Design and Analysis of a Compact Dual-Band Printed Rectenna Circuit at WiFi and GSM Frequencies for Microwave Power Transmission

Ahmed Abdul-Kadhem Salih[1,a)] , Abdulkareem S.Abdullah[2,b)]

[1]*Computer Technology Engineering Department, College of Information Technology, Unversity of Imam'Jafer AL-Sadiq, Nassiriya, Iraq*
[2]*Department of Electrical Engineering, College of Engineering, University of Basrah, Basrah, Iraq*

[a)] Corresponding author: ahmed.abd-alkadhim@sadiq.edu.iq
[b)] abdulkareem.abdullah@uobasrah.edu.iq

ABSTRACT: In this paper, a dual-band printed rectenna of compact size (38×24) mm^2 has been designed and analyzed to work at GSM frequency of 900 MHz and WiFi frequency of 2.4 GHz for wireless power transmission. The purpose of this design is to harvest energy at two different frequencies to increase the probability of receiving power from ambient field. The antenna part of this rectenna is printed on FR4 substrate and has the shape of meander line with two arms for double-band operation. The rectifier part of this rectenna consisted of impedance matching network, AC-to-DC conversion circuit and a DC filter. The design and simulation results of this rectenna have been done with the help of CST 2019 and ADS 2018 software packages. At a received input power of -30 dBm and a load resistance of 1900 Ω, the maximum conversion efficiencies obtained by this rectenna at frequencies of 900 MHz and 2.4 GHz are found as 23% and 42% respectively.

Keyword: Rectenna, HSMS-282B Schottky diode, microwave power transmission, conversion efficiency, patch antenna

INTERODUCTION

A rectenna circuit (antenna + rectifier) is one of the applications of converting the electromagnetic energy to direct current (DC) power [1]. A rectenna is used in systems of wireless power transmission in which the power is transmitted by radio waves. A circuit of simple rectenna consists of antenna with radio-frequency (RF) diode connected with it. The RF diode converts microwave energy to DC power and provides it to the load. Schottky diode is mostly used as a rectifier because it has less voltage drop and high speed as well as less power loss due to conduction and switching [2]. A large rectenna circuit contains array, which has many dipole antennas to increase the ambient receiving power, convert it to DC power and saving for use in various applications. Figure 1 represents general block diagram of rectenna. It consists of receiving antenna, impedance matching network, rectifier and DC pass filter. The output voltage of rectenna is fed to the load resistance [3].

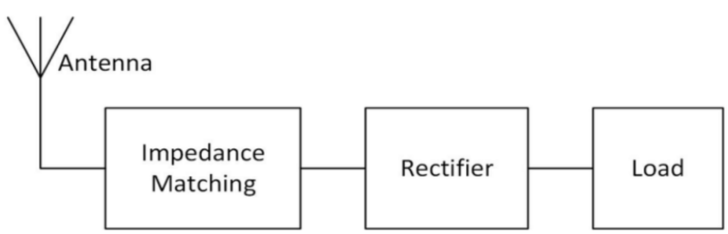

FIGURE 1. Block diagram of a rectenna

In this paper, a dual-band printed rectenna that works at WiFi frequency of 2.4 GHz and GSM frequency of 900 MHz is intended to be designed and analyzed using Computer Simulation Technology (CST) software package [4] and Advance Design System (ADS) software package [5]. The design procedure of the antenna part of this rectenna is provided. The necessary steps to design its rectifier part are presented, and conclusion that is extracted by rectenna performance is also declared.

ANTENNA DESIGN

In this paper, a monopole antenna is proposed that has the shape of meander line with two arms for double-band operation as shown in Figure 2. The first arm is a thin printed meander line used for 900 MHz operation and the second arm is a thick printed meander line used for 2.4 GHz operation. This antenna is designed with the help of CST software package.

