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Improved design and performance of the global rectenna system for wireless power transmission applications around 2.45 GHz

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ABSTRACT

This work proposes a new conception of the global microstrip rectenna system operating around 2.45 GHz. This improved rectenna system associates a receiving antenna with a rectifier circuit. This rectenna is printed on an FR4 substrate. The proposed antenna is a 1×4 microstrip antenna patch array with pentagonal patches using the defective ground structure method and operates with circular polarization. To show the effectiveness of this array, the results obtained by the computer simulation technology microwave studio (CST MWS) software prove that this array is good in terms of high gain, high directivity, high efficiency, wideband, small volume, and well-adaptation, and all these results are confirmed by another solver high-frequency structure simulator (HFSS). The improved rectifier is a microstrip rectifier that uses an HSMS2852 Schottky diode by using a series topology. The effectiveness of this rectifier is proved by the simulation results using advanced design system (ADS) software in terms of well-matching input impedance, high efficiency, and important output direct current (DC) voltage value. The proposed rectenna system is more efficient compared with the existing works and is very appropriate for several applications of wireless power transmission to power supply electronic instruments in various fields cleanly on our planet.

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1. INTRODUCTION

The progress of several electronic devices has continued to appear over the last few years. Recently, the development of these devices serves to miniaturize their volumes, make their weights light, make them multifunctional, and ensure their autonomous energy [1], [2]. The big challenge is focused on powering devices environmentally cleanly, without wires [3] and batteries. Wireless power transmission (WPT) is an effective strategy for powering wireless devices. WPT is effective in areas where wires and batteries are inaccessible, and it is a strategy that serves to produce electricity in a non-polluting way and leads to preserving the primary resources of fossil and nuclear power plants. WPT system is decomposed into a transmission part and a reception part called the rectenna system [4], [5]. The first part involves converting the direct current (DC) to microwave power. The second part consists of converting the microwave-to-DC which is useable energy to meet the needs in terms of power supply for many devices in several areas such as domestic, space, medical, and military.

The most attractive system in the field of WPT is the rectenna system as illustrated in Figure 1. A rectenna system, which means a rectifying antenna, combines a receiving antenna and a rectifying circuit. The most recently used technology for rectenna systems is the microstrip technology thanks to low weight, small volume occupancy, ease of integration, low manufacturing cost, elimination of wires and cables, and low power generation without batteries. The rectenna system is divided into five blocks as shown in Figure 1 [6], [7]. The rectenna system contains the microstrip receiving antenna and a radiofrequency-to-direct current (RF-DC) conversion circuit [1]. The interest of this paper is to investigate the reception part of WPT which is called the rectenna.

