis formula as in (3)

$$P_{out} = \frac{V_L^2}{R_L} \tag{2}$$

$$P_{recived} = G_t G_r P_t (\frac{\lambda}{4\pi r})^2 \tag{3}$$

Where V_L, R_L, G_t, G_r, P_t, and r are the DC load resistor, voltage across the DC load resistor, transmitter gain, receiver gain, transmitted power, and distance between the transmitter and receiver, respectively.

3.3 The Rectenna Bandwidth and Cutoff Frequency

The rectenna is a combination of antenna and rectifier, and its bandwidth depends on both simultaneously. The antenna bandwidth is well defined throughout the literature, which considers the antenna with VSWR ≤ 2 as a good radiator and receiver. However, this range of the VSWR will not guarantee the high absorption of the electromagnetic energy as discussed in [34-36]. As a result, VSWR has to be measured in the lab for confidence. On the other hand, for MPT and energy harvesting systems, there is no specific definition of the cutoff frequency of the rectifier circuit. In this work, the cutoff frequency of the rectifier circuit is defined as half of the average power delivered to the rectifier circuit. Then, depending on how the rectifier circuit efficient is, the RF-DC efficiency will be increased in the cutoff frequencies. So, from (1) in the ideal case where there are no losses of power, the RF-DC conversion efficiency will be 50% at the higher and lower cutoff frequencies. As a result, the cutoff frequency of the rectifier corresponds with -3dB level of the rectifier's reflection coefficient (S_11). This reflection coefficient can be found using the Large-Signal S-Parameter

(LSSP) simulation on ADS. In this work, by considering the diode loss (as described in section 3.5) the -3dB level of the rectifier was found to correspond with approximately 30% RF-DC conversion efficiency. Therefore, we will use it as a reference to evaluate the rectenna bandwidth.

3.4 Antenna

3.4.1 Background

The antenna was used to collect the electromagnetic waves and convert it into AC signal. There are many types of antennas; however, the most popular antennas used in energy harvesting and MPT are wire and microstrip patch antennas. The main reasons for focusing on these two types are the dimensional and industrial advantages. For narrow band rectenna, dipole [26, 37], patch [38], bow-tie [39], printed loop [40], and folded-dipole [41] antennas are proposed for rectenna system. On the other hand, for a wideband rectenna, cross dipole [3, 33], printed monopole [4], and printed dipole [42] antennas have been used as a receiving element in the broadband rectenna. This work focuses on the microstrip patch antenna, because it is easy to fabricate and integrate with the rectifier circuit.

3.4.2 Microstrip Patch Antenna

The microstrip patch antenna is one of the most broadly used technologies in RF applications. It is gaining popularity compared to the other antennas, because it is easy to fabricate, tune its input impedance, and attach it with the rectifier. Furthermore, it has a low profile, low cost, small size, and light weight. Although the microstrip patch antenna is widely used due to its advantages, it also has disadvantages. For instance, it is provides poor power capability, low gain, and high loss [43, 44].

The microstrip patch antenna consists of two conducting surfaces separated by a dielectric substrate. The radiating patch is printed on the top surface, and the bottom surface presents the ground plane as in Figure 3.2. There are many possibilities of the conductor clad material; however, the copper is the most popular material due to its low-cost and high conductivity. On the other hand, the dialectic constant and highest of the substrate have to be selected efficiently. In general, high efficiency and wide bandwidth could be achieved using a substrate with low dielectric constant. In addition, decreasing the substrate thickness will increase the efficiency and narrow the bandwidth [45].

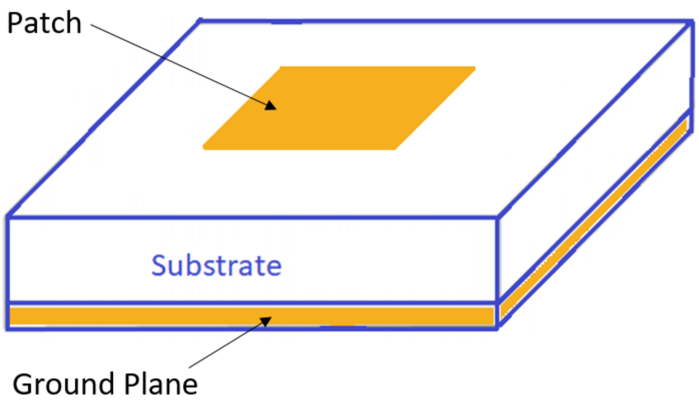


Figure 3.2. Rectangular microstrip patch antenna

The popular shapes of the radiating patch are rectangular, circular, and square; however, it could take any shape [17]. Changing the radiating patch or the ground plane shapes controlled some antenna characteristics such as the bandwidth, radiation pattern, and polarization. For instance, in [46] adding a slot to the patch antenna increased the bandwidth 25%. Also, in [47] removing the ground plane that directly located below the radiating patch changes the radiation pattern and gives an omnidirectional antenna.

Another important aspect in the microstrip patch antenna is the feeding mechanism. There are various types of the feeding mechanism such as microstrip transmission line, coaxial probe, aperture coupled, and proximity coupled feeds [43]. Each one of these types has its own properties in terms of bandwidth, matching, fabrication, and loss. In this work, the microstrip transmission line feed is used, because it is easy to integrate with rectifier. Furthermore, it gives wide possibility of varying the antenna’s input impedance which made the matching easiest. Moreover, it could enhance the bandwidth by using tapered shape as in [48]. In another word, the microstrip transmission line feed gives a high flexibility in the design which makes it suitable for different applications. For these reasons, the microstrip transmission line feeding is suitable for rectenna system, and it is the most popular used technique in the literature.

3.4.3 Selected Antenna

From the previous dissections, the microstrip patch antenna has been chosen as a receiver element within the rectenna system for its advantages, however, the regular types of this antenna have a narrow bandwidth. Various designs of printed monopole antenna with broad band properties have been proposed as a solution due to their broadband performance such as the Bow-Tie monopole [49], rectangular monopole [22], circular monopole [50], and U-shape monopole [51]. In this work the elliptical planar monopole antenna, which introduced in [52], is used in this work as a receiver element within the rectenna system; however, some adjustments applied to the antenna in order to obtain the proposed rectenna's requirements. The changes apply to the substrate type, ground plane shape, and the feed mechanism. The purposes of these adjustments are having the same substrate of the rectifier and the antenna, enhancing the matching between the antenna and rectifier, connecting the antenna to the rectifier easily. Because the rectifier impedance is a frequency dependent, the antenna impedance has to be optimized in order to maximize the bandwidth and enhance the matching.

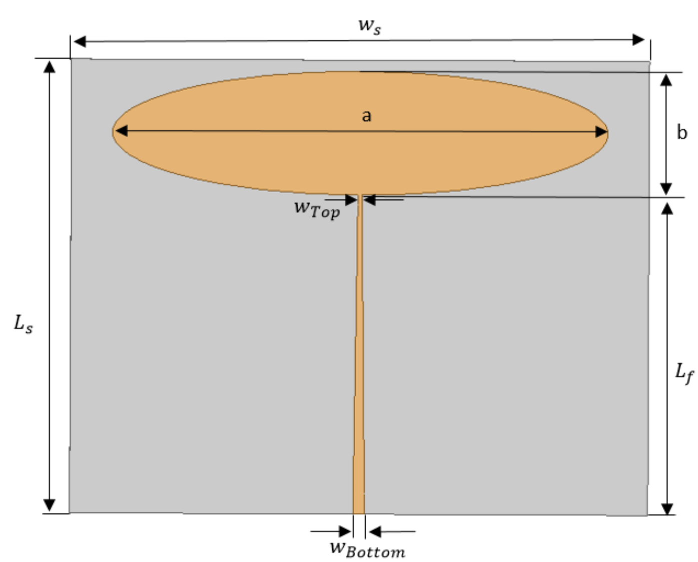


Figure 3.3. Top view of elliptical planar monopole antenna, where a=120mm b=30mm L_f =77.3mm L_s= 110mm w_s= 140mm w_{Bottom}= 2.7mm w_{Top}=1mm

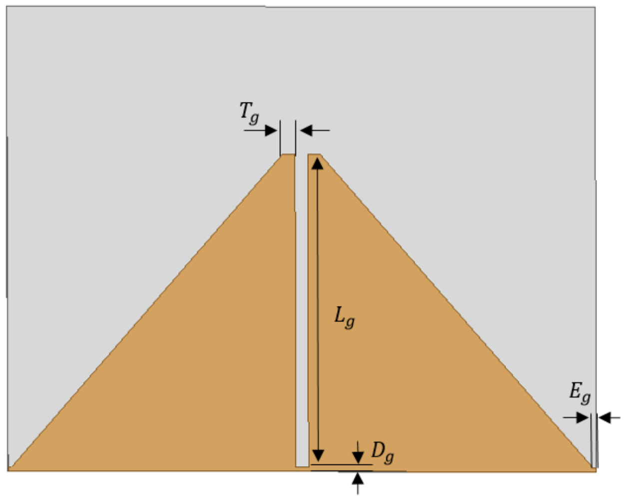


Figure 3.4. Bottom view of the elliptical planar monopole antenna, where D_g= 1mm, E_g= 0.9mm, L_g= 74mm, T_g= 3mm

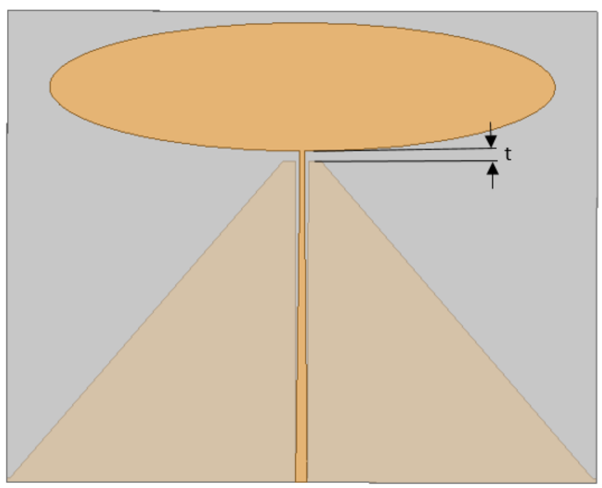


Figure 3.5. The whole structure of the elliptical planar monopole antenna, where t=2.3mm

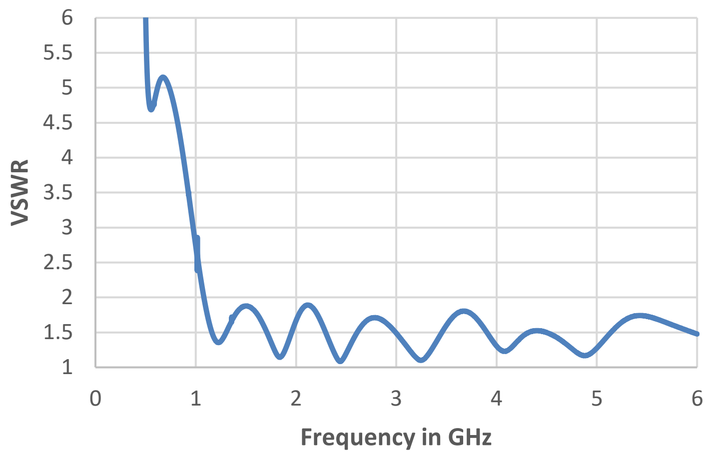


Figure 3.6. VSWR of the elliptical planar monopole antenna, when it is excited by a 50Ω port

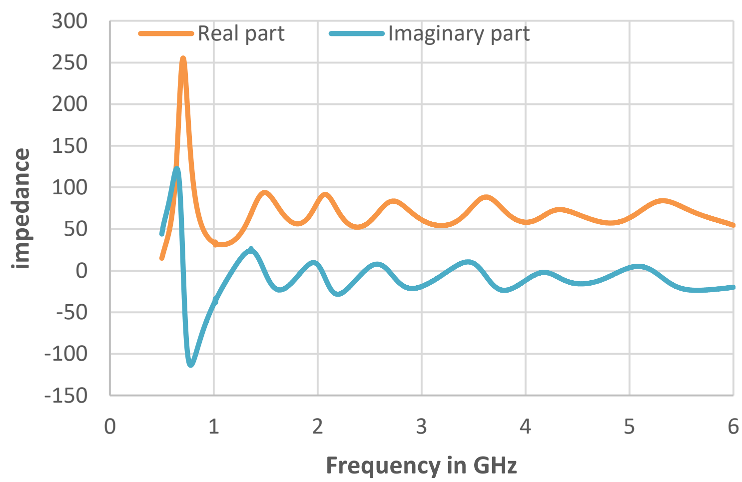


Figure 3.7. Input impedance of the elliptical planar monopole antenna, when it is excited by a 50Ω port

The proposed antenna operates from 1.1GHz to 14GHz, when it is excited by a 50Ω discrete port. The VSWR and input impedance of the antenna are illustrated in Figure 3.6 and Figure 3.7 respectively. An important point to mention here that the antenna impedance is optimized in order to be matched to the rectifier impedance in broadband. As a result, when the antenna connected to the rectifier, wider bandwidth is expected. This wide band frequency results from different factors, which are the patch shape, ground plane, and feeding. Firstly, In terms of the patch shape, the elliptical and circular patches recoded the widest bandwidth in the literature [53]. Secondly, the ground plane is affecting the frequency bandwidth [54], and the trapeziform ground plane found to give wide bandwidth [52]. Thirdly, the distance between the edge of the ground plane and radiating patch is controlling the lowest bandwidth frequency [55]. Finally, the used microstrip tapered feeding is contributing of expanding the frequency bandwidth [55].