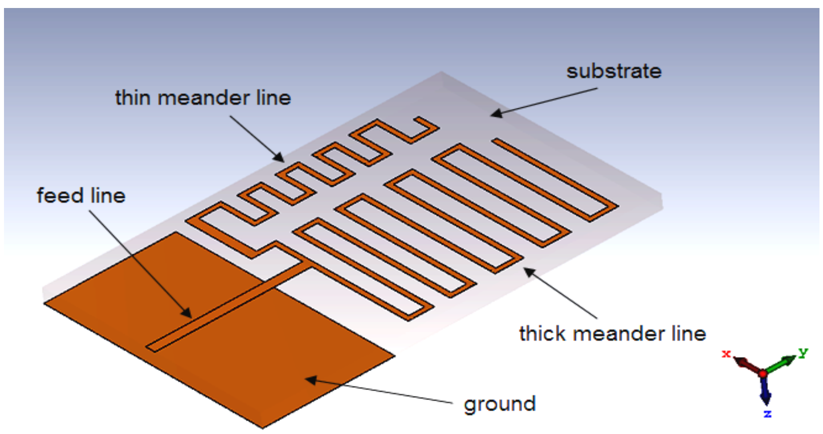

FIGURE 2. Double-band printed meander line patch antenna

An FR4 substrate is used to design this antenna, with dielectric constant ε_r=4.4, substrate height h=1.6mm, and loss tangent of 0.004. The aim of this design is to provide:

1. Specific frequencies of 900 MHz and 2.4 GHz,
2. VSWR $\leq$ 2,
3. Reflection coefficient that is less than -10 dB.

All dimensions of thick and thin meander lines, shown in Figure 3 have effect on reflection coefficient (S_{11}). The optimum values for these dimensions have been obtained by parametric study as shown in Table 1.

There are some analyses that should be done to identify that the antenna satisfy the required results at the desired frequencies of 900 MHz and 2.4 GHz, such as VSWR, reflection coefficient, gain and radiation patterns.

1. VSWR

To transmit a maximum energy from transmitter to the antenna by the feeder line, the feeder line must be matched to the antenna. To achieve this, the range of VSWR must be between 1 and 2 at the designed frequency of antenna [6]. Figure 4 shows the response of VSWR against frequency. The VSWR values of the double-band printed meander line patch antenna at 900 MHz and 2.4 GHz are found as 1.5163 and 1.2513 respectively.

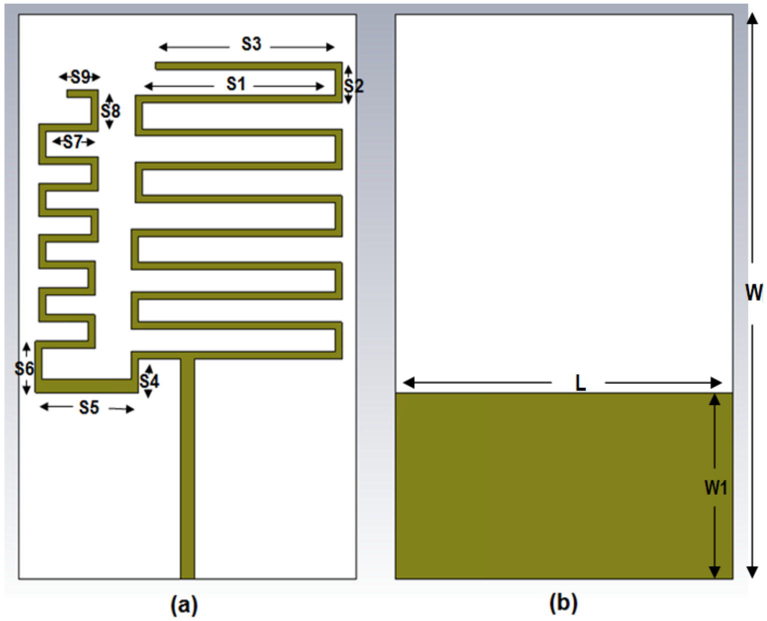

FIGURE 3. Dimensions of the double-band printed meander line patch antenna (a) Top view (b) Back view

TABLE 1. The optimum design dimensions of double-band printed meander line patch antenna.

