Design and characterization of an radio frequency reused energy system for nano-devices

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Article Info

Article history:

Received Jun 28, 2022
Revised Jun 14, 2022
Accepted Jul 21, 2022

Keywords:

Nano devices
Powerless devices
Radio frequency
Reused energy

ABSTRACT

In this work a simple, high conversion efficiency, and high output voltage energy harvesting device was designed and simulated. The harvesting device consists of microstrip antennas, matching and rectifier circuits. Both mono patch and array antennas are designed to be operated at 5.8 GHz. The simulation work was implemented using central standard time (CST) studio. Results showed an accepted return loss and high gain. To more elevate the device gain and then to obtain greater output energy, an array of microstrip antennas was designed. To convert the radio frequency (RF) energy to dc output voltage, a rectifier, which consists of a voltage doubter and schottky diodes was designed using advanced design system (ADS) simulator. Furthermore, to achieve 50 Ω impedance, a matching circuit was designed by adjusting the microstrip line patterns. The output voltage of the device was 6.2 V at input power 20 dBm and 560 Ω load resistance.

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1. INTRODUCTION

Demand has increased recently towards the use of portable devices with very low power consumption such as low power communication systems [1]–[5], measuring instruments [6]–[10], self-powered devices [8], [11]–[14] and nano-devices [15]–[18]. Basically, current semiconductor technologies intensely searching for lower operating powers and the batteries could be replaced by alternative sources. One of the promising alternative technologies is the energy harvesting. In today's environment there are many radios frequency (RF) sources such as internet routers, satellite communications, cell phone stations, radio and TV broadcasting, and more. Every single system of these represents a cheap energy source that radiates in almost everywhere.

The wireless energy can be collected by using a suitable rectenna (rectifier and antenna) system. It consists of a microstrip antenna, matching circuit, a rectifier, and a low pass filter. The rectifier converts the RF power into a dc voltage. A resistor is usually connected at the output of the rectifier as a load to obtain the dc voltage.

Currently, several rectenna technology have been reported to fit various applications. Ren and Chang [19] proposed an array of rectinas for power transmission that is not sensitive to variation of the incident energy. However, since the algebraic sum of the rectennas outputs is lower than the summation of the individual rectenna, the device got declined in its efficiency. Another approach for increasing the efficiency of the harvesting system is by enhancing the antennas beamwidth [20]. Enhancing of the RF-to-dc power conversion have achieved by designing a rectenna with 1x4 quasi-yagi array with a dual-band rectifier [21].

Fabrication of rectenna with two diodes has been proved to supply twice the dc voltage than the conventional rectenna with one diode [22]. Ultra-wideband rectennas has successfully achieved by using hybrid resistance compression technique. This technique is depending on reducing the nonlinear effects of the rectifier and improving the performance of the impedance matching over a relatively broad bandwidth ultra-wideband rectennas has successfully achieved by using hybrid resistance compression technique [23]. Millimeter-wave rectenna has been developed for energy harvester at 35 GHz. 16 antenna elements were used to improve the outputdc voltage. A special diode, made of GaAs was used in the rectifier circuit [24].

In this work, various rectennas based on array antennas were designed at 5.8 GHz. The proposed design is simple, high conversion efficiency, and high output voltage. Linear and dual polarization antennas were constructed. Excellent return loss with high gain were achieved, meaning that, more captured energy.

2. STRUCTURE AND MECHANISM OF THE HARVESTING SYSTEM

Basically, energy harvesting system consists of antenna, rectifier, filter, and matching circuit. The purpose of these components is to convert the RF energy of the surrounding environment into smooth dc output voltage. The conversion efficiency (η) can be calculated [25] by:

$$\eta = \left(\frac{V_{DC}^2}{R_{load}}\right)\frac{1}{P_d A_{eff}} \tag{1}$$

Where, $A_{eff} = \left(\frac{\lambda_0^2}{4\pi}\right) G_r$ where, λ and G_r are the wavelength of the received signal and the antenna gain respectively. P_d is the power density. Furthermore, the received signal power can be calculated at any given distance from the transmitter by,

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2 \tag{2}$$

Where, $G_{t,\,r}$ and P_t are the transmitted/received gain and the transmitted power respectively, while R is the transmitter-RF source interspace. Notably, the received power decreases as the distance between the transmitter and reliever increases. Frequency of 5.8 GHz was picked in this work as it is appropriate in terms of attenuation and antenna dimension.