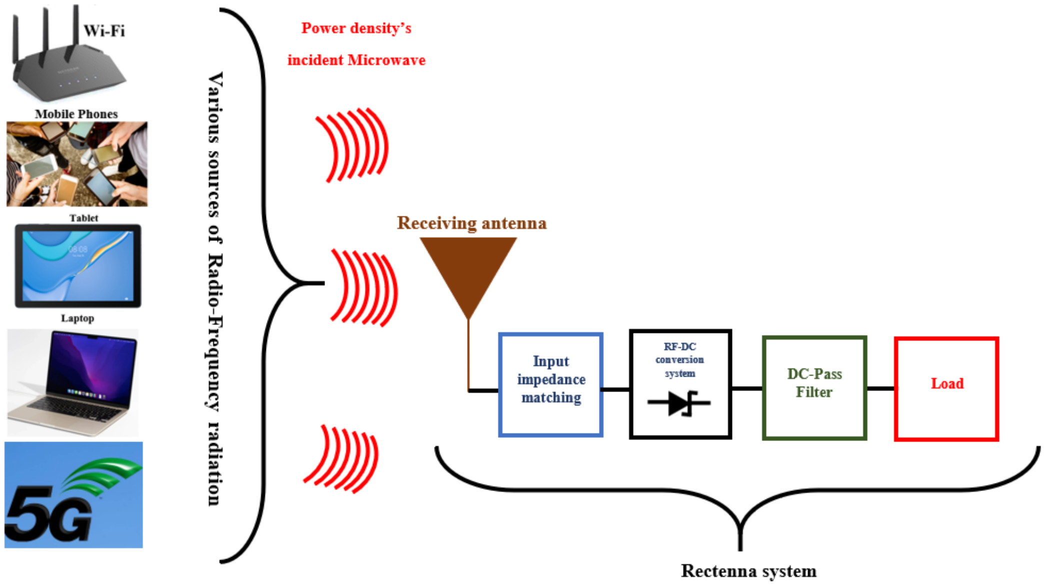

Figure 1. The rectenna operating principle

In the literature, the existing works focus on the study of microstrip patch antenna (MPA) without considering the rectification circuit [1], [8]. These works are used to increase the performance of the microstrip receiving antenna in terms of gain, directivity, bandwidth, overall size, and adaptation to the port by choosing the shape of the patch [1], [9], the operating frequency (such as 2.45 GHz [1] and 5.8 GHz [10]), the characteristics of the substrate, and the type of polarization (such as linear polarization [11], circular polarization [12], [13]). Other works focus on studying the rectifying circuit without considering the antenna [14]. These works serve to enhance the output voltage value and RF-DC efficiency by choosing the type of diode used and its topology (series [15], doubler [16], [17], shunt [18], and multiplier [14]).

The strong contribution of this paper is to investigate the complete rectenna system by analyzing its proposed MPA and its proposed microstrip rectification circuit and then by designing and simulating them. The whole rectenna is operated at 2.45 GHz in the industrial, scientific, and medical (ISM) band and printed on FR4-Epoxy substrate with a dielectric constant of 4.4, thickness of 1.58 mm, and tangent of losses of 0.025. The improved antenna is an MPA network based on the defective ground structure (DGS) method [19], which has four pentagonal patches and operates in a circularly polarized way. The proposed RF-to-DC microstrip rectifier circuit uses an HSMS2852 Schottky diode mounted in series topology. The obtained results from the proposed MPA array using computer simulation technology microwave studio (CST MWS) and high-frequency structure simulator (HFSS) software and the simulation results from the proposed rectifier circuit obtained by advanced design system (ADS) software prove that the improved microstrip rectenna system gives good performances, able to power supply the devices without wires (such as sensors, sensors network, wireless actuators, hand lamp, and light-emitting diode (LED) lighting of a football field), and it is suitable for other WPT applications.

The rest of this paper will be divided into three sections. Section 2 analyzes and considers two proposals one for the receiving antenna and the other for the rectifying circuit. Section 3 focuses on the antenna design under CST MWS and HFSS and the rectifier design under ADS followed by their comments that prove their best performances. Section 4 summarizes the strengths points of the proposed overall rectenna system.

2. METHOD

To design a microstrip rectenna system that contains two essential sub-systems which are the MPA and the microstrip rectifier, two necessary steps for this design are the choice of the resonant frequency and the choice of the characteristics of the substrate. The selected frequency is 2.45 GHz in the ISM band thanks to its low atmospheric losses. The selected substrate is an FR4-Epoxy with a dielectric permittivity constant of 4.4, thickness of 1.58 mm, and tangent of losses of 0.025. This selected substrate is the most used material in manufacturing. The proposed MPA array is described in subsection 2.1 and the proposed microstrip RF-DC conversion system is described in subsection 2.2.

2.1. Proposed microstrip patch antenna design

The developed basic element for MPA is a pentagonal radiator element [20], [21] thanks to its ability to operate with an excellent circular polarization way which is fed by a port of 50 ohms and deposed on an FR4-Epoxy substrate. This substrate is deposed on the ground affected by the DGS method to miniaturize the total size of MPA and realize the wideband around 2.45 GHz. The dimensions of the MPA's patch are calculated based on (1) to (3) [22]. Where: W is the patch's width, ε_{reff} is the dielectric effective permittivity, h is the thickness of the substrate, λ is the wavelength, f_r is the resonance frequency, and C is the speed of light in a vacuum. To improve the MPA performances, the MPA array is developed which contains four patches identical to the basic element MPA. This proposed 1×4 MPA array as shown in Figure 2 has good performances that are proven by simulation results given in Section 3 using CST MWS and confirmed by HFSS solver. Figure 2 illustrates the 1×4 MPA array and its optimized dimensions.