Ground plan size (W_1 x L)	12.5×24 mm^2
Substrate size (W x L)	38×24 mm^2
Feed line	15× 1 mm^2
Conductor thickness	0.035 mm(Copper)
Size of S1 and 8 equivalent parts in patch	15× 1 mm^2
Size of S2 and 8 equivalent parts in patch	2× 0.5 mm^2
Size of S3	13.25× 0.5 mm^2
Size of S4	2.5× 0.5 mm^2
Size of S5	7.1 × 0.9 mm^2
Size of S6	3 × 0.5 mm^2
Size of S7 and 8 equivalent parts in patch	4× 0.5 mm^2
Size of S8 and 8 equivalent parts in patch	2 × 0.5 mm^2
Size of S9	2.25 × 0.5 mm^2

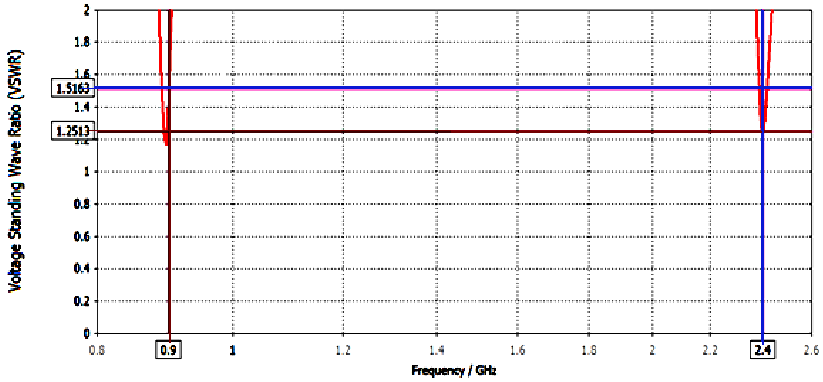

FIGURE 4. VSWR vs. frequency of the double-band printed meander line patch antenna

2. Reflection Coefficient

Reflection coefficient represents the power reflected back to the source (P_r) divided by the power transmitted from the source (P_i). By calculating the reflection coefficient, it is possible to determine the loss of the power when transmitting from a transmitter to an antenna [7]. Figure 5 shows the values of the reflection coefficient (in dB) with respect to frequency. The values of reflection coefficient of the double-band printed meander line patch antenna at 900 MHz and 2.4 GHz are found as -22.228 dB and -19.413 dB respectively as shown in Figure 5.

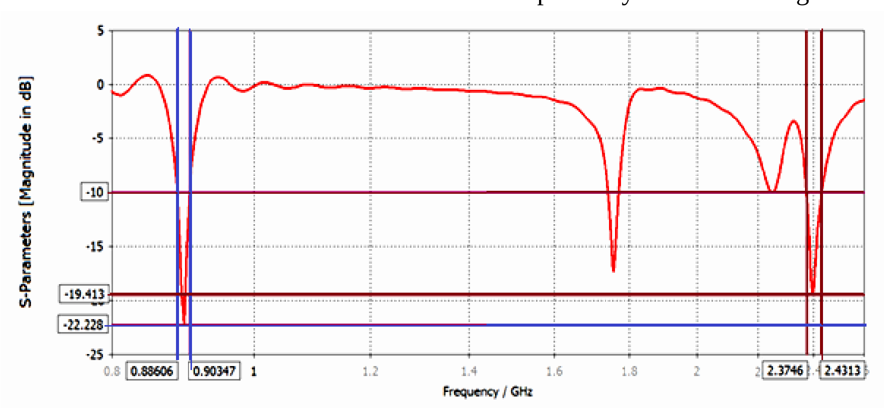

FIGURE 5. VSWR of the double-band printed meander line patch antenna at 2.4GHz & 900MHz

3. Gain

The antenna gain is very important to calculat the rectenna efficincy because it determines the receiving power according to Friis Formula [8]. The antenna gain values against frequency are shown in Figure 6. Gain values of -5.7877 dB and 0.41214 dB are found at 900 MHz and 2.4 GHz respectively.

