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RESEARCH ARTICLE

A Spurious Free Dual Band Microstrip Patch Antenna for Radio Frequency Energy Harvesting

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Abstract

Objectives: To design high gain square slots loaded dual-band rectangular microstrip patch antenna having harmonic suppression capability and rectifier circuit (Rectenna (Antenna + Rectifier) for Radio Frequency Energy Harvesting (RFEH). **Methods:** To achieve the objectives, the square slots are loaded on the four corners of the rectangular microstrip patch in order to enhance the current distribution which resulted in improved impedance matching at desired frequencies with dual isolated bands. The proposed antenna is simulated in Computer Simulation Technology (CST) Studio Suite Three-Dimensional Electromagnetic Simulation (3DEM) software. A rectifier with an LC impedance matching network is designed, simulated, and optimized in Agilent Advanced Design System (ADS) software. **Findings:** The overall size of the proposed antenna operating at 2.49 GHz and 3.73 GHz (WiMax) is $57\times48\times2.5$ mm^3. The proposed antenna is assessed in terms of its simulated performance parameters: Return loss (S1,1), Impedance (Z1,1), Voltage Standing Wave Ratio (VSWR), Gain, Directivity, and Efficiency. The proposed antenna exhibits improved performance over the conventional rectangular patch antenna, in terms of (S1,1), Impedance (Z1,1) and Gain. The results obtained from the simulation indicate -35.47 dB and -37.42 dB of S1,1 at 2.49 GHz and 3.73 GHz respectively with the Gain of 4.74 dBi and 3.62 dBi respectively. Further, a rectifier circuit is proposed at 2.45 GHz. The complete rectenna system is simulated over a range of input power levels (1dBm-10dBm) for 4.7 kOhm load resistance. The simulated rectenna result presents the maximum output voltage of 3.34 V. **Novelty and Applications:** The proposed rectenna design with its harmonic suppression capability can be used for RFEH to drive the Internet of Things-Sensor Network (IoT-SN) and Wireless Sensor Network (WSN). The novelty of the proposed work is harmonic suppression capability. harmonic suppression capability is achieved by inserting the square slots at the four corners of the conventional square patch.

Keywords: Radio Frequency; Energy Harvesting; Efficiency; Gain; Rectifier; Schottky diode

1 Introduction

In this emerging high technological world, handheld electronic gadgets are becoming prevalent. These gadgets were operated by batteries with a restricted lifetime and replaceable/rechargeable batteries which increase maintenance cost as well as time. In the last two decades, there is a revolution in the Wireless Communication Technology (WCT) (Advanced Mobile Phone Service (AMPS) to 6^{th} G). WCT transmits information over the air using electromagnetic waves like Infrared (IR), Radio Frequency (RF), Satellite, GPS, Wi-Fi, Satellite television, Wireless computer parts, wireless phones that include 3G and 4G networks, and Bluetooth. In this high-tech world, there is a significant increase in the amount of electromagnetic/RF energy in the atmosphere[(1–4)]. RFEH is one of the most favourable technologies for the continual energize ultra-low-power hand-held electronic devices and battery-operated IoT and WSN.

A dual-band slotted rectangular antenna for microwave energy harvesting from WiMAX band operating at 2.45 GHz and 3.84 GHz with a gain of 4.35 dBi and 2.78 dBi is presented in[(5)]. A simulation result of a novel three-point star rectenna for RF energy harvesting at 2.4 GHz having an antenna gain of 6.28 dBi and an antenna efficiency of 74.8% with 88.02% maximum conversion efficiency of rectifier at 28 dBm for an 810 Ω load resistance is reported[(6)]. The specifics of Schottky diode selection for the rectenna circuit and monopole helical antenna for scavenging RF energy from Ultra-High Frequency (UHF) are presented[(7)]. A slot loaded rectangular antenna operating at 2.453 GHz and single diode rectifying circuit is discussed in[(8)], the simulated power conversion efficiency of 54 % and 732 mV is reported. Coplanar waveguide (CPW) feed, stub impedance matching, inverted L-strip with slot and circular polarization dual band rectenna operating at the two WLAN frequency bands 2.45 GHz and 5 GHz is explained in[(9)]. In[(10)] a rectangular antenna with circular slots and rectangle slot are created to operate antenna in WLAN 2.4 GHz and 5.8 GHz frequency, also two separate four-stage RF rectifiers with LC impedance matching networks are carefully chosen for maximum RFEH. Two slot dual band inset feed microstrip antenna operates at 2.4 GHz and 5.4 GHz for RF energy harvesting is presented in[(11)], A rectangular dual-band microstrip patch antenna operating at 2.4 GHz and 5.0 GHz Wi-Fi frequency is presented in ref.[(12)], the harmonic frequency spikes are observed in the simulation and measured results. A Circular Polarized (CP) patch antenna with the partial ground is reported in[(13)], $\lambda/4$ resonator is introduced coupled to the radiating patch to enhance bandwidth and to suppress higher-order harmonics.