The radiation pattern of the optimized antenna is showing in Figure 3.8. It is closed to the omnidirectional pattern. As it was mention previously that this radiation pattern can be achieved by removing the ground plane that located directly below the radiating patch.

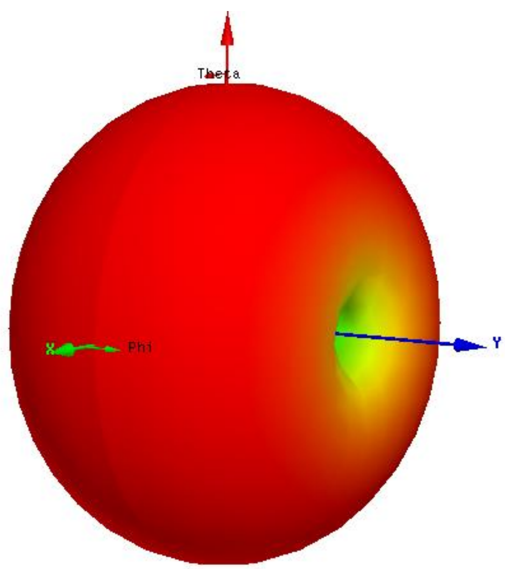


Figure 3.8. Radiation pattern of the elliptical planar monopole antenna with maximum gain of 2.5dB

3.5 Rectifier Circuit

In this section, a detail's study of the main elements of the rectifier circuit is presented; starting from the basic component which is the diode and its model, power capability, cutoff frequency, and losses. Finally, the rectifier topologies and its effect on the rectenna bandwidth are discussed.

3.5.1 Schottky Diode

Schottky diode junction consists of a metal-semiconductor contact. This novel combination of materials found to boost the diode switching time by introducing a small junction capacitance and small series resistance simultaneously, in order to operate within the microwave frequency range [56].

3.5.2 Diode Model

Figure 3.9 illustrates the equivalent circuit of Schottky diode [23]. It consists of R_s, R_j, and C_j which are the series resistance, junction resistance, and junction capacitance respectively. The R_s presents the ohmic loss of the diode (or the wave losses while the wave transmitting in the junction), which is inversely proportional to the rectification efficiency [15, 56]. In other word, once R_s increased the maximum efficiency of the rectification decreased. In the other hand, C_j is directly related to the operating frequency because it can increase or decrease the diode switching time [2]. Finally, R_j is the nonlinear resistor of the diode, which represents the diode's nonlinearity [56].

By referring to [37], the overall input impedance of Schottky diode Z_d can be calculated by applying kirchoff's voltage law to the illustrated circuit in Figure 3.9

$$Z_d = \frac{\pi R_s}{Cos\Theta_{on}\left(\frac{\Theta_{on}}{cos\Theta_{on}} - sin\Theta_{on}\right) + j\omega R_s C_j\left(\frac{\pi - \Theta_{on}}{cos\Theta_{on}} + sin\Theta_{on}\right)} \tag{4}$$

Θ_{on} is the turn on angular and it depends on the incident power as it can be seen in the follows equation

$$tan\Theta_{on} - \Theta_{on} = \frac{\pi R_s}{R_L\left(1 + \frac{V_{bi}}{V_o}\right)} \tag{5}$$

Where V_{bi} and V_o are the threshold voltage of the diode and the output DC voltage across the resistor respectively.

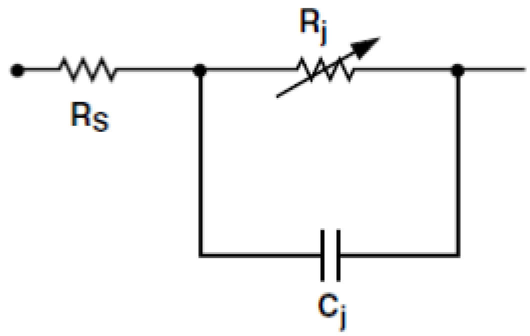


Figure 3.9. An equivalent circuit of Schottky diode [23]

3.5.3 Power Capability

The diode is the basic element in the rectification circuit. It used to convert the AC power to a useful DC power. Some applications required high output power such as solar power satellite and powering the electric devices. As the required output power increased the movement from energy harvesting to MPT systems should be made, because of the low level for ambient power in the free space typically < -30dBm/cm^2 [37, 41].

In order to choose the right diode for the rectenna system the power level range should be determined, because each diode has its own breakdown voltage, which limits the maximum input power. Exceeding this level of power may affect the diode and burn it down. The breakdown voltage can be found in the diode's spice parameters. By exceeding the reverse voltage, a reverse current will flow through the diode. The level of the critical input power which associated with the reverse-voltage can be calculated from [56]

$$P_{critical} = \frac{V_{br}^2}{4R_L} \quad (6)$$

Where V_{br} is the breakdown voltage

3.5.4 Diode Cutoff Frequency

Each diode is optimized to operate for certain frequency bandwidth which defined by the cutoff frequency. By exceeding this frequency the conversion efficiency will drop dramatically. The fabrication characteristics of the diode which represented by the equivalent circuit in Figure 3.9 will defined the cutoff frequency [57]

$$\omega_c = 2\pi f_c = \frac{1}{R_s C_j} \tag{7}$$

Then, in order to increase the cutoff frequency of the diode either C_j or R_s has to be decreased. However, tradeoff between C_j and R_s will be faced, because both of them depend on the junction thickness. On the other hand, the diodes are often designed to be operated in a wideband frequency [23]. Simultaneously, choosing the proper load resistor, matching technique, and harmonic's rejection methodology are the keys to achieve broadband rectenna system and take use of the whole diode bandwidth.

3.5.5 Diode Losses

The main factors of the diode losses are the diode threshold voltage, diode series resistance Rs, junction capacitance Cj, harmonics, and parasitic elements. Furthermore, the losses increases by exceeding the breakdown voltage. Also, for low incident power (less than the diode’s threshold voltage) a low efficiency will be expected. Furthermore, more losses will be generated in higher frequencies [15].

In MPT and energy harvesting systems, for a proper designed rectifier, the highest source of losses is the threshold voltage. In [58] the diode losses due to the threshold voltage calculated as

$$Loss = \frac{V_{bi}}{V_o + V_{bi}} \tag{8}$$

The maximum output DC voltage across the diode is [32]

$$V_{o,DC} = \frac{V_{br}}{2} \tag{9}$$

For the maximum output DC voltage across the resistor, the peak-to-peak voltage of the incident signal is equal to the breakdown voltage. Then, we can defined the minimum approximated loss of the diode due to the threshold voltage as

$$Minimum\ Loss\ due\ to\ V_{bi} \approx \frac{V_{bi}}{\frac{V_{br}}{2} + V_{bi}} \tag{8}$$

So, from the previous discussion and by using (10) for HSMS2860 Diode (the used diode in this work) the minimum approximated loss due to threshold voltage is 15.66% of the input AC signal. There will be a certain level of incident power that corresponds to the minimum loss of the rectifier circuit; however, as the operating point is moving away from that point the losses continue increasing till it reaches 100% where there is no output DC power.

3.5.6 Diode Selection

The main categories toward choosing the right rectifier diode are determining the interested operating frequency band and the input power level range. After determining the cutoff frequencies and input power level, the available selections of diodes will be limited. For instant, for low power applications, a diode with low forward voltage is desired such as HSMS285x, SMS7630, and BAT43W which utilized in [3, 40, 59]. However, these diodes have a small breakdown voltage which decreased the diode's power capability. Thus, for highest input power level, a diode with higher breakdown voltage is required such as HSMS286x and HSMS-282x [60]. On the other hand, each of these diodes optimized to operate in a certain frequency band, which could be found in the diode's data sheet.

3.5.7 The selected diode

This work focusing in designing a wideband rectenna system in terms of frequency and power. The incident RF power of the rectenna is considered to be higher than 0dBm in order to get a useful amount of the DC power that could be utilized in different applications. The interested frequency selected to be lower than 6GHz, because of the available measurement tools, circuits' equipment, and the various applications working on that band such as mobile cells and WiFi. As a result, the HSMS2860 is found as the best chose for our requirements. It is optimized to operate at frequency band of 915MHz to 5.8GHz with 0.65V and 7V as forward and breakdown voltage respectively [23].

3.5.8 Rectifier Topology

In Figure 3.10, various topologies for rectifier circuit used for rectenna system in the literature is illustrated such as series diode, shunt diode, voltage doubler, and full rectifier [3, 19, 31, 61]. The series diode is a half wave rectifier. It is rectifying the positive half wave and block the negative half wave of the incident signal. It considers as the easiest topology to understand and analyze. The shunt topology is similar to the series diode rectifier; however, it used to rectifying the negative half wave of the input signal. According to the literature, these two configurations are more suitable for low power applications because of their low losses [58]; however this can be traded for power handling capability [2]. By implementing these two types of rectifiers for rectenna system using the ADS simulation tool, I found that they generate high second and third harmonic comparing to the other harmonics as shown in Figure 3.11. This may refers to the relatively low amount of incident power, because as the level of the incident power increased the harmonics effect will increase [56]. This characteristic will create a difficulty while designing the wideband rectenna, because of the interferences between the fundamental and harmonics' bands.

The third rectifier topology is the voltage doubler. It contents two diodes; each one of them is rectifying different half of the cycle. This topology could be considered as a combination of series and shunt diode rectifiers. The output DC voltage will be twice the incident voltage. By simulating this type of rectifier within the rectenna system, I found that the odd harmonics will be dominated as shown in Figure 3.12. Also, the dominate harmonic is embedded on the third harmonic, which simulated over the interested frequency as in Figure 3.13. This result will be an advantage of this topology to be used for wideband rectenna. The reason behind that as illustrated above is minimizing the interferences between the fundamental frequency band and the harmonics' bands, especially the second harmonic's band.

In this work, for simplicity the comprehensive study and design procedure of the wideband rectenna will be described for a series diode rectifier, including the simulation and fabrication. Then, the same proposed design procedure will be followed to design a broader rectenna by employing the voltage doubler rectifier, which has the ability to achieve wider bandwidth and higher RF-DC conversion efficiency according to the previous discussion and simulation results.