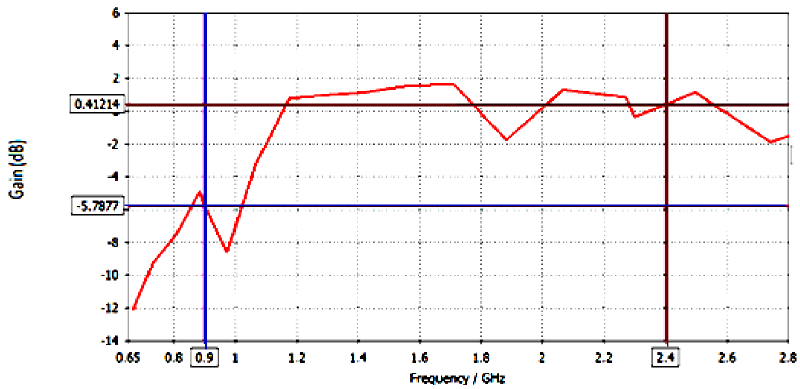

FIGURE 6. Gain vs. frequency of the single-band printed question mark patch antenna

4. Radiation pattern

The E-plane pattens of the double-band printed meander line patch antenna at 900 MHz and 2.4 GHz are shown in Figure 7. The directions of main lobes are found at -6^o and 8^o respectively for the above two frequencies.

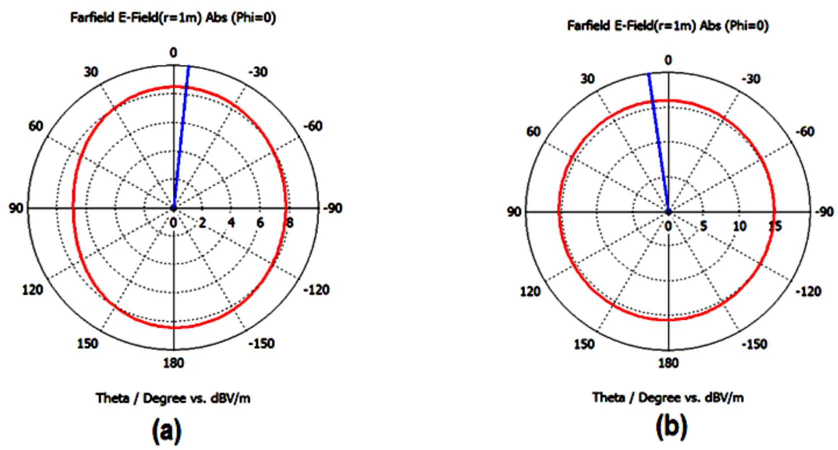

FIGURE 7. E-plane pattern of the double-band printed meander line patch antenna at (a) 900 MHz (b) 2.4 GHz

The H-plane patterns of the double-band printed meander line patch antenna at 900 MHz and 2.4 GHz are shown in Figure 8. The 3D radiation patterns of this antenna at 900 MHz and 2.4 GHz are shown in Figure 9 and Figure 10 respectively.

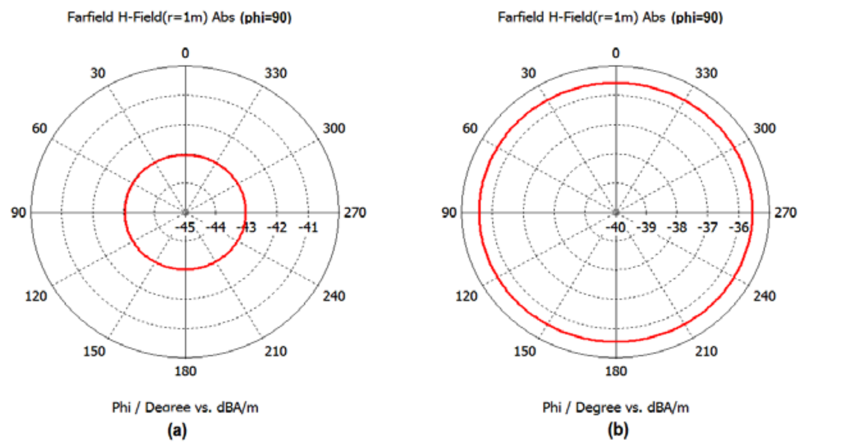

FIGURE 8. H-plane pattern of the double-band printed meander line patch antenna at (a) 900 MHz (b) 2.4 GHz