3. PROPOSED RECTENNA

The energy can be collected from the environment by connecting the antenna to the desired matching circuit, rectifier, and low pass filter. These components convert the received energy into a dc voltage by blocking the high order harmonics and hence, raising the efficiency. The significant part in the rectification circuit is the diode that should be selected carefully. Moreover, a load resistor is required in the out of the circuit to measure the output dc voltage.

3.1. Linear polarization 1x2 array antenna

A linear polarization 1x2 array antenna was designed and simulated. Parallel feeding technique was utilized to construct the array. A suitable transition line was used to feed, in parallel, the patches. The central standard time (CST) simulator was used to convert the impedance to antenna lines. Figure 1 shows the layout of the inset type 1x2 array microstrip antennas, and the details of the microstrip dimensions is shown in Table 1.

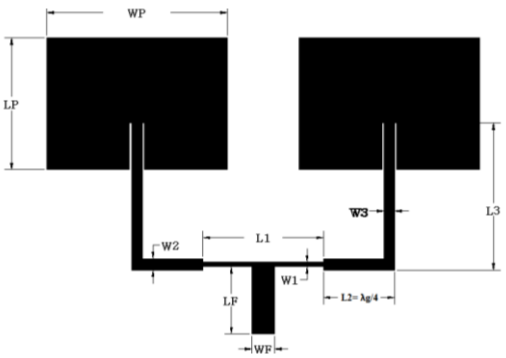
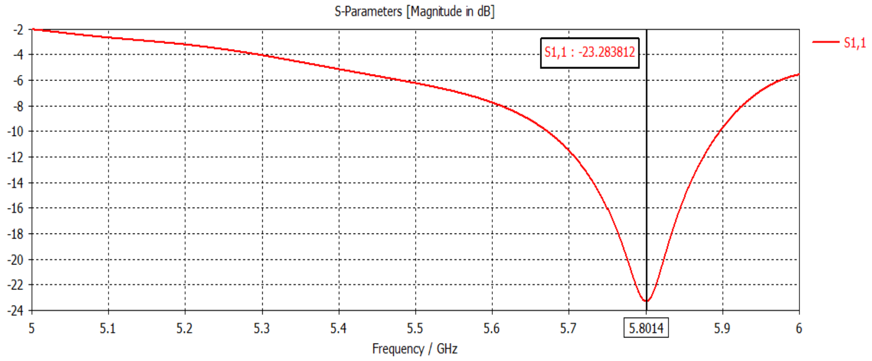


Figure 1. Dimensions of 1x2 linear polarization array patch

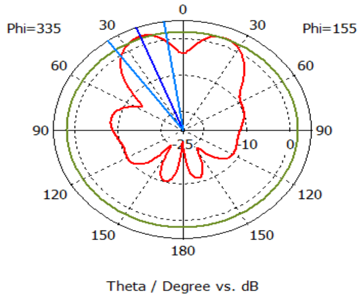
Table 1. The microstrip antenna dimensions

Microstrip lines characteristics	Dimensions (mm)
Feed line length (LF)	9
Feed line width (WF)	3
L1	16
W1	0.55
L2	9.5
W2	1.5
L3	18
W3	1.45

Based on the simulation result, the obtained return loss (S11) was -23.283 dB. While the bandwidth is 225 MHz and the cutoff frequency was 58 GHz (Figure 2(a)). The values of impedances was normalized to 50 **Ω.** The achieved half power radiation pattern was 21^0 for both h-plane and e-plane, while the radiation power was 0.107 W. Figure 2(b) shows the 2D radiation pattern of the antenna that displayed in Figure 1.