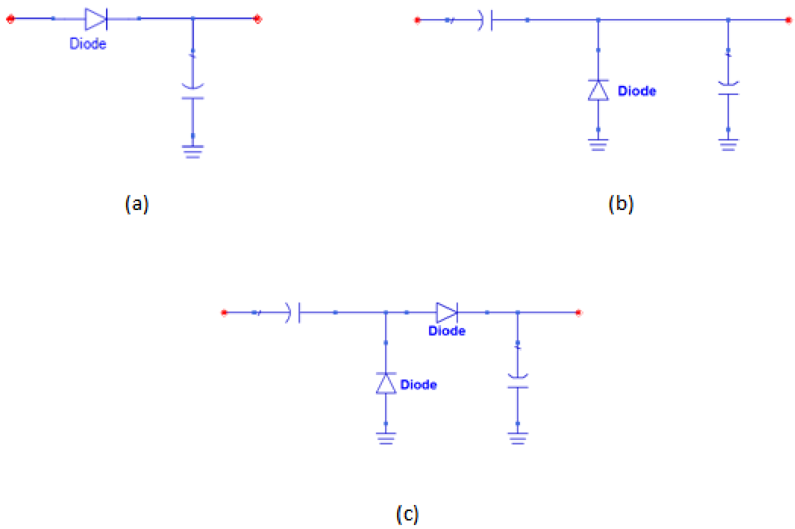


Figure 3.10. The most used rectifier topologies for rectenna system a)series b)Shunt c)voltage doubler

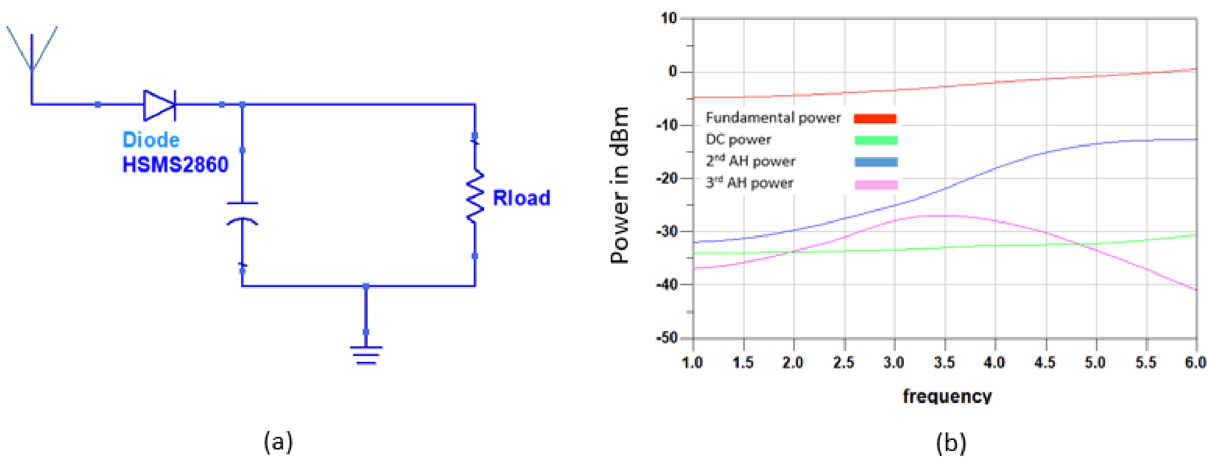


Figure 3.11. The simulated reflected AH of the series diode topology connecting to a 50 Ω antenna a) the circuit configuration b) the reflected AH using ADS

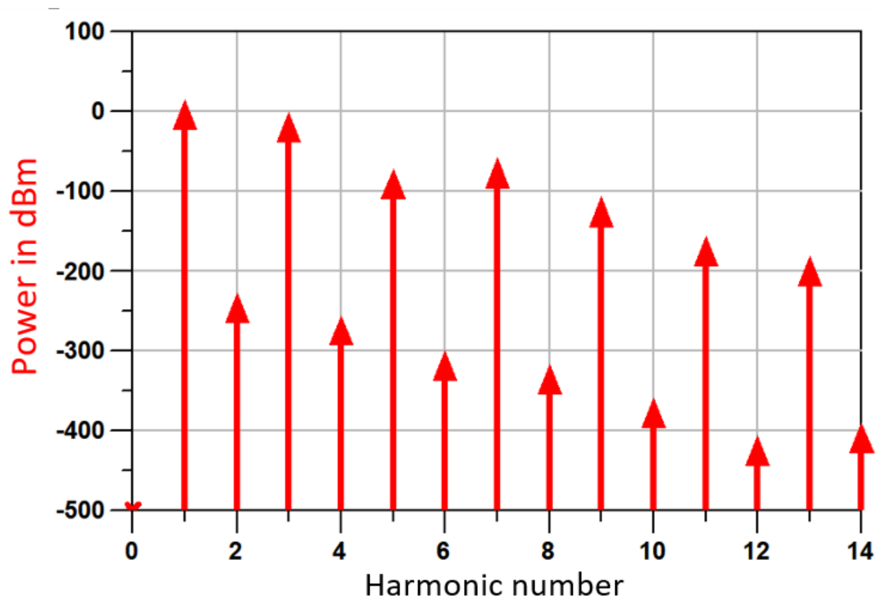
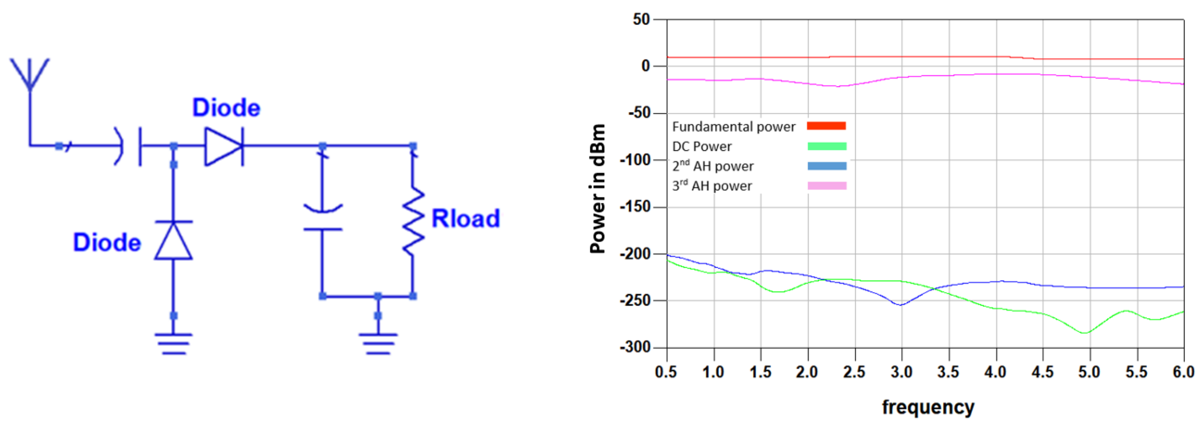


Figure 3.12. Harmonics' power of the voltage doubler rectifier



(a) (b)

Figure 3.13. The simulated reflected AH of the voltage doubler topology connecting to a 50 Ω antenna a) the circuit configuration b) the reflected AH using ADS

3.6 DC Load Resistor

The DC load resistor is one of the parameters that vary the input impedance of the diode and then affect the quality of the matching network by reflecting more power to the source [10]. Furthermore, for every level of incident wave power, there is an optimal load resistance; in another word, as the incident power level gets higher, the optimal load impedance decreased Figure 3.14 [62]. Moreover, in [15] higher efficiency for low incident power has been achieved when the DC load resistor is large. Based on these founding, we can conclude that choosing the DC load resistor of the rectenna largely depends on the incident power level. Then, for high incident power the DC load resistor has to be small, and vice versa.

From the above discussion, it is obvious how the load impedance value can directly affect the rectenna performance and its efficiency. For this reason, many designers started to develop different circuits to decrease the effect of the DC load resistor variations. For instance, power management circuit between the diode and the DC load resistor has been discussed in [63, 64]. Furthermore, in [65] a dynamic switching circuit between the diode and DC load resistor is implemented.

In this work, I investigated the effect of the DC load resistor on the frequency bandwidth using the ADS simulator. Figure 3.15 shows the impedance variation from 1-6 GHz of the rectifier circuit in Figure 3.11a, when the DC load resistor is 50Ω and 100kΩ. It is obvious that decreasing the DC load resistor will decrease the rectifier impedance variations. As a result, wider frequency bandwidth will be achieved.

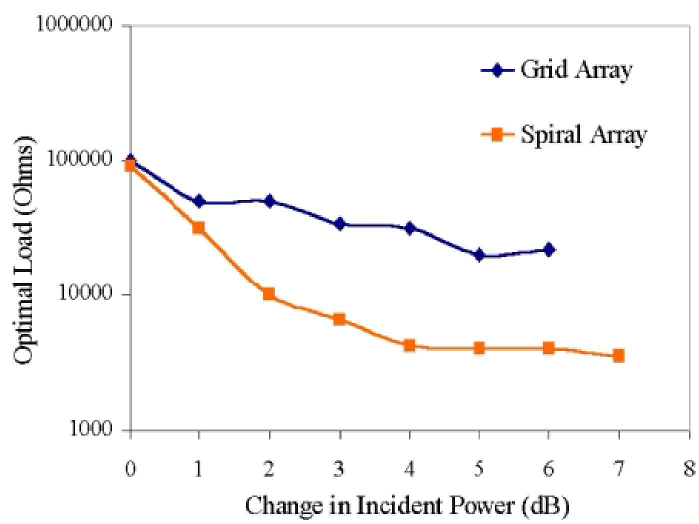


Figure 3.14. The effect of the incident power level on the optimal DC load resistor [62]

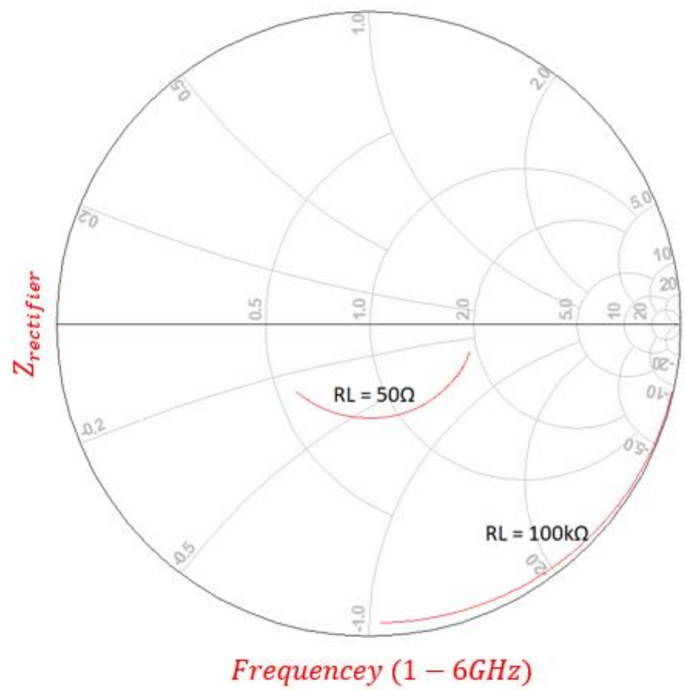


Figure 3.15. The effect of the DC load resistor on the rectifier impedance bandwidth for the circuit in Figure 3.11a.

3.7 Rectenna's harmonics

3.7.1 How The Rectenna's Harmonics Generated

From the previous discussions, the diode considers as the most complex element within the rectenna system because of its nonlinearity properties, and it highly depends on the input power level, resonance frequency, and DC load resistor [24]. Furthermore, the diode input impedance may vary with the harmonics [1]. The diode input impedance changes with these parameters and depending on the applied current which causes the nonlinearity. Actually, the dependence of the diode's junction resistance on the applying current is what causing the changing in the diode's input impedance in a nonlinear fashion [56]. This variation of the junction resistance can be illustrated by the I-V curve of the diode at DC Figure 3.16.