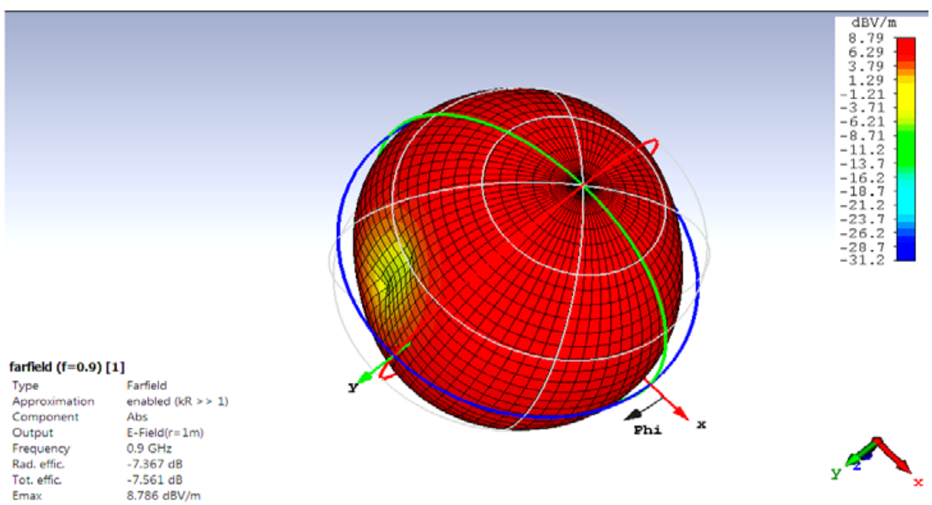

FIGURE 9. 3D radiation pattern of the double-band printed meander line patch antenna at 900 MHz

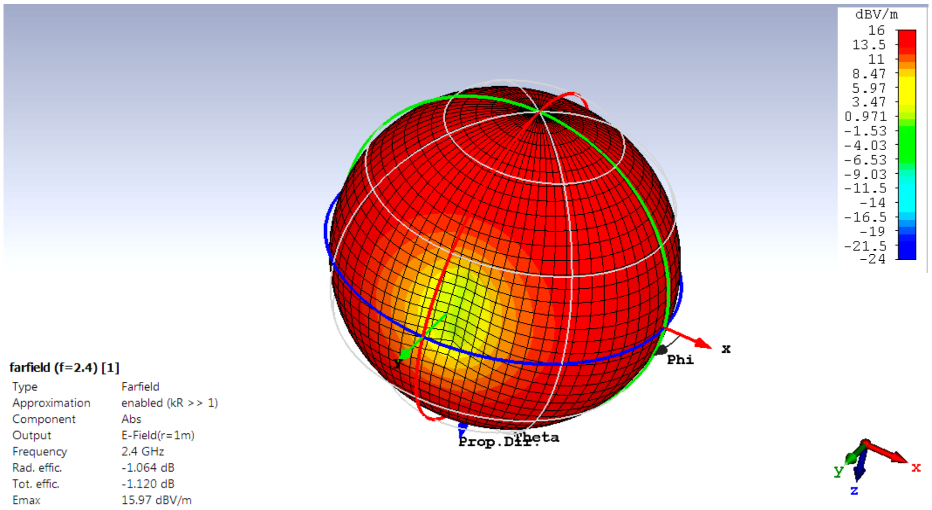

FIGURE 10. 3D radiation pattern of the double-band printed meander line patch antenna at 2.4 GHz