$$W = \frac{C}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \tag{2}$$

$$\lambda = \frac{C}{f_r\sqrt{\varepsilon_{reff}}} \tag{3}$$

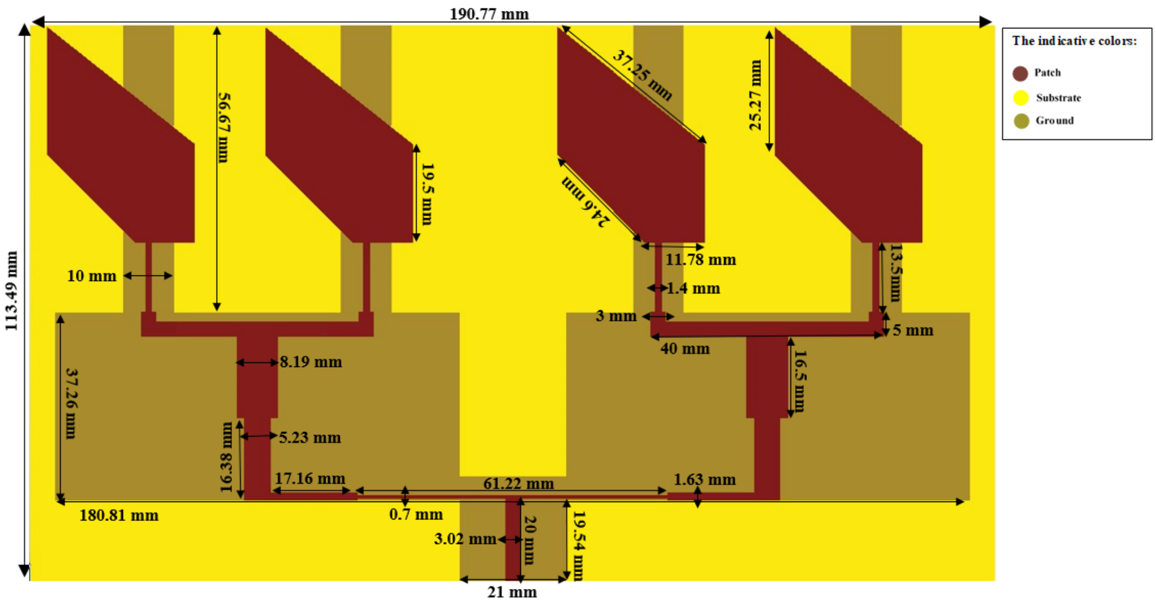

Figure 2. Developed MPA network design containing four patches and using the DGS method

2.2. Proposed microstrip rectifier circuit design

The block diagram depicted in Figure 3 shows the main steps to obtain an effective design of the rectifier circuit. Based on Figure 3, three fundamental steps to obtain an efficient rectifying circuit. The first step is to specify the type of material and its characteristics, the technology of the used diode, and the topology investigated of the used diode. The second step is to make the design including the selected topology of the diode, the selected structures of the input matching circuit, and the DC-pass filter. The last step is to simulate this design and verify if all the results confirm the imposed requirements, if not the optimization process is repeated until the optimal dimensions are reached while satisfying the imposed goals. In this paper, the main goal of the developed RF-DC conversion circuit is to obtain high efficiency and high output DC voltage value at lower incident power. This rectifier uses an HSMS2852 Schottky diode mounted in series topology without using any via-hole connections and any bypass capacitor that can degrade the performance of the rectifier and damage it. This HSMS2852 Schottky diode is selected thanks to its low barrier height, its high saturation current, its ability to give high output DC voltage value, and its high efficiency at low and medium power input. The equivalent linear model of the HSMS2852 Schottky diode is illustrated in Figure 4 [23]. The HSMS2852 Schottky diode's parameters are shown in Table 1 [24].