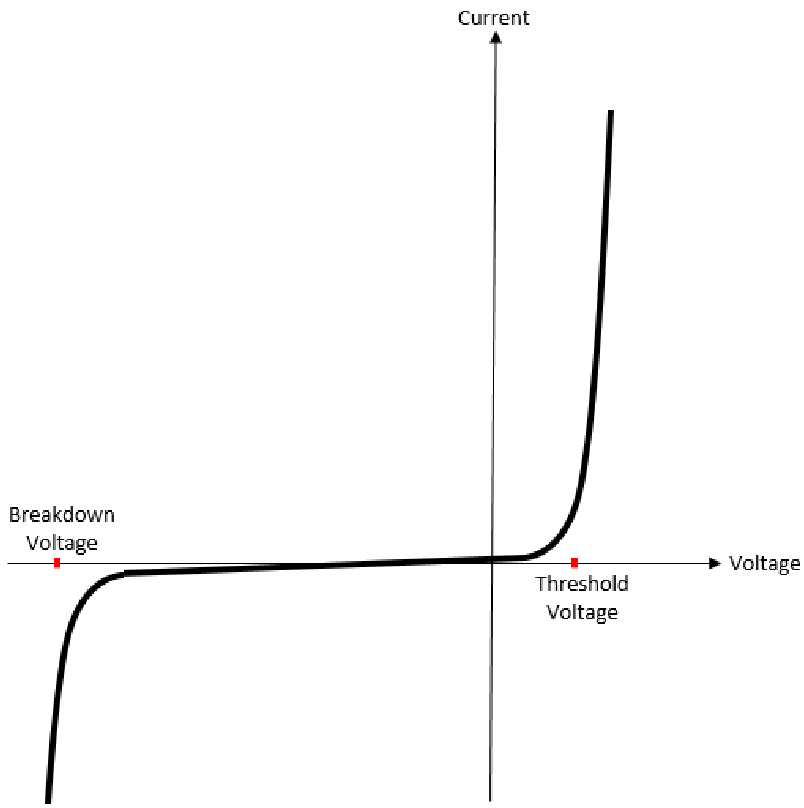


Figure 3.16. DC I-V curve characteristics of Schottky diode

The most important characteristic of a nonlinear device is producing harmonics. These harmonics are generated because of the changing in the input waveform. Also, because a small amount of input voltage leads to a high output current as illustrated in Figure 3.16, which leads to a waveform that is not a pure sinusoidal. By transforming this signal from the time domain into frequency domain using Fourier transforms; the harmonics will appear across the spectrum as impulses. Each of these impulses represents a sinusoidal wave which can be converted to the time domain using the inverse of Fourier transform. So when a sinusoidal wave incident to a rectifier diode a distribution wave will be generated, which is a combination of a fundamental wave and harmonics. This complexity creates challenges while designing the rectification circuit, especially in the matching network design for a wideband rectenna.

From the above discussion, the harmonics will be generated within the rectenna system, and each harmonic has it is own magnitude. For low input power level, the harmonics' effect will be small; however, for high incident power, the harmonics' effect will increase [56]. Because the nonlinearity characteristic of the diode raises as a consequence of the incident power increasing. These harmonics will affect the input impedance of the diode, causing a change that depends on the harmonics' level [1]. So understanding the facts of the rectenna harmonics is very substantial in order to design the rectenna efficiently.

In this work, a comprehensive study for the rectenna harmonics is introduced for the first time. In the previous works, a complete study of the whole rectenna's harmonics is missing. For this reason, this work presents an inclusive investigation of the rectenna's harmonics by using ADS simulator. I found that the generated harmonics in the rectenna system divided into active and reactive harmonics, which has to be controlled efficiently.

3.7.2 Impedance Matching and Harmonics Controlling

The main goal of impedance matching is maximizing the transfer power (matching) and/or minimizing the reflected power (blocking) as much as possible. There are many techniques that can be used to design the impedance matching network between two elements; some techniques used to achieve a narrow band matching such as lumped elements, doubler stub, single stub and quarter wave transformer, while other techniques used to achieve a wide band matching such as radial stub, tapered transformer, multisection quarter wave transformer, Chebyshev multisection transformer and binomial multisection transformer [45]. Usually, wideband matching networks are more complicated and required larger number of elements and consequently area. For this reason, narrow band matching network techniques are used to achieve wideband characteristics with simple design and small size.

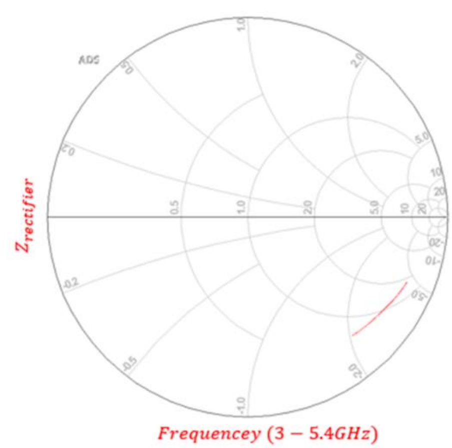


Figure 3.17. The impedance variation of the series rectifier circuit in Figure 3.11a using HSMS2860 diode when R_L=1kΩ

In this work, a new design procedure for a wideband rectenna system is proposed. In a wideband rectenna system the impedance matching and/or harmonics' rejection considered as a challenging task because of the interferences between the fundamental frequency band and harmonics' frequency bands. As a result, a new design procedure is developed here. First of all, I found that the HSMS2860 diode can be efficiently used for the proposed wideband rectenna, because it will allow the rectifier circuit within the rectenna system to operate in a wideband frequency with small variation in the input impedance as shown in Figure 3.15, and the impedance variation in the interest frequency shown in Figure 3.17. This leads to conclude the possibility to design a rectenna that able to cover the whole diode bandwidth, however, designing a network that matched wide frequency band and block wide frequency bands simultaneously is very challenging. So in order to solve this issue two methods are proposed here.

1. Adding an inductor after the diode (will eliminate the third AH)
2. Choosing the right rectifier topology (will eliminate the second AH)

Firstly, by looking to the produced harmonics of the series diode rectifier before the matching Figure 3.11, the second AH contains the highest level of power and then the third AH. Adding an inductor between the diode and the load as in Figure 3.18a, will prevent the third AH from generated backward to the source Figure 3.18b. Furthermore, it will match the rectenna in wide frequency and power range. So, adding the inductor is efficient to match the antenna to the diode and to reduce the third AH effects, which will facilitate the task of blocking the harmonics. Furthermore, it will prevent the higher RH from reaching the load which will improve the rectenna performance as will describe in the next section.

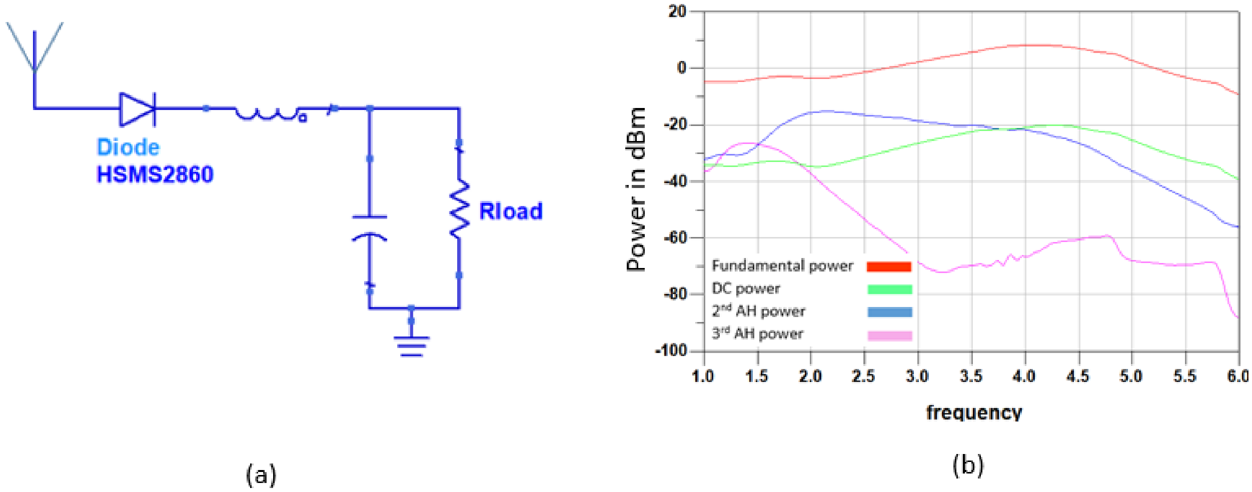


Figure 3.18. The effect of adding an inductor after the diode a) rectenna circuit b) its active power and harmonics between the diode and the antenna

The second proposed method to eliminate the second harmonic is the rectifier topology. There are different rectifier topologies that can be elected Figure 3.10; however, each one of them has it is own properties. In this work, I conclude that for a wideband rectenna, the voltage doubler rectifier is more suitable, because it eliminates the even harmonics which allows to insert a network that pass the fundamental frequency and reject the reflected harmonic from reaching the antenna as shown in Figure 3.12. An important point here is that in a wideband rectenna system, the second harmonic has the large impact on the performance, because it highly interferes with the fundamental frequency band; which gives an advantage of using the voltage doubler rectifier circuit. In another word, it will assist in avoiding the interference between the fundamental frequency band and the second harmonic band, which leads to a rectenna with wider bandwidth.

The rectenna efficiency will still be affected by the reflected second harmonic and DC current as in Figure 3.18. So adding a DC block and reject the second harmonic are important to increase the RF-DC efficiency and prevent the reradiation of the harmonics [1]. Therefore, the HSS (Hybrid Short Stub) between the antenna and the diode has been proposed as a solution Figure 3.19. The HSS will appear as a short circuit for the DC current and the second AH simultaneously. As a result, the RF-DC efficiency will be improved. The response of the HSS is shown in Figure 3.19.

Finally, while designing the matching and/or blocking network between the antenna and the diode, there are two options. Firstly, the harmonics could be reflected back to the diode as in [11, 56], but these harmonics may change the diode’s input impedance [1]. As a result, this will not be the desired solution, especially for a wideband rectenna. However, in [56] the author states that the reflected harmonics could increase the efficiency, which may appear as a logically conclusion if the reflected DC considered. Otherwise, he did not consider the harmonics voltage across the diode in the analytical solution; by giving an assumption for closed-form equations. These are the reasons why the author refers to this type of matching as an efficient matching, which may not always the case. The second solution, the harmonics could be directed into the ground plane and lost there. I consider this solution as the most desirable for a wideband rectenna, since the change of the diode’s impedance over the frequency bandwidth is minimized. Also, because the power range in this work is higher than 0dBm, the generated harmonics' power will be relatively high [2]. As a result, these harmonics' effect on the diode’s input impedance will increase [1].

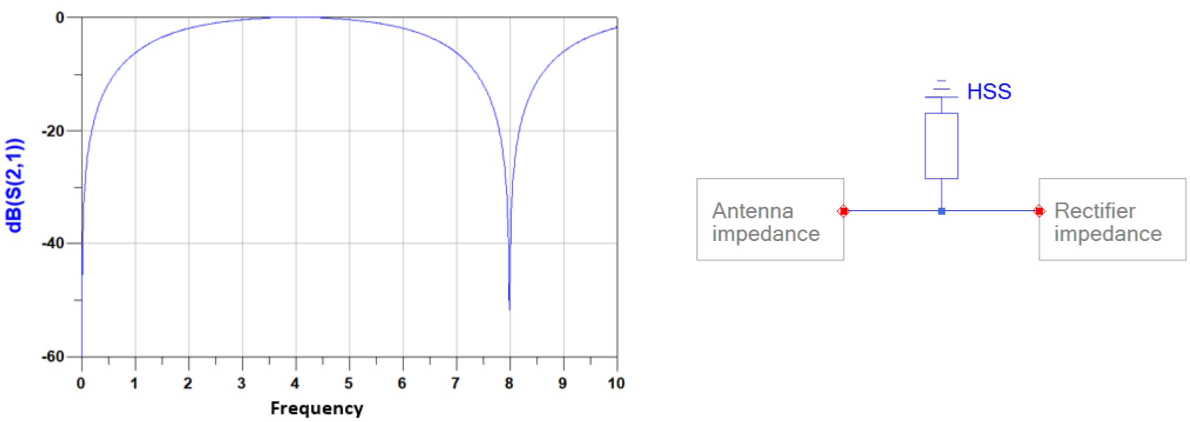


Figure 3.19. Frequency response of HSS

3.7.3 Active and Reactive Harmonics

A detail study for the fundamental power and it is associated harmonics that flowing in the rectenna system is introduced under this section. To achieve better understanding of the rectenna’s harmonics perspectives, an assumption of a constant real input impedance (50 Ω) of the receiving antenna over the whole bandwidth is considered. The harmonic balance simulation in ADS is used to perform the rectenna’s power.