RECTIFIER CIRCUIT DESIGN

The structure of the classical double-band rectenna is designed by ADS software 2018 and it works at frequencies of GSM 900 MHz and WiFi 2.4 GHz as shown in Figure 11. A dual-band rectifier circuit contains two impedance matching networks (IMNs), where each one consists of two capacitors and one inductor. The first IMN (L1, C2, C4) is connected between the antenna and the two HSMS-282B Schottky diodes (D1, D2) for matching at 900 MHz. The second IMN (L2, C1, and C6) is connected between the antenna and the two HSMS-282B Schottky diodes (D3, D4) for matching at 2.4GHz. RF signal at 900 MHz is rectified by HSMS-282B diodes D1 and D2, while RF signal at 2.4 GHz is rectified by HSMS-282B diodes D3 and D4 .Then two capacitors (C3, C5) are used as a DC filter. The optimum values for elements of the two IMNs, DC filter and load have been obtained via a parametric study and tabulated as shown in Table 2.

TABLE 2. Optimum values of double-band rectifier.

Component Name	Value	Component Name	Value
L1	34 nH	L2	2.68 nH
C1	0.9 pF	C2	26 pF
C3	0.24 pF	C4	5.5 pF
C5	100 pF	C6	30 pF
R	1900 Ω		

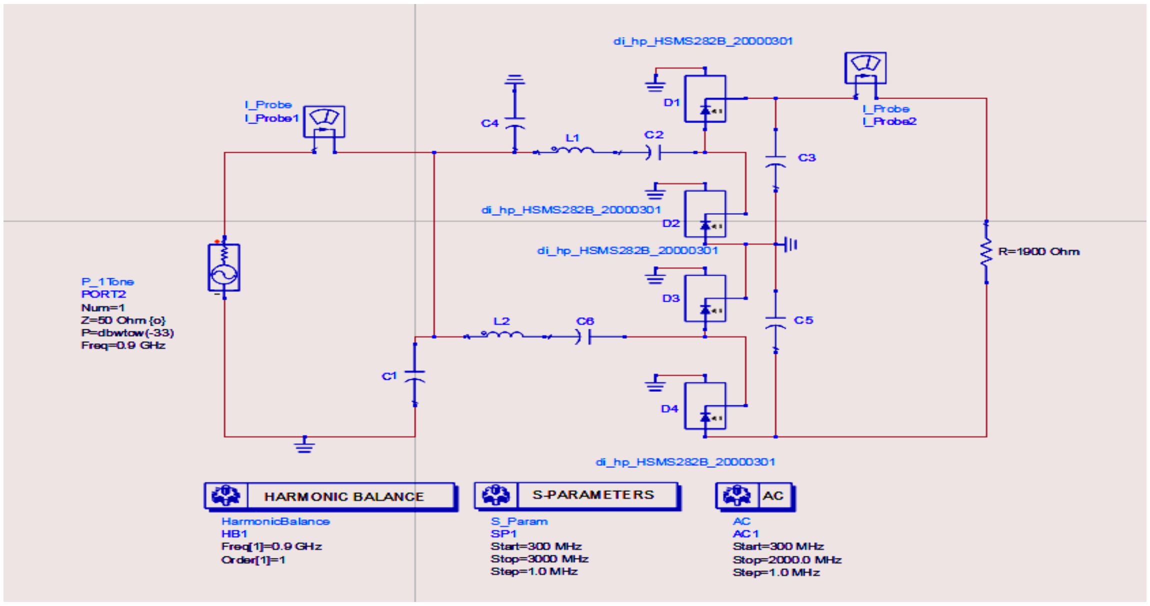

FIGURE 11. The double-band rectifier designed by Advance Design System (ADS) software package.

The reflection coefficient values of the double-band rectifier circuit are found as -16.4 dB at GSM-900 MHz and -15 dB at WiFi 2.4 GHz as shown in Figure 12.