(a)



(b)

Figure 2. Device simulation (a) S11 of the array antenna shown in Figure 1 and (b) its radiation pattern 5.8 GHz

The list of the CST simulator results for 1x2 array is shown in Table 2. The directivity and the gain were shown in the same table. By reviewing the table, we notice that all results agree with the general principle of the harvesting system, particularly in terms of gain, return losses, and bandwidth. These results were obtained at 5.8 GHz.

Table 2. simulation results of the 1x2 array patch antenna

Type	Array patch
Return loss	-23.283 dB
Bandwidth	225 MHz
Directivity	9.36 dBi
Gain	2.72 dB
Power radiated	0.107 W
HPBW (E-Plane)	21°
HPBW (H-Plane)	21°

3.2. 1x2 dual polarized array antennas

Dual polarized antennas was designed to achieve dual polarization array. Figure 3 shows the layout of two structure array antennas, facing left and right with 45 polarization angles. Results observed that bandwidth for the 1x2 array with + 45º polarization was 214 MHz, while the return loss was -23.4 dB. Same results were obtained for the 1x2 array with -45º polarization angle. Figure 4 shows the return losses for the + 45º and -45º polarized array antennas. Only one cure shows because they are similar. Certainly, the value of the S11 of the designed array antenna is accepted for the harvesting application. Resulting radiation energy of the facing left/ right array is revealed in Figures 5(a) and (b), individually. Obviously, this antenna structure exhibits a wider radiation pattern and higher gain compared to a device with a single patch.

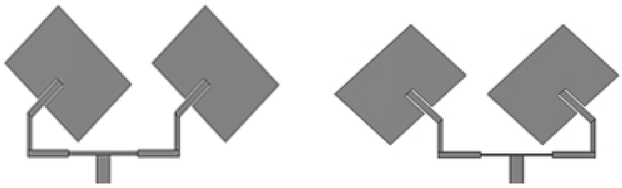


Figure 3. 1x2 array with + 45º and 1x2 array with -45º polarization angles

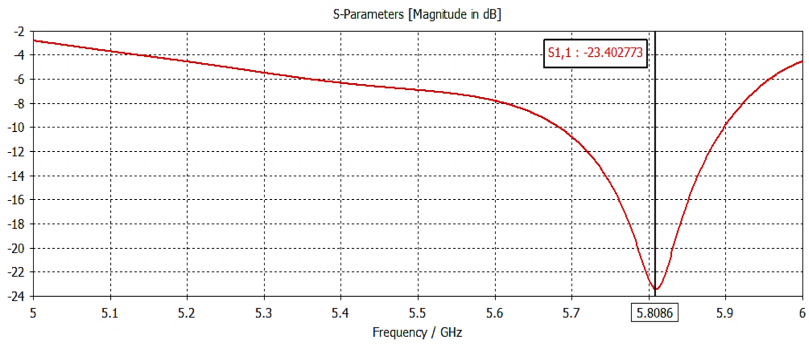
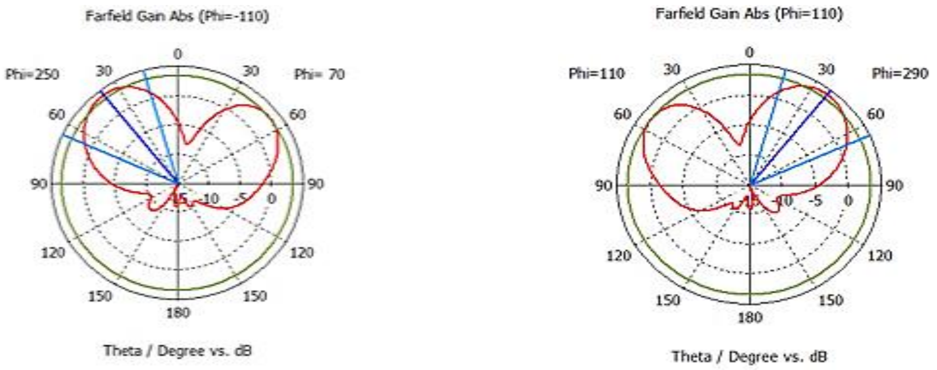