The main contribution points in this section:

1. Introducing the active and reactive power concepts to understand the rectenna's harmonics facts
2. The AH (Active Harmonics) will not be generated after the diode (toward the load), however, the RH (Reactive Harmonics) will do.
3. The RH will not be generated before the diode (toward the antenna), however, the AH will do.
4. The active power after the diode is embedded in the DC component only.
5. A reactive power in the fundamental frequency band will be reflected toward the antenna, unless the rectifier impedance is pure real (not necessary to be matched).
6. In the fundamental frequency band, the reflected power from the diode consists of active and reactive power.
7. The input matching network and the imaginary part of the antenna's impedance will introduce a reactive part before the diode and enforce a small amount of RH to reflect toward them.

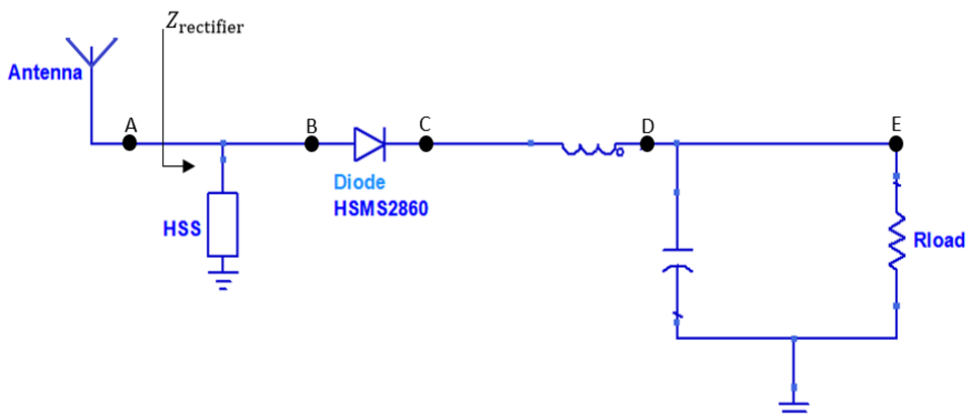
According to the presented simulation results on ADS, the power flowing in the rectenna can be divided into two parts: Active power and Reactive power, and each one of them have its own harmonics (AH and RH). The active power is the power that absorbs by the real impedance; however, the reactive power will not. From this known fact and by looking to the rectifier impedance ($Z_{rectifier}$) from 1 – 40 GHz of the half wave rectifier circuit as a part in the rectenna system as shown in Figure 3.20, it is obvious that the active power will be absorbed by the diode in the fundamental frequency band only. In harmonic frequency bands, the rectifier impedance will be pure imaginary, which will generate reactive power after the diode; this reactive power distributed on the fundamental frequency and higher RH bands as illustrated in Figure 3.21. Simultaneously, the reactive power will be reflected to the antenna in the fundamental frequency band only as shown at point A in Figure 3.21. On the other hand, the diode output will not contain any AH; however, the DC component will be the only active power that appears after the diode as in Figure 3.22. In this simulation the active power measured as

$$P_{Active} = real(0.5 V_P I_P^*) \quad (11)$$

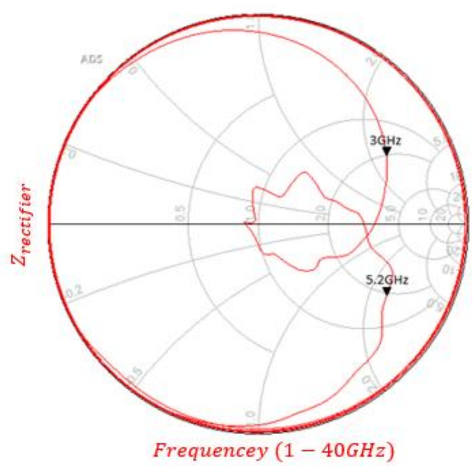
Where V_p and I_p are the peak voltage and current respectively. The reactive power measured as

$$P_{Reactive} = im(0.5 V_P I_P^*) \tag{12}$$

Finally, adding the input matching is substantially to improve the rectenna performance; however, the RH will be reflected to the matching network as shown at point B in Figure 3.21. Although these RH will not reach the antenna, they have to be controlled correctly as described in the previous section.



(a)



(b)

Figure 3.20. a) Circuit configuration of a wideband rectenna system operating from 3 - 5.2 GHz with series diode configuration and HSS (Hybrid Short Stub) b) its rectifier input impedance

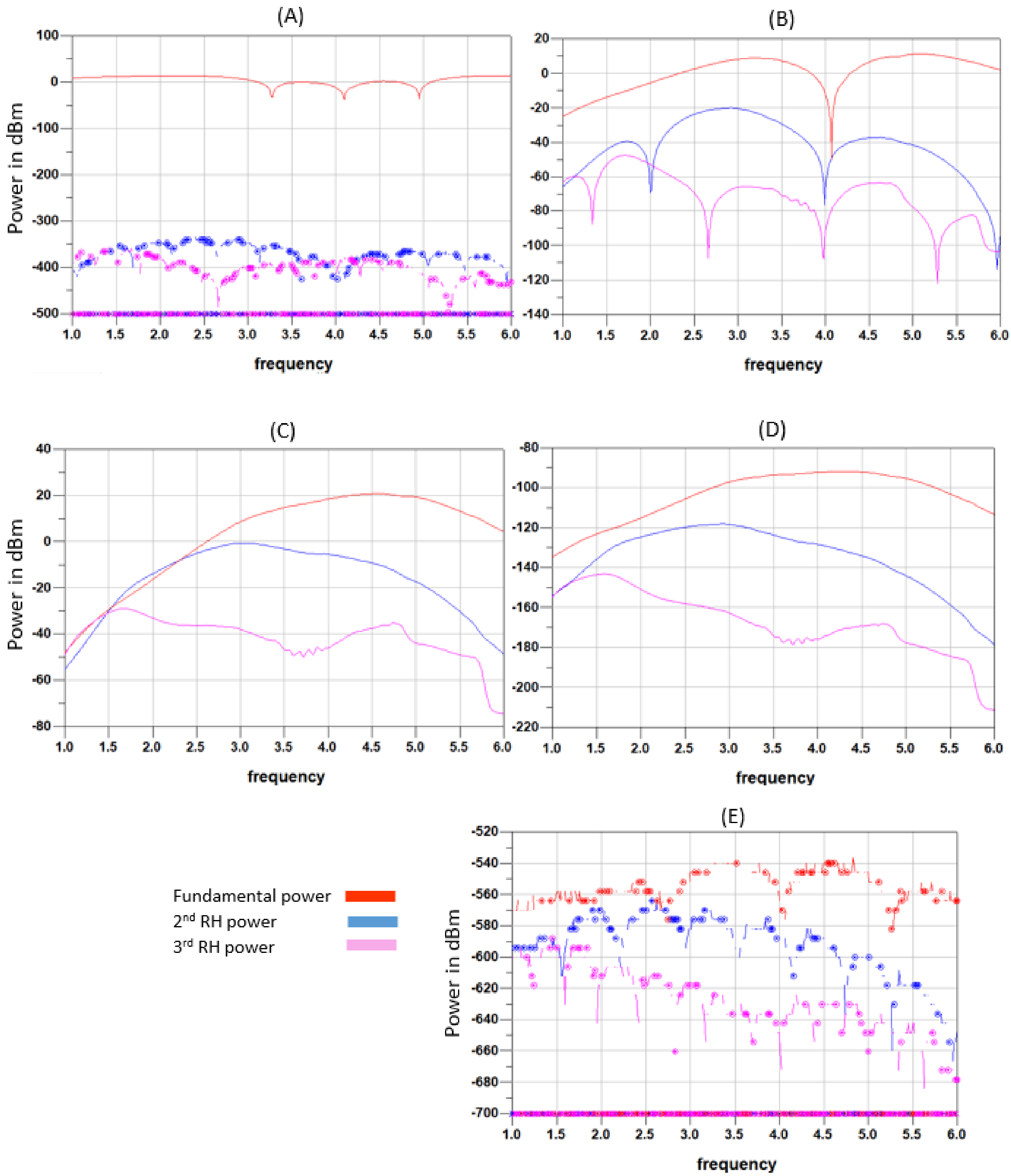


Figure 3.21. The reactive power of the fundamental frequency band and the 2nd and 3rd harmonics, at the points A, B, C, D and E which indicated in Figure 3.20a.

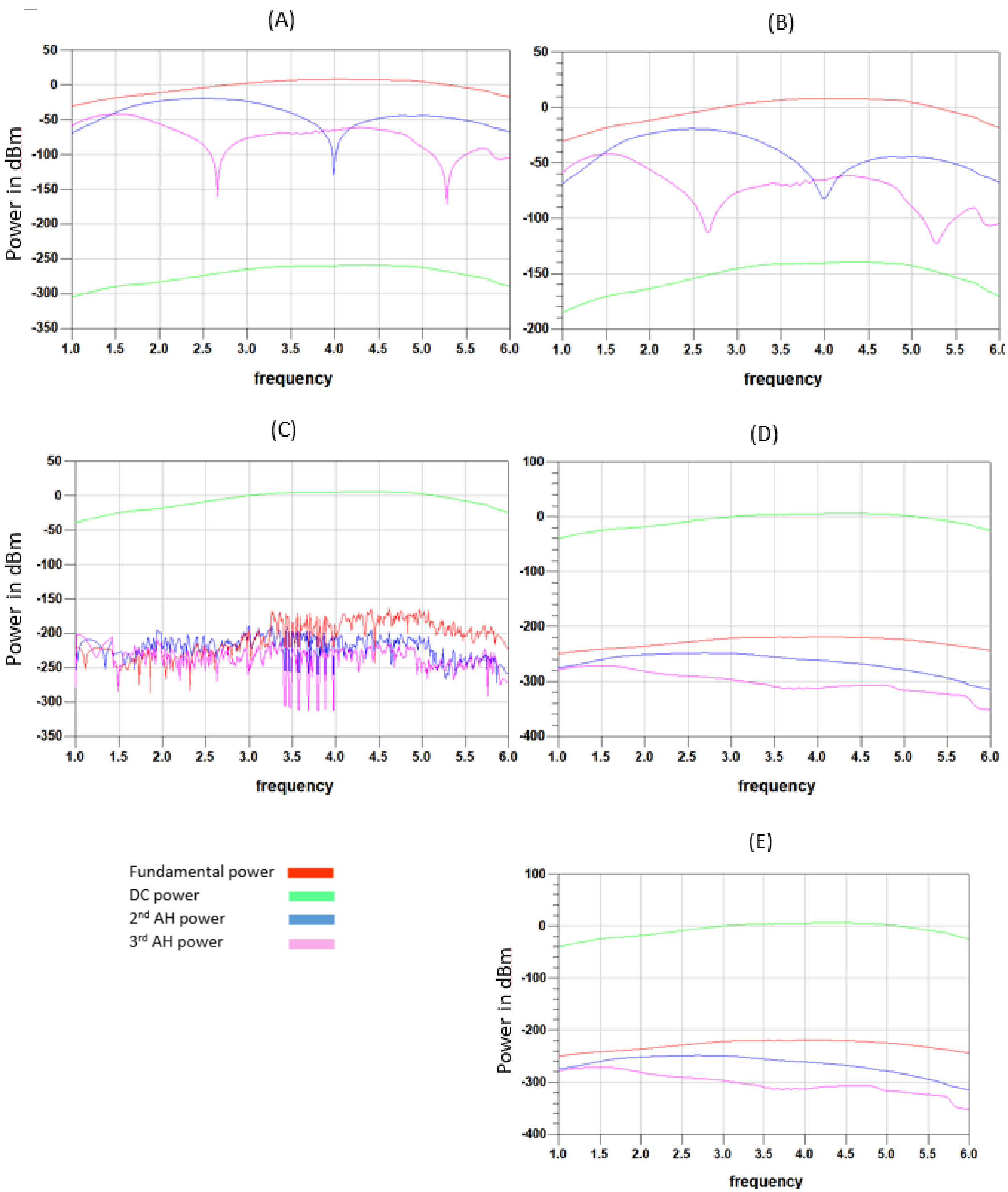


Figure 3.22. The active power of the fundamental frequency band, DC power component and 2nd and 3rd harmonics, at the points A, B, C, D and E which indicated in Figure 3.20a.