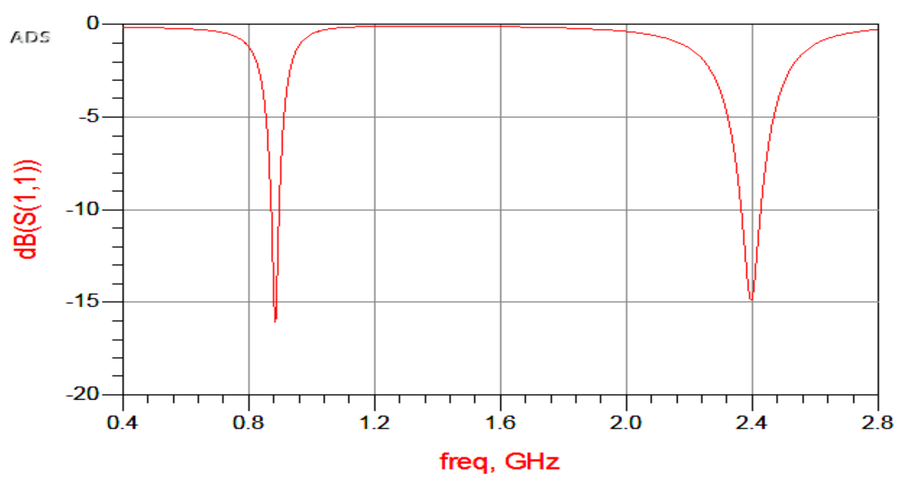

FIGURE 12. Reflection coefficient vs. frequency of the double-band rectifier circuit

Simulated conversion efficiency as a function of input power for frequency GSM-900 MHz and WiFi 2.4 GHz for 1900 Ω is depicted in Figure 13. The maximum conversion efficiency for frequency 2.4 GHz is found as 42% at an input power of -30 dBm, which can easily be received by antenna. The maximum conversion efficiency for the frequency 900 MHz is found as 38% at an input power of 40 dBm, which is difficult to be received by the antenna. However, for an input power of -30 dBm, the maximum conversion efficiency at 900 MHz is found as 23%. Therefore, the best input power of the double-band rectifier is considered as -30 dBm for both frequencies and the conversion efficiencies become as 42% and 23% for the frequencies 2.4 GHz and 900 MHz respectively.

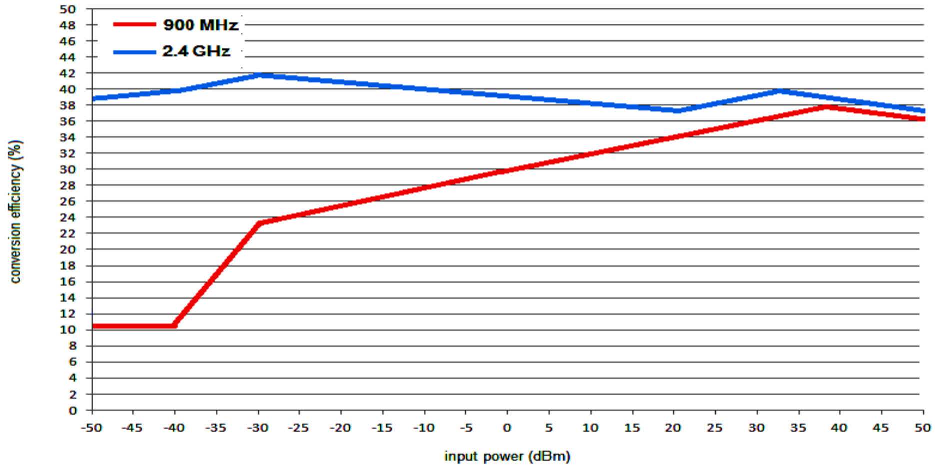

FIGURE 13. Simulation conversion efficiencies vs. input power with 1900 Ω load at 900 MHz and 2.4 GHz

Figure 14 shows variation of simulated conversion efficiency with frequency for the double-band rectifier when the input power is -30 dBm.