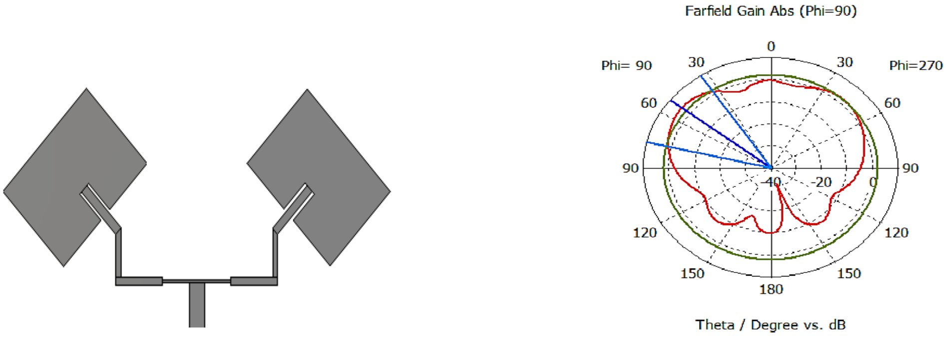
Figure 4. The S11 for ± 45º polarized antennas



(a) (b)

Figure 5. The radiation energy of (a) facing right (+45º polarized) array antenna and (b) facing left (-45º polarized) array antenna. For both the magnitude of the main lobe and the radiation pattern are 4.05 dB 30 deg respectively. The resonance frequency is 5.8 GHz

Another design was done that is a structure of two antennas, one facing to the left with -45° and one facing to the right direction with 45° as Figure 6(a) depicted. Also, Figure 6(b) displays the radiation energy of the array antennas with dual polarization. Obavously, in this structure an improvement in directivity and gain were achieved compared to 1x2 array at polarization angle of + 45/ -45.



(a) (b)

Figure 6. The device structure (a) structure of the dual polarization and (b) its radiation pattern at 5.8 GHz

The return loss of this antenna was designed to be -25 dB Figure 7 while the bandwidth and center frequency of 265 MHz. The comparison results between single patch and 1x2 array patch is shown in Table 3. This table gives clear indication about the antenna properties such as return loss, bandwidth, directivity, the radiated power, and gain. Therefore, one can pick the best antenna structure for energy harvesting system. From Table 3, the dual linear polarization 1x2 array + 45° and -45° is the best design in terms of return loss, gain and radiated power.