3.8 The Proposed Wideband Rectennas

In this section, three wideband rectennas have been proposed. The concept of wideband here includes the frequency bandwidth and the incident power range simultaneously. The three proposed rectennas operating with the same principle but for different frequency bands and power ranges. The first proposed rectenna is used in section 3.2 in order to explain the work principle of the rectifier circuit. The rectifier circuit of the first and second designs is a half wave rectifier, and it is a voltage doubler for the third proposed rectenna. The antenna in section 3.1 is used as a receiver element for the three designs. The antenna's input impedance file is exported from HFSS and imported to ADS, which described in details by [24]. The first, second, and third rectennas have the frequency bandwidth of 3 - 5.4GHz, 1.5 – 5GHz, and 0.5 – 5.6GHz with power range of -5 to 13dBm at 4.3GHz, and 3 to 25dBm at 3.4GHz, and -5 to 22dBm at 4.4GHz respectively. The minimum RF-DC conversion efficiency is 30% on the edges; and the maximums are 82%, 62%, and 80% for the first, second, and third rectennas respectively. Detail's discussion of the results in the coming sections.

3.8.1 The First Proposed Wideband Rectenna

Figure 3.20a shows the block diagram of the first rectenna system. The antenna discussed in section 3.2 is implemented here, which connected to a series diode rectifier circuit. The inductor in the output matching network is used to tune the diode's impedance in order to be matched to the antenna in a wideband Figure 3.18. The HSS in the input matching network is utilized to block the harmonics from reaching the diode and reradiate as illustrated in Figure 3.19. The rectenna operates from 3 to 5.4 GHz with a maximum and minimum efficiency of 82% and 30% respectively, when the received power is 8.9dBm as in Figure 3.23. Furthermore, the proposed rectenna operates within a wide range of incident power -5 to 13 dBm with 30% minimum RF-DC conversion efficiency at 4.3GHz as illustrated in Figure 3.24.

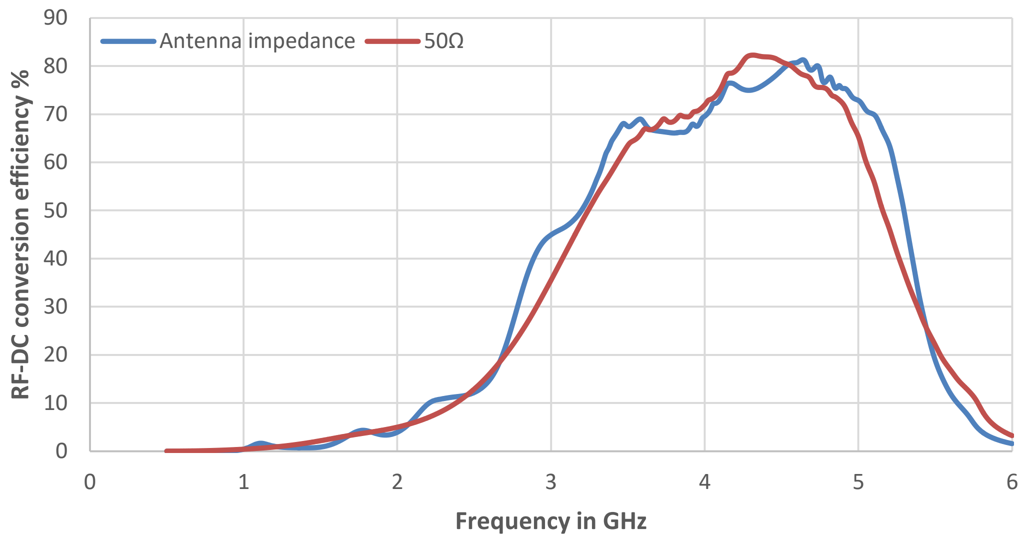


Figure 3.23. The frequency bandwidth for the first proposed rectenna at 8.9dBm

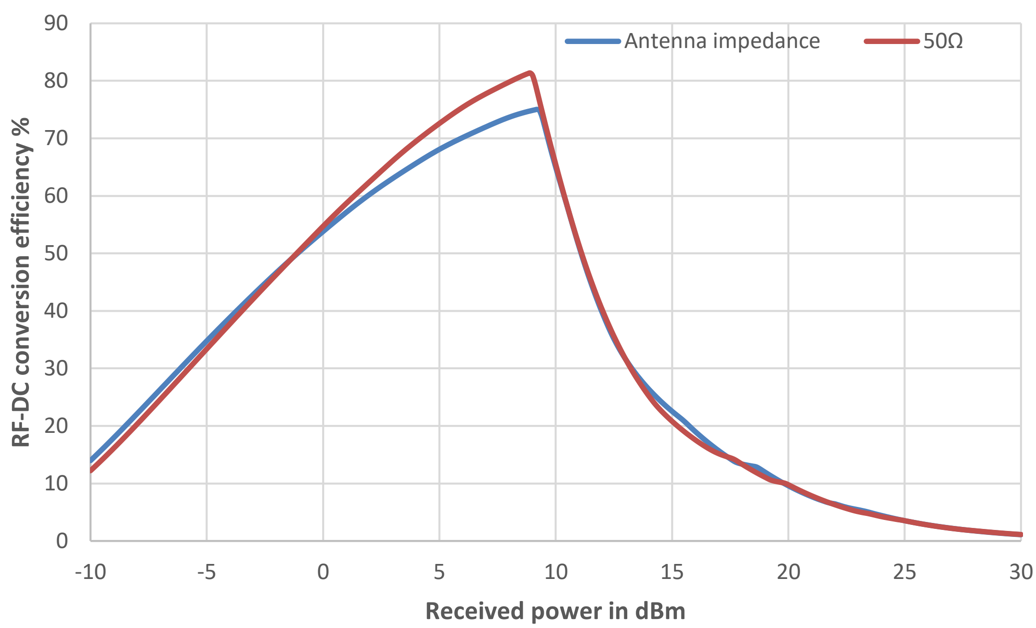


Figure 3.24. The power range for the first proposed rectenna at 4.3GHz

3.8.2 The Second Proposed Wideband Rectenna

This rectenna with a series diode configuration provides wider frequency bandwidth and power range comparing to the first proposed design; however, the RF-DC conversion efficiency is lower. Figure 3.25 shows the proposed rectenna structure. The design is operating from 1.5 to 5 GHz within 62% and 30% maximum and minimum RF-DC conversion efficiency respectively as in Figure 3.26. Also, it has maximum and minimum RF-DC conversion efficiency as 62% and 30% for incident power range 3 to 25dBm at 3.4GHz as shown in Figure 3.27. In order to let the rectenna operates in low frequency range and wider bandwidth HOS (Hybrid Open Stub) into the output matching network. Simultaneously, small DC load resistor is used to enhance the bandwidth as described in section 3.6.

One of the limitations of this rectenna design that the second and third AH effects could not be eliminated efficiently in the same time, because of the high interferences between them and the fundamental band as in Figure 3.28. These interferences decreased the overall efficiency, which can be minimized by the voltage doubler rectifier circuit as in the next section.