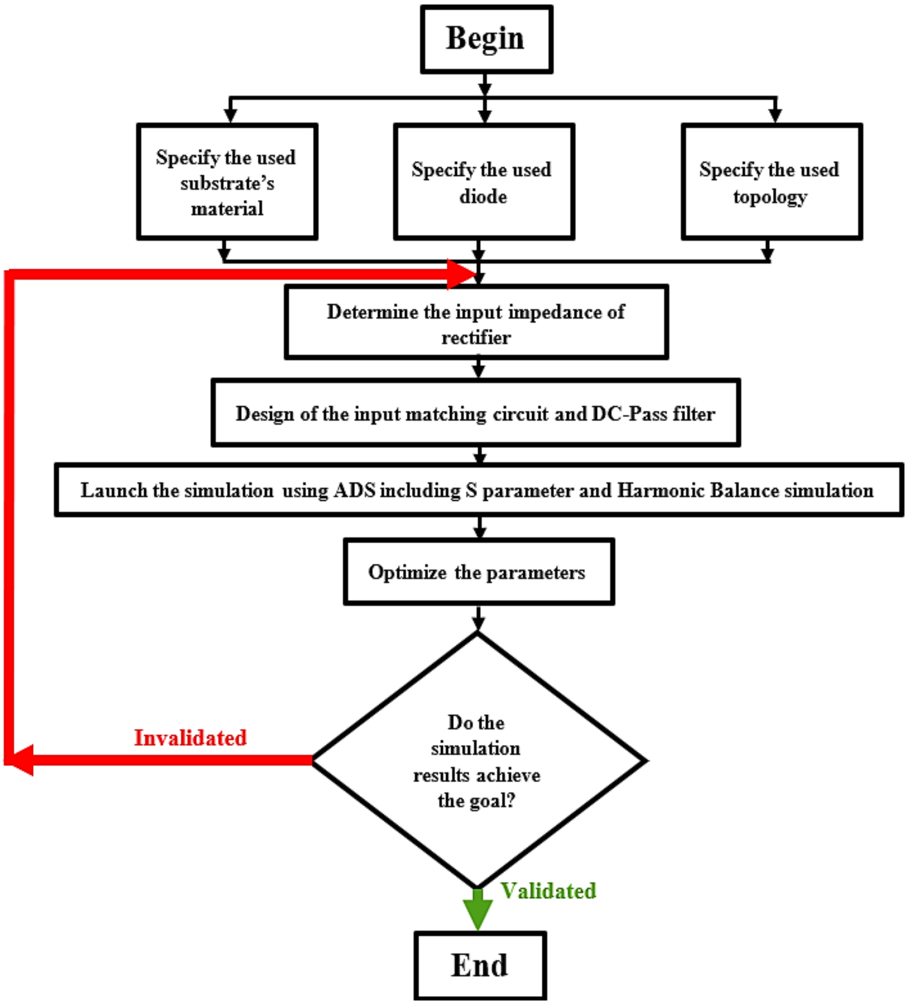

Figure 3. Microstrip rectifier block diagram

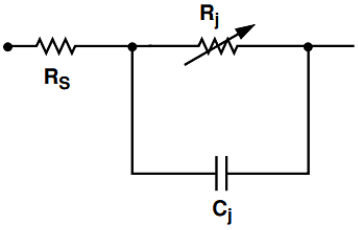

Figure 4. Equivalent linear circuit model

Table 1. HSMS2852 Schottky diode's parameters

Parameter	Value	Unit
Series resistance (R_S)	25	Ω
Junction capacitance (C_j)	0.18	pF
Breakdown voltage (B_V)	3.8	V