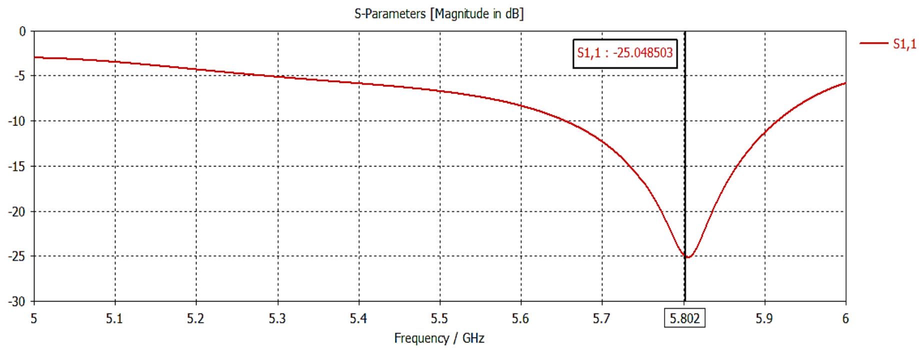


Figure 7. S11 of the dual polarized array

Table 3. Comparison results between single element and 1x2 array antennas

Design	Return Loss (dB)	BW (MHz)	Gain (dB)	Directivity (dBi)	Radiated Power (W)
Single patch	-23.371	212.3	2.19	6.27	0.189
Linear Polarization 1x2 Array	-23.283	225	2.72	9.36	0.107
Single patch +45°	-14.404	151	4.43	8.63	0.182
Single patch -45°	-14.347	152	4.44	8.64	0.182
Dual Linear Polarization 1x2 Array +45°	-23.402	216	4.05	9.05	0.156
Dual Linear Polarization 1x2 Array-45°	-23.239	213	4.05	9.05	0.156
Dual Linear Polarization 1x2 Array +45°and -45°	-25.04	265	4.11	8.68	0.195

4. RECTIFIER DESIGN

The main property of the rectenna is its efficiency, which is usually found by measuring losses that arises during RF to dc power conversion. The efficiency of the conversion can be determined using (3) [26],

$$\eta_{rec} = \left(\frac{P_{DC}}{P_r}\right) = \frac{V_R^2/R}{P_R} \quad (3)$$

where, V_R is the load voltage, Pr is the RF received power, and P the output power across the load (R). The designed rectifier efficiency is depending on the conversion power of device. HSMS2820 schottky diode was utilized in this work since it has low reverse time and high efficiency. Table 4 shows the diode specification.

Table 4. The HSMS2820 schottky diode parameters

Description	Magnitude	Units
series resistance RS	6	W
zero bias junction capacitor Cj0	0.7	pF
forward voltage VF	0.34	V
breakdown voltage VB	15	V

The rectifying circuit which was proposed in this work consists of a capacitor for blocking dc, schottky diode, matching lines and a low pass filter Figure 8. The device was constructed on the an FR4 substrate with the dialectric constant, height, and thickness of 4.3 mm, 1.6 mm, and 0.035 mm respectively. The optimized circuit was achieved by utilizing the ADS simulator. This design was proposed to be sufficient for 5.8 GHz resonance frequency.