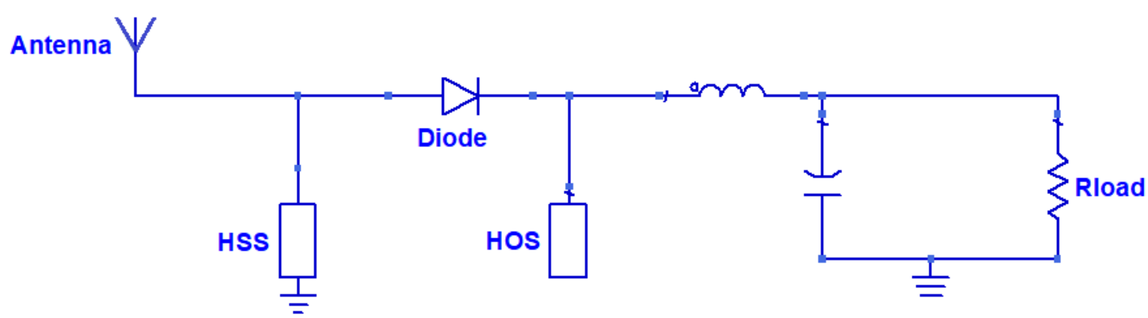


Figure 3.25. Block diagram for the second proposed wideband rectenna

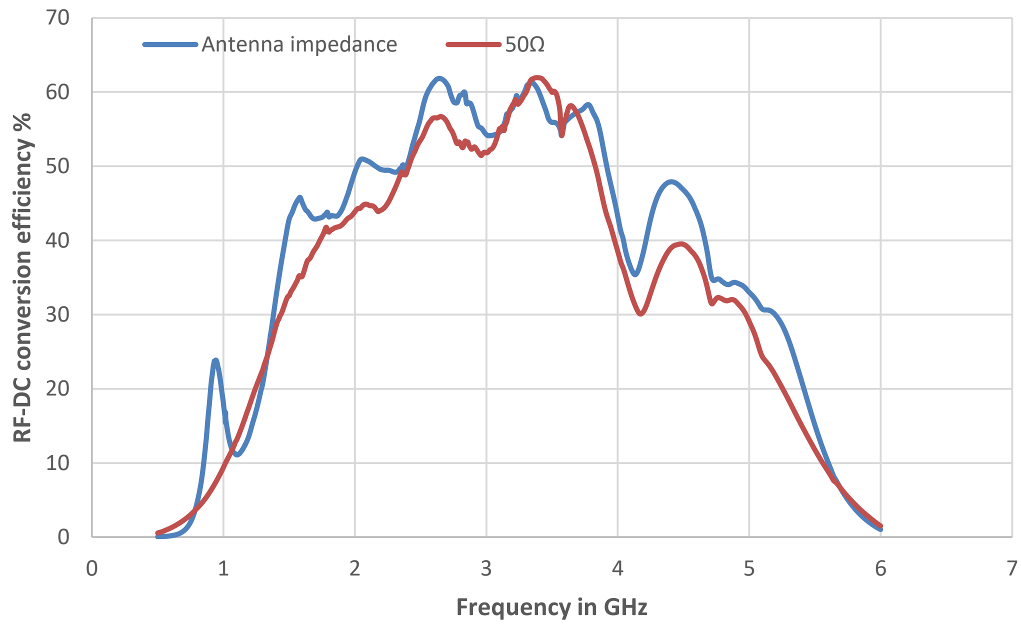


Figure 3. 26. The frequency bandwidth for the second proposed rectenna

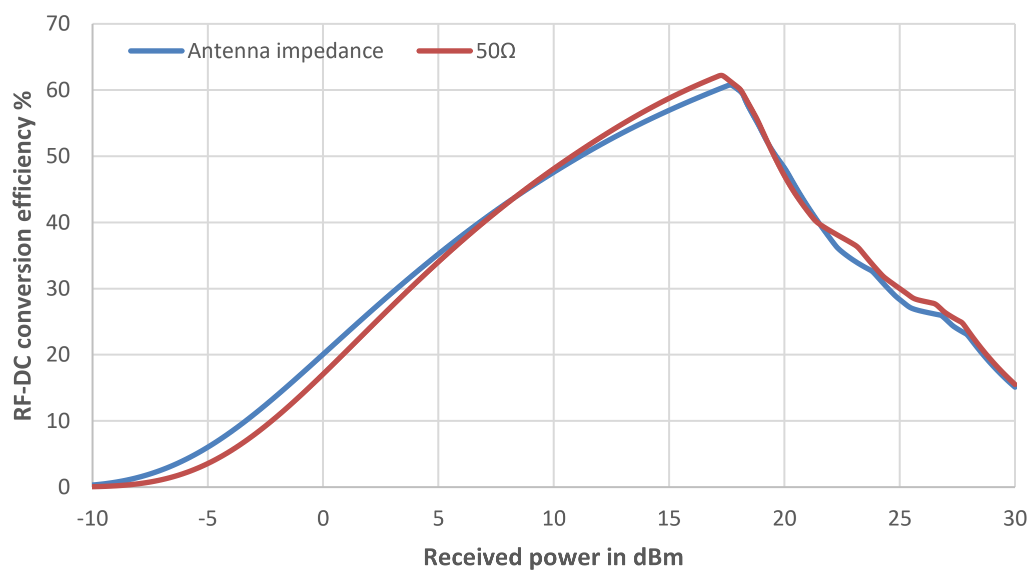


Figure 3.27. The power range for the second proposed rectenna at 3.4GHz

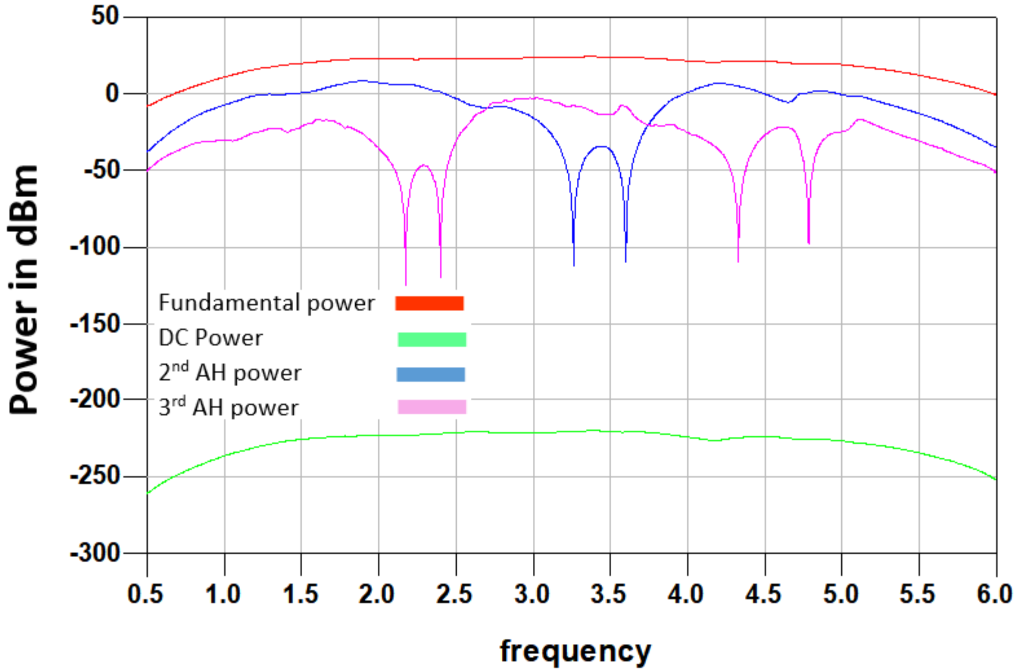


Figure 3.28. The active power of the fundamental frequency band, DC power component and 2nd and 3rd harmonics of the second proposed rectenna.

3.8.3 The Third Proposed Wideband Rectenna

In the previous two sections, a series diode rectifier is discussed. In the second design, we tried to maximize the frequency bandwidth; however, a drop in the overall efficiency is experienced because of the bands' interferences as in Figure 3.28. The voltage doubler rectifier circuit is proposed here as a solution to overcome the interferences between the AH and the fundamental frequency bands. The voltage doubler rectifier circuit will eliminate the second AH as discussed in section 3.5.8 in Figure 3.13. Figure 3.29 shows the block diagram of the proposed rectenna. It is operating from 0.5 to 5.6 GHz with 80% maximum efficiency at 0.668GHz when the received power is 16.7dBm As a result, the proposed rectenna is harvesting the electromagnetic energy in the entire HSMS2860 diode's frequency bandwidth. Figure 3.30 and Figure 3.31 are showing the variation of the RF-DC conversion efficiency versus the frequency and the received power level respectively.

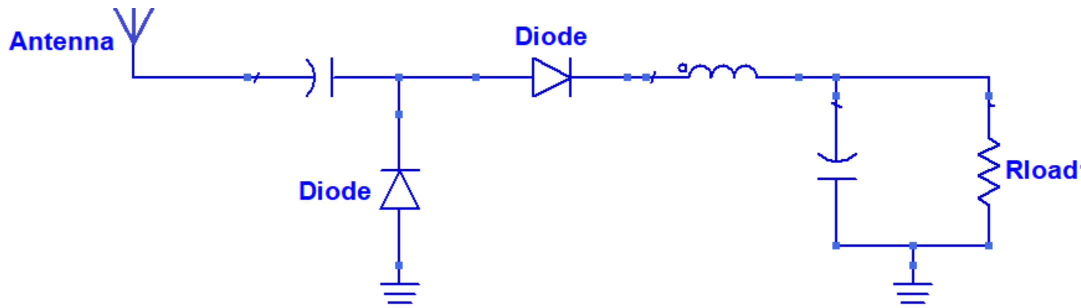


Figure 3.29. Block diagram for the third proposed wideband rectenna

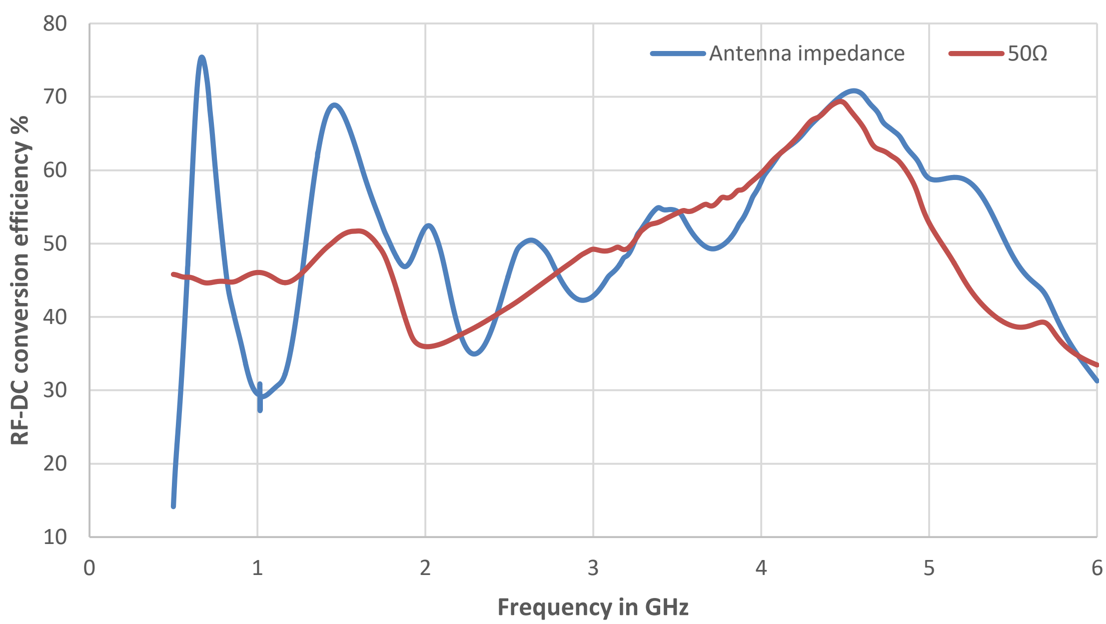


Figure 3.30. The frequency bandwidth for the third proposed rectenna

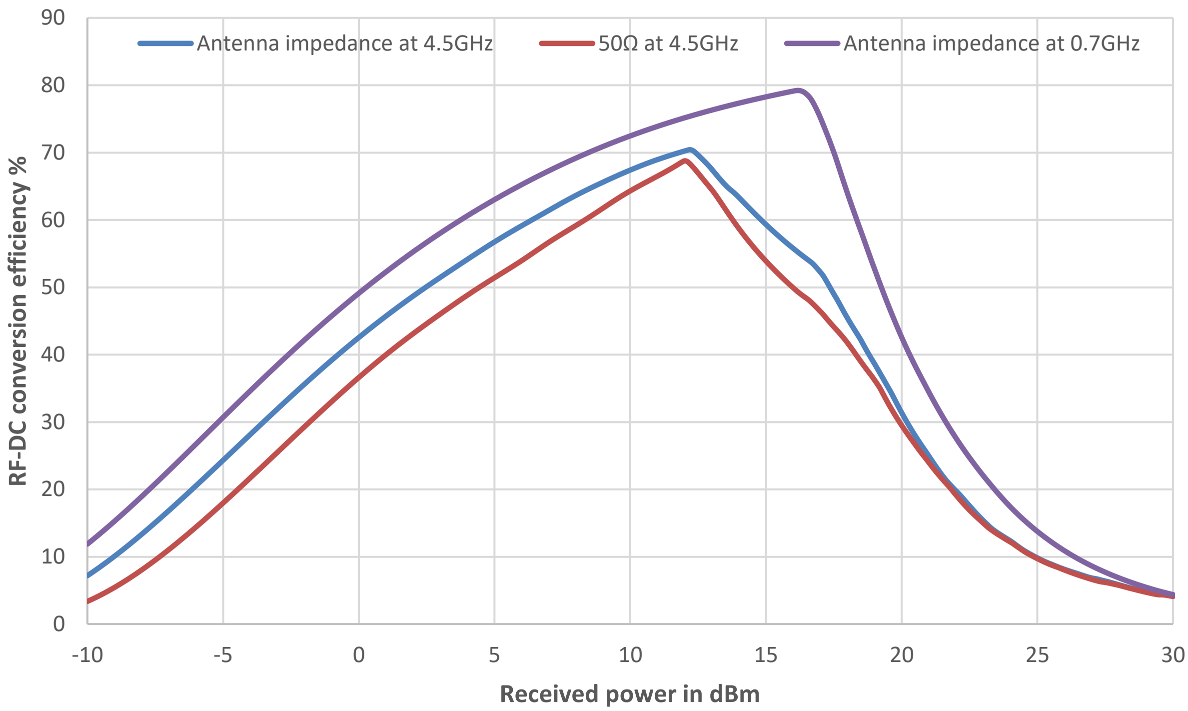


Figure 3.31. The power range for the third proposed rectenna

Chapter 4
Fabrication and Measurement

4.1 Introduction

This chapter presents the fabrication and the measurement for the proposed wideband devices. Furthermore, comparing the simulation and measurement results is provided. The results is showing a promising results which consider as the best comparing to the literature. The used substrate is RO5880 due to its relatively constant characteristics over wideband of frequency with dielectric constant $\varepsilon_r = 2.2$, tangent loss tan δ = 0.0004, and thickness of 0.787 mm.

4.2 Receiving Antenna

The proposed receiving antenna has been shown in Figure 3.3. The measured S11 is illustrated in Figure 4.1. It is measured using the VNA (Vector Network Analyzer). The measurement results showing a good agreement with the simulation results.