The port of 50 ohms schematized in Figure 5 is an RF power generator representing the proposed receiving microstrip antenna as shown in Figure 2. This generator is used to inject P_{RF} power at 2.45 GHz into the rectifying circuit. Figure 5 shows the design of the improved rectifier containing the input matching circuit, HSMS2852 diode, and DC-pass filter. The input matching circuit aims to eliminate the harmonics of higher-order generated by the HSMS2852 and make the adaptation between the rectifier and the antenna at 50 ohms. The DC-pass filter is described by three fan-shaped stubs and transmission lines in series. The objective of the DC-pass filter is to make the adaptation between the rectifier and the load and remove the harmonics generated by the nonlinear behavior of the HSMS2852 Schottky diode. Consequently, this rectifier is more advantageous thanks to its ease of implementation, high efficiency at low and medium power densities, and important output DC voltage value. Equation (4) aims to calculate the RF-DC efficiency of the rectifier [25]. Where η_{RF-DC} is the efficiency, P_{DC} is the power produced at the load, and P_{RF} is the power received at the receiving microstrip antenna. The P_{RF} is computed from the equation of Friis transmission as in (5) where λ is the operating wavelength r is the distance between the transmitting part and receiving antenna, P_T is the transmitted power of the transmitting antenna, G_T and G_R are the gain of the transmitting antenna and the receiving antenna respectively.

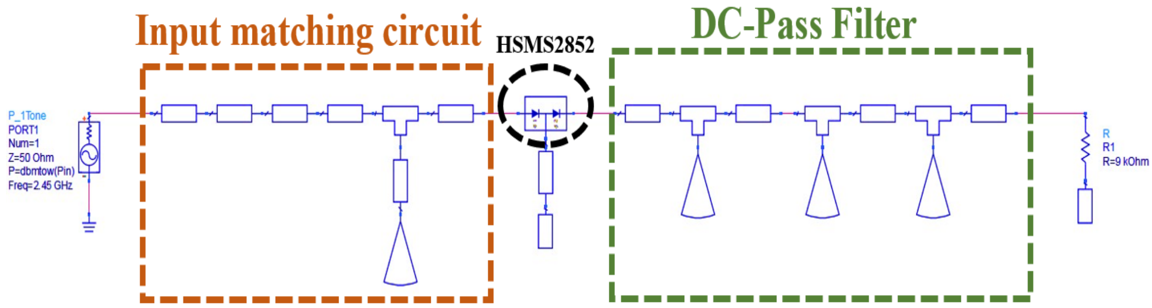

Figure 5. Improved microstrip rectifier circuit design using HSMS2852 Schottky diode

$$\eta_{RF-DC}[\%] = \frac{P_{DC}}{P_{RF}} \times 100 \quad (4)$$

$$P_{RF} = \left(\frac{\lambda}{4\,\pi\,r}\right)^2 \times P_T\, G_T\, G_R \quad (5)$$

3. RESULTS AND DISCUSSION

The effectiveness of the global overview of the improved design of the rectenna system is proved by the simulation results. The major characteristics of the developed receiving microstrip antenna are the coefficient reflection, the axial ratio, the directivity, the gain, and the efficiency. Figure 6 shows the simulation results of these important characteristics to ensure this proposed antenna is very efficient. Figure 6(a) illustrates the curve of the coefficient reflection (S_{11}) which is about -33.54 dB at 2.45 GHz by CST MWS and is about -18.36 dB at 2.45 GHz by HFSS. From these results, this array is well adapted at the port of 50 ohms, is capable of transferring the maximum of the power with low losses and has a wideband of around 2.45 GHz which equals 265.47 MHz. Figure 6(b) shows the axial ratio which equals 1.92 dB at 2.45 GHz by CST MWS and is about 0.29 dB at 2.45 GHz by HFSS. From these results, this array is well functioning in a circular polarization way. Figure 6(c) indicates the value of the directivity which is about 8.17 dBi at 2.45 GHz obtained by CST MWS, and the value of the gain equals 7.94 dBi at 2.45 GHz obtained by CST MWS. Figure 6(d) illustrates the curve of the efficiency of this array. At 2.45 GHz, the efficiency is about 94.83% from Figure 6(d). These results prove that this array is very efficient thanks to its capability to operate with a circular polarization way and its maximum transfer power with low losses.