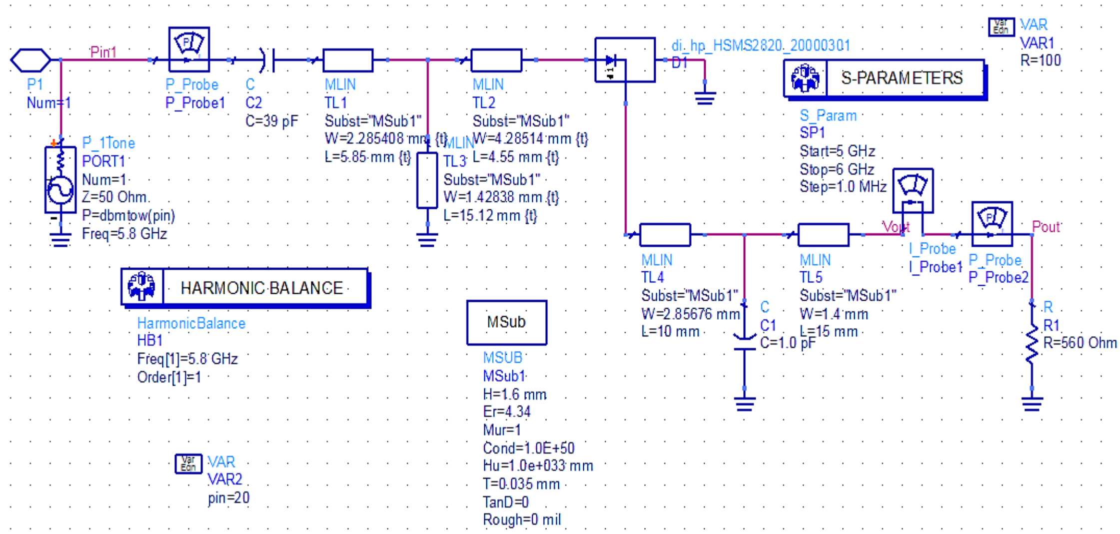
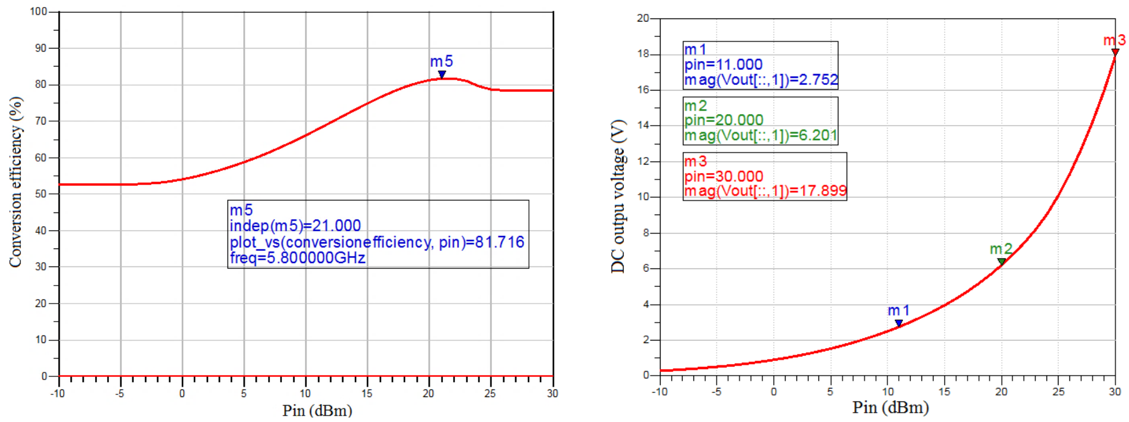


Figure 8. Schematic diagram of the rectifying circuit

The conversion efficiency was measured at the injected power range from -10 dBm to 30 dBm. The optimal load was determined to be 560 Ω for 20 dBm input power. The highest obtained conversion efficiency was 81.7% at 21 dBm Figure 9(a). The efficiency rises slowly with the increasing of the applied power, reaching its maximum at 21 dBm. Then the curve declined due to diode breackdown. Figure 9(b) implies that the dc output voltage is 2.506 V at 10 dBm, 6.201 V at 20 dBm and reaches 17.899 V at 30 dBm.



(a) (b)

Figure 9. Conversion relations (a) conversion efficiency vs. RF applied power and (b) dc output voltage vs. applied RF power

Furthermore, the rectifying circuit layout was designed and simulated on Fr-4 substrate with 1.6 mm height and perfect conductor PEC with a thickness of 0.035 mm. Figure 10 shows the layout of the proposed rectifier.

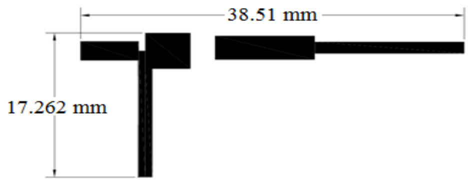


Figure 10. Rectifier layout

5. CONCLUSION

In this work, the rectenna for RF energy harvesting was designed and investigated. For this purpose, several antennas were designed and simulated. Due to high directivity and gain, an array of dual linear patch antenna with inset feed was designed for energy harvesting using CST simulator. Furthermore, a +45° and -45° oblique antennas was designed, which further increases the gain and rotates the polarization of the 1x2 array. To harvest energy from multiple directions an array of dual polarization was simulated. The output DC voltage was simulated by advanced design system (ADS) software. For 20 dBm input power at 5.8 GHz, 6.2 Vdc is presented at the output with maximum conversion efficiency of about 81%. Based on our experience, energy harvesting system can enhance the lifetime of the low power devices and reduce the usage of batteries.

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