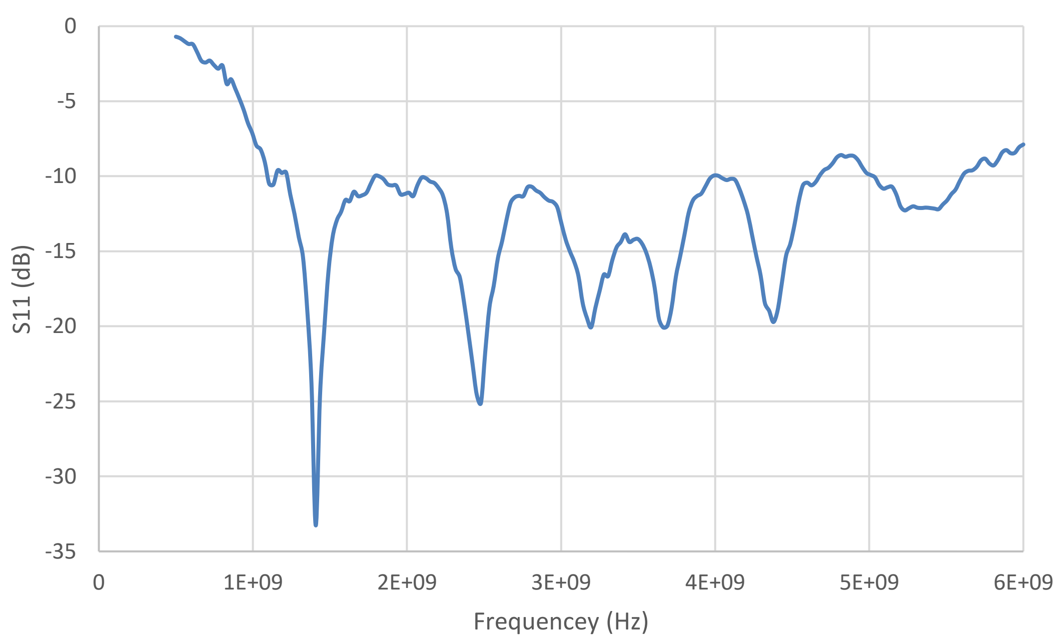


Figure 4. 1.The measurement reflection coefficient of the antenna in Figure 3.3

4.3 The Proposed Wideband Rectennas

This section presents the measurements of the rectennas in Figure 3.24 and Figure 3.28. In this measurement, the signal generator with 50 impedance is used to represent the receiving antenna. It is connected directly to the rectifier circuit. Then, the frequency and input power have been swept over the interested band.

Firstly, for the rectenna illustrated in Figure 3.24. When the receiving power is fixed on 18 dBm, the frequency swept and the output power across the DC load resistor has been measured at different points in the spectrum. The result is showing in Figure 4.2, which indicates good agreement between the measurement and simulation. Furthermore, in Figure 4.3 the variation of the RF-DC efficiency with respect to the received power level is measured. Also, good agreement with the simulation results has been achieved.

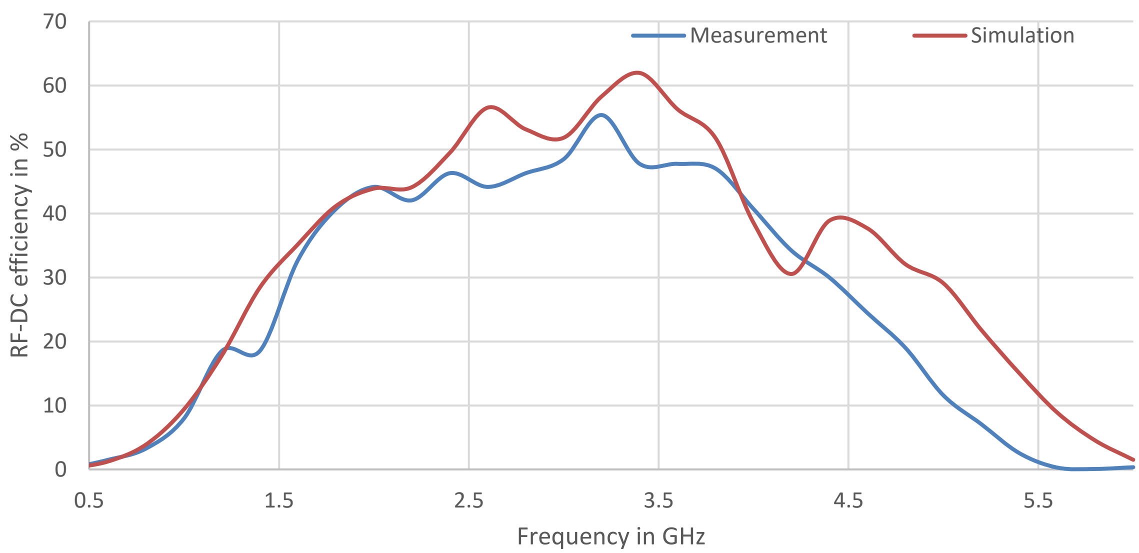


Figure 4.2. The measurement of RF-DC efficiency of the rectenna in Figure 3.24

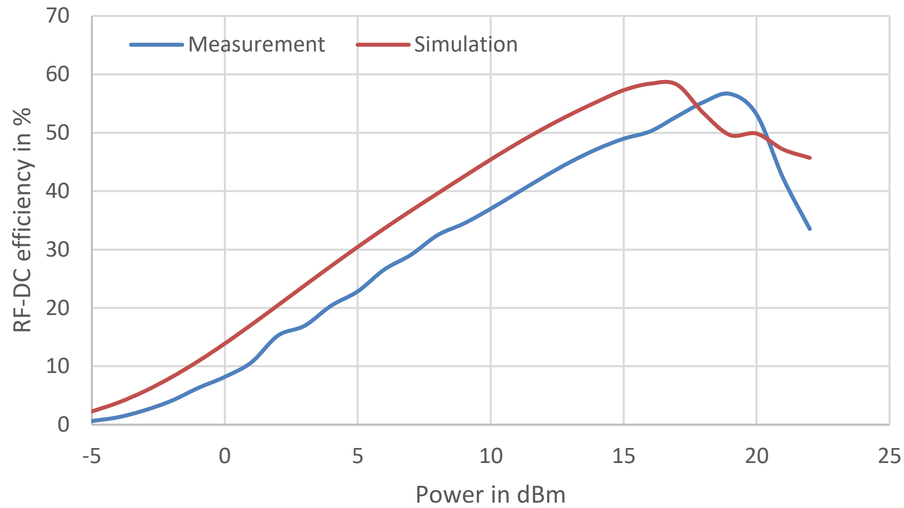


Figure 4.3. The measurement RF-DC efficiency with respect to the received power level

Secondly, the measurements steps of the previous rectenna has been followed to evaluate the rectenna performance in Figure 3.28. When the received power specified as 16dBm, the variation of the RF-DC efficiency with respect to the frequency is showing in Figure 4.4. On the other hand, Figure 4.5 is illustrating the variation of the RF-DC efficiency, when the frequency is 1.8 GHz. The result is very promising since it verifies the possibility to operate in the whole diode bandwidth. However, there is a disagreement in the high frequency measurement comparing to the simulation results in Figure 3.29, which will discussed in the next section.

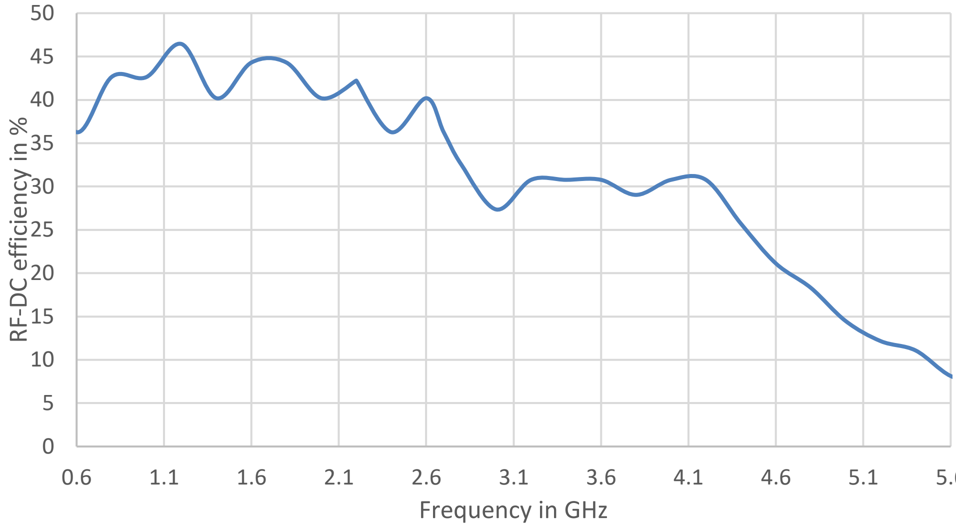


Figure 4.4. The measured RF-DC efficiency with respect to the frequency

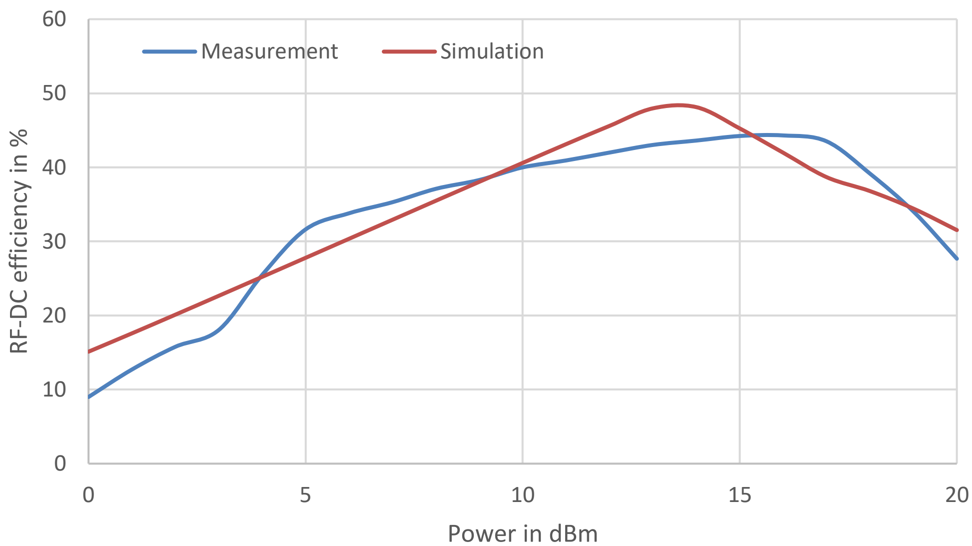


Figure 4.5. The measured RF-DC efficiency with respect to the received power level

4.4 Discussion and Conclusion

The disagreement in the high frequency measurement of the second design that showing in Figure 4.4, can be a consequence of one of the following

1. Diode Model
2. Harmonic Balance Simulation

Since the first rectenna design presents a good agreement with the measurement results, and because the same diode model has been used in both designs. This can be consider as an indication of the right model of the diode. Furthermore, to verify this point the rectenna has been designed in the CST simulator, which used the harmonic balance simulation. Different diode model than the one used in the ADS has been inserted to the CST. Then, the output power across the DC load resistor is simulated, which shows good agreement between the ADS and CST as in Figure 4.6. This observation leads to conclude that the disagreement is resulting from the HB simulation. Professor Michael in [66] states that as the non-linear elements increased in the circuit, the efficient of the HB will be affected. And by referring to the circuits in Figure 3.24 and Figure 3.28 they are half wave rectifier (with one diode) and voltage doubler (with two diodes) respectively. Then, simulating the rectenna using the PSS (Periodic Steady-State) will be more suitable for the circuits with high number of diodes especially in the high frequencies.

Chapter 5
Conclusion and Future Work

5.1 Conclusion

In this thesis, a literature review for the microwave power transfer system was presented. Then, detailed study of the rectenna system and its elements were provided. Furthermore, the techniques to provide wideband rectenna and its related harmonics were illustrated. A new perspective of the rectenna's harmonics was introduced and studied to achieve better understanding of its fact. In addition, useful definition of the rectenna's bandwidth was presented to evaluate the wideband rectenna performance which consider the losses associated with the diode and guarantee the efficient of the designed rectenna performance over the identified bandwidth. Also, different rectennas design were simulated, fabricated, and investigated. The results prove the possibility of designing a rectenna that covers the whole diode bandwidth with acceptable RF-DC efficiency.

5.2 Future Work

The following points are indicating possible future research directions:

- Provide low power and wideband rectenna operating in the ambient power level
- Implement a diode with wider bandwidth characteristics in order to extend the bandwidth
- Investigate different rectifier topologies such as the full wave and bridge rectifiers.
- Simulate the rectenna system using the PSS (Periodic Steady-State) method

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