The paper is organized into six sections: In section one, overview of RFEH is expressed. Section two, provides design details of antenna, while section three, and presents antenna simulation results and their analysis. In section four, details of the rectenna (Antenna + Rectifier) implemented in ADS are explained. In section five, ADS simulation rectenna results are presented. The paper is concluded in section six with the concluding remark.

1.1 Antenna design

The choice of the resonating frequency is an important consideration in RFEH. In order to avoid oversized rectenna, difficulty in fabrication and installation, the industrial, scientific, and medical (ISM) frequency and unlicensed frequency bands allotted by regulatory authority[(14)] can be considered as a suitable option for RFEH. The

Transmission Line (TL) based model equations are used to calculate the initial antenna parameter[15]. The antenna is designed, simulated, and optimized on Rogers XT8100 substrate of dielectric constant 3.5, loss tangent 0.049, and height 2.5 mm. Table 1 and Table 2 presents the details of antenna parameters and substrate.

Table 1. Microstrip antenna parameters

Parameter	Unit (mm)
Wg (Ground plane width)	57
Lg (Ground plane length)	48
W (Microstrip Width)	42
L (Microstrip Length)	33
Y (Inset Length)	6.0
Lf (Length of Microstrip Feed)	13.50
Wf (Width of Microstrip Feed)	3.0

Table 2. Substrate details

Substrate material	Rogers XT8100
Dielectric constant	3.5
Tangential losses	0.0049
H (Substrate thickness)	2.5 mm
Conductivity	5.8e+007
Metal thickness	0.035μm

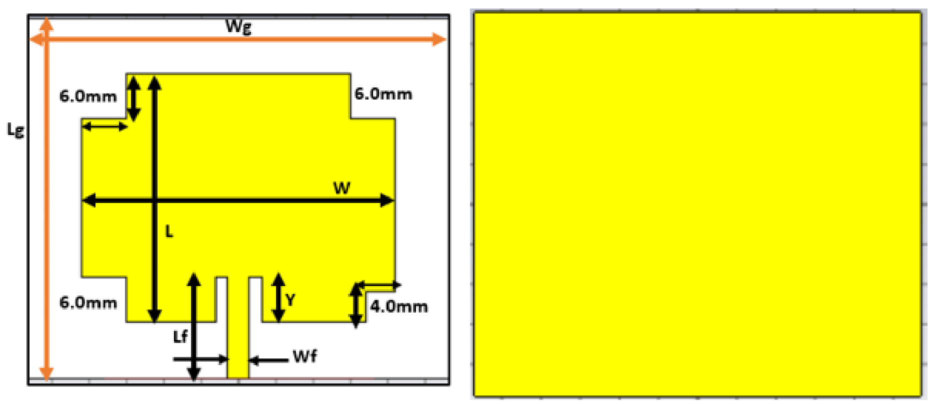


Fig 1. Proposed antenna (a) Top view (Antenna) (b) Bottom view (Ground plane)

2 Antenna simulation results and analysis

The [Figure 1] shows the proposed antenna geometry with square slots loaded on the four corners of the patch. [Figure 2] shows the progression of the proposed antenna from Iteration_0 to Iteration_4. The antenna simulation is carried out in CST MW Studio. [Figure 3] depicts S1,1 characteristics of Iteration_0 to Iteration_4. [Figures 3, 4 and 5] shows that, iteration_4 depicts improved performance in terms of S1,1, Z1,1, and VSWR compared to Iteraton_0 to iteration_3 which is the result of introducing the square slots. At iteration_4, S1,1 at frequency 2.49 GHz is -35.475dB and at frequency 3.73 GHz -37.42 dB is observed with Z1,1 of 50.80 Ohm and 49.10 Ohm respectively. Figure 5 indicates the Voltage Standing Wave Ratio (VSWR) at Iteration_4, the VSWR value at 2.49 GHz and 3.73 GHz is 1.05 and 1.02 respectively.

Figure 6 shows the surface current distribution at 2.49 GHz and 3.73 GHz for the Iteration_0 to Iteration_4. It is observed that at Iteration_4 the maximum surface current distribution is on the edges of the antenna at 2.45 GHz and 3.73GHz. When square

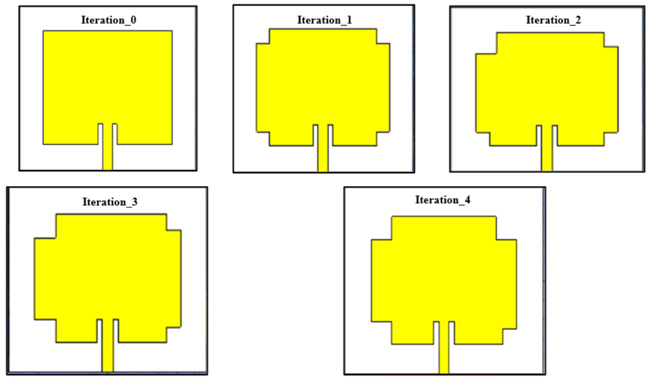


Fig 2. Progression of proposed antenna (Iteration_0 to Iteration_4)

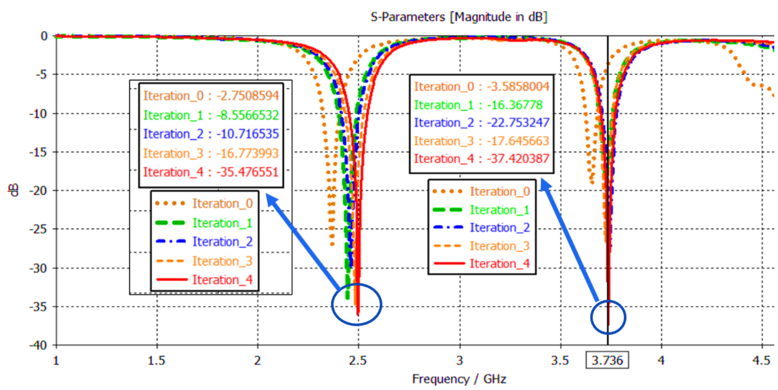


Fig 3. S1, 1plot for Iteration_0 to Iteration_4

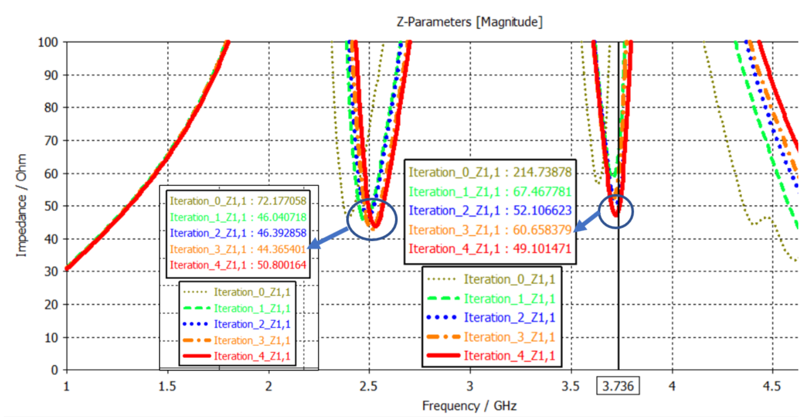


Fig 4. Z1, 1 plot for Iteration_0 to Iteration_4

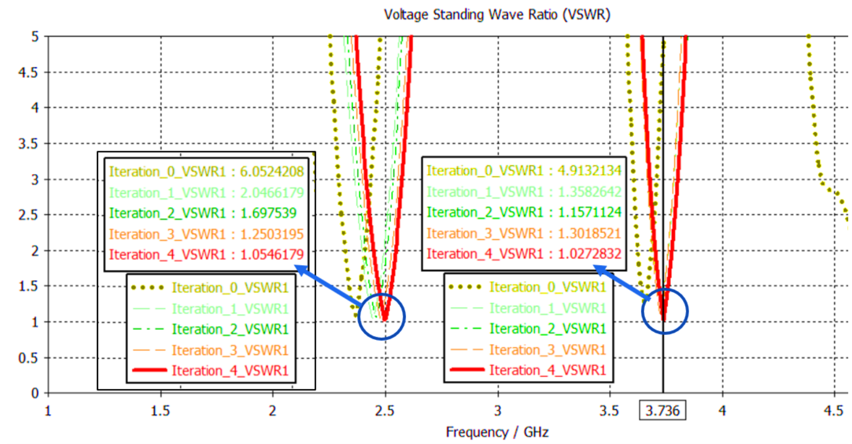


Fig 5. VSWR plot for Iteration_0 to Iteration_4

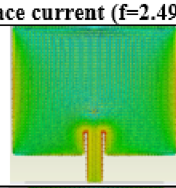
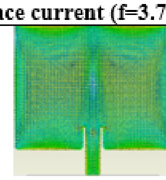
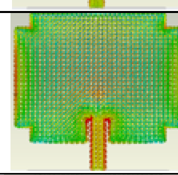
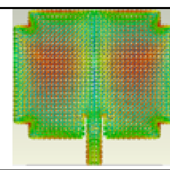
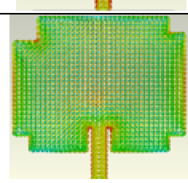
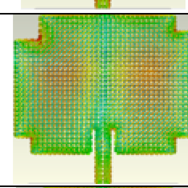
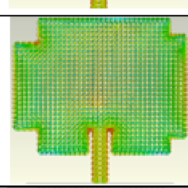