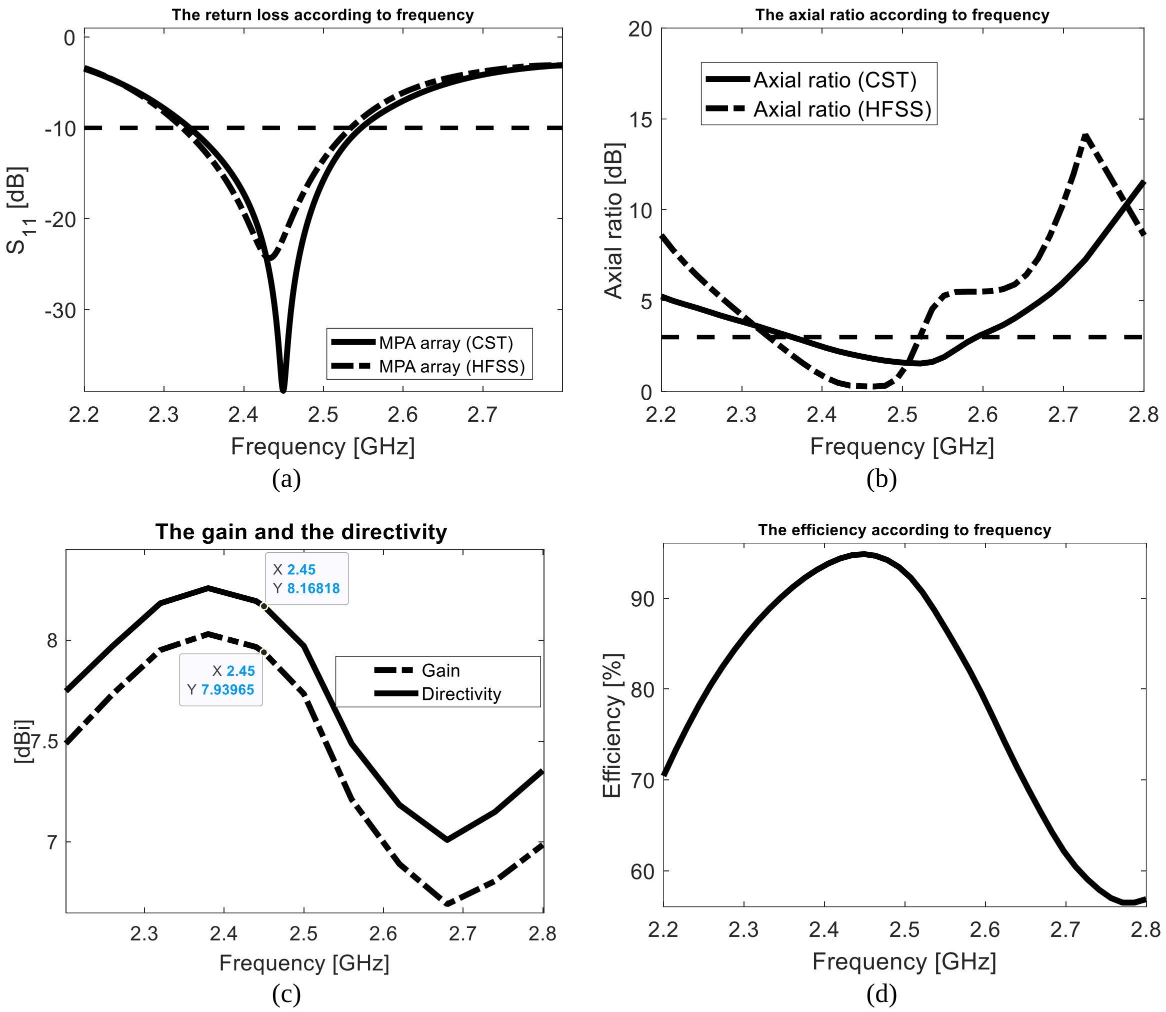

Figure 6. Simulation results for various characteristics of MPA array

Figure 7 illustrates the simulation results of the essential characteristics of the rectifying circuit to prove this proposed rectifier circuit has good performance. Figure 7(a) shows the coefficient reflection according to frequency. From Figure 7(a), at 2.45 GHz, the coefficient reflection equals -26.02 dB. This value explains why this improved rectifier is well-adapted at the port of 50 ohms. Figure 7(b) shows the curve of the return loss according to input power. From Figure 7(b), at 0 dBm, the return loss equals -24.29 dB which proves this proposed rectifier is well-matched with the RF power generator. This proposed design of the rectifier circuit has a good performance in terms of adaptation from -30 dBm to 8 dBm. Figure 7(c) illustrates the curve of the output DC voltage as a function of input power. From Figure 7(c), at low power densities such as 0 dBm, we obtain a high output DC voltage value is about 2.575 V. At -10 dBm, the value of the output DC voltage is 0.602 V. At -15 dBm, the value of the output DC voltage is 0.312 V. These values of the output DC voltage of this proposed rectifier are very suitable to power supply the devices at the low power densities. Figure 7(d) shows the efficiency according to input power at several load values. At 0 dBm, the RF-DC efficiency equals 73.68% for the load equals 9 KΩ. At -15 dBm, the RF-DC efficiency equals 34.14% for the load equals 9 KΩ. At -10 dBm, the RF-DC efficiency equals 40.29% for the load equals 9 KΩ. Figure 7(e) illustrates the curve of the output DC voltage according to the time at different input power density values.

Table 2 shows the efficacy of the developed microstrip rectenna system by comparing it with other works in the literature. Based on the numerical results shown in Table 2, the improved design of the rectenna system is more efficient in terms of the utility of one diode mounted in series topology, high efficiency at low power densities, and high value of output DC voltage. This developed rectenna design is powerful for RF-DC applications to power electronic devices with low power thanks to its benefits as mentioned in Table 2.