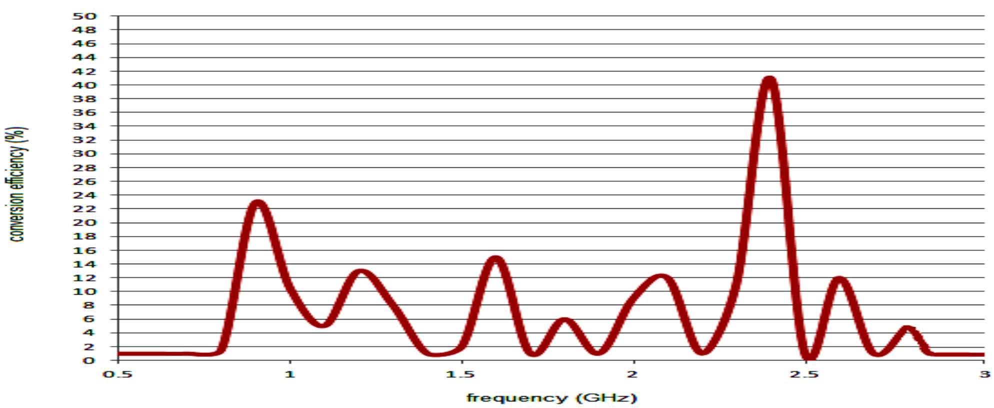

FIGURE 14. Variation of conversion efficiency vs. frequency of rectifying circuit at an input power of - 30 dBm and load resistance of 1900 Ω

The Double-band printed rectenna is compared with some certified researches regarding frequency, load, efficiency, received power and the complexity of design, and is shown in Table 3. From this table, it can be concluded that:

- The design is simple and not complicated.
- The conversion efficiency is high. A value of 42% at a frequency 2.4 GHz is obtained.
- The input power is very small (-30 dBm) that gives a maximum conversion efficiency at a frequency of 2.4 GHz. However, it is relatively large at 900 MHz.

TABLE 3. Comparison of the double-band printed rectenna with related works.

Reference	Frequency	Load	Efficiency	Received Power	Complexity of design
our design	900 MHz 2.4 GHz	1900 Ω	23% & 42%	-30 dBm	Medium
Ref. [9]	900 MHz 1800 MHz	8200 Ω	30.4% & 20%	-20 dBm	Difficult
Ref. [10]	915 MHz 2.45 GHz	270 Ω	12.5% & 12.5%	-19.5 dBm & -25 dBm	Difficult
Ref. [11]	900 MHz 2.45 GHz	1000 Ω	27% & 28%	-20 dBm	Medium
Ref. [12] (2017)	900 MHz 800 MHz	5000 Ω	41% & 30%	-10 dBm	Difficult
Ref. [13]	800 MHz 900 MHz	(20-30) KΩ	30 % & 30%	0 dBm	Difficult

CONCLUSION

A rectenna is a modern technique for harvesting the microwave energy that available in ambient. In this paper, a dual-band printed rectenna that works at GSM frequency of 900MHz and WiFi frequency of 2.4 GHz has been designed and analyzed. The receiving antenna for the RF signal is composed of a monopole that has a shape of meander line with two arms for double-band operation. The overall dimension of this antenna is (38 x 24) mm^2. A simple rectifier circuit that consists of impedance matching network is used to transfer the maximum energy from the receiving antenna to AC-to-DC converter (Schottky diode-HSMS-282B) and DC filter. With a load of 1900 Ω, the maximum conversion efficiency obtained by this rectenna at a frequency 2.4 GHz is found as 42% at an input power of -30 dBm, which can easily be received by antenna. The corresponding maximum conversion efficiency for the frequency 900 MHz is found as 38% at an input power of 40 dBm, which is difficult to be received by the antenna. Therefore, the best input power of the double-band rectifier is considered as -30 dBm, and as a result the maximum conversion efficiency at 900 MHz is then found as 23%.

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