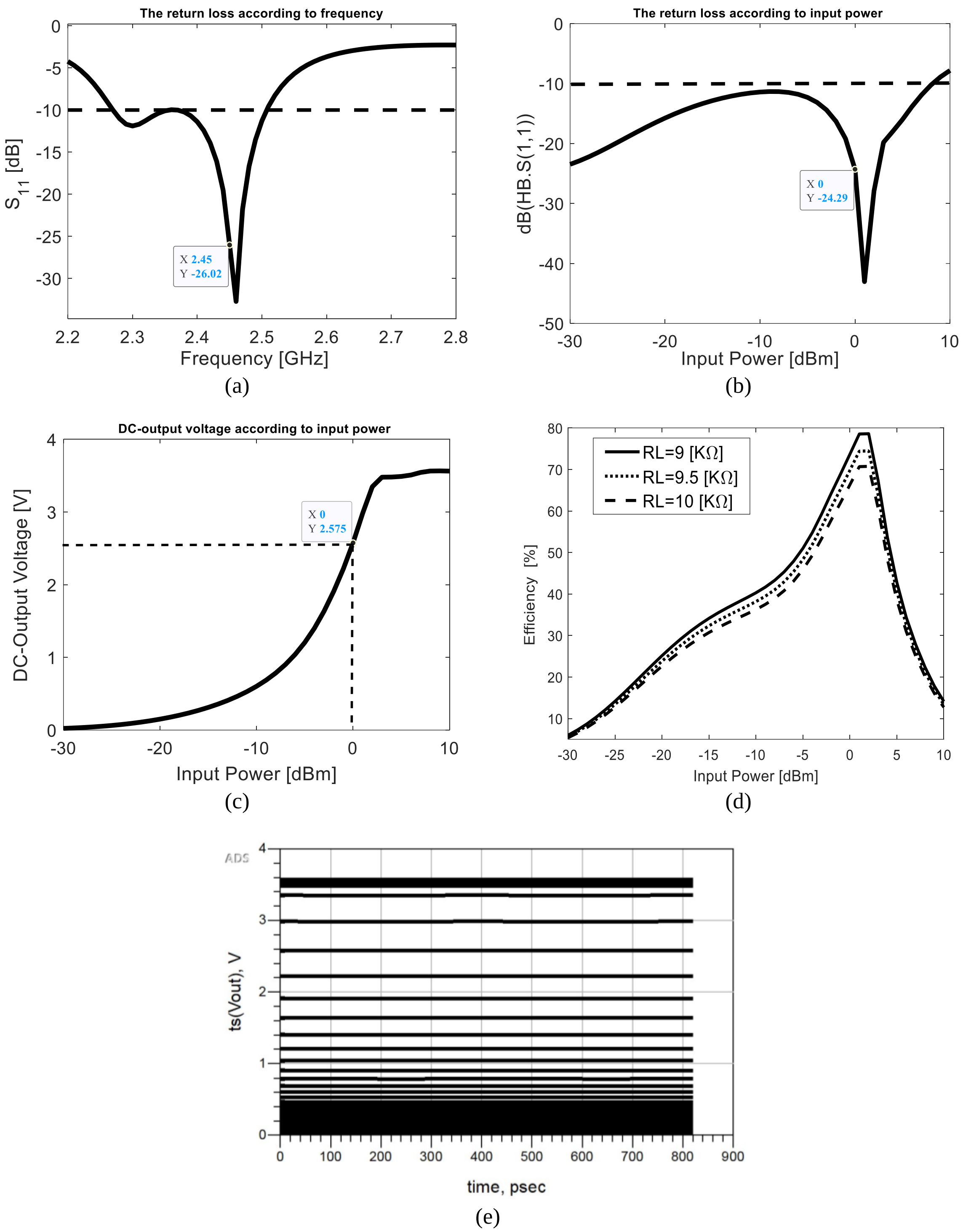

Figure 7. Simulation results for essential characteristics of rectifier circuit

Table 2. Comparative study of the global rectenna system

References	Antenna size [mm^3]	Rectifier circuit type	Input power [dBm]	RF-DC efficiency [%]	Load [Ω]	Output DC voltage [V]
[15]	110 × 90 × 0.635	Diode in series	-3.2	83	1.4 K	1
[17]	24.9 × 8.6 × 1.6	Voltage doubler	-20	20	4.7 K	97 m
[18]	135 × 93 × 1.5	Shunt and series	13	72.50	900	No cited
[26]	18 × 30 × 1.6	Cockcroft-Walton	5	68	5 K	3.24
[27]	50 × 50 × 1.6	Voltage doubler	0	52	10 K	2.17
Our proposed design	190.77 × 113.49 × 1.58	Diode in series	0	73.68	9 K	2.575

4. CONCLUSION

This paper has focused on a complete rectenna system based on the microstrip technology that works at 2.45 GHz in the ISM band, and that has been designed, optimized, and simulated. The improved rectenna incorporates a microstrip receiving antenna and a microstrip rectifier that is printed on an FR4-Epoxy with a dielectric permittivity constant of 4.4, a thickness of 1.58 mm, and a tangent of losses of 0.025. The developed receiving antenna is an MPA array based on the defective ground structure method, which has four pentagonal patches and operates in a circularly polarized manner around 2.45 GHz. This proposed MPA network is efficient in terms of the gain is about 7.94 dBi, the directivity equals 8.17 dBi, the bandwidth is about 265.47 MHz, the important radiation efficiency is about 94.83%, and the reduced volume of $190.77\times113.49\times1.58$ mm^3 using both CST MWS and HFSS software. The proposed RF-to-DC microstrip rectifier circuit uses an HSMS2852 Schottky diode mounted in series topology. This rectifier structure gives better performances in terms of output DC voltage equals 2.57 V, efficiency of about 73.68% at the input power level is around 0 dBm with a load of 9 KΩ using ADS software. The developed microstrip rectenna has excellent performances in terms of low cost, simplicity to fabricate, availability of cheap components, and high efficiency at lower power densities for power supply various devices. Future research will be carried out on fabricating this proposed global rectenna system and making it under experimentation tests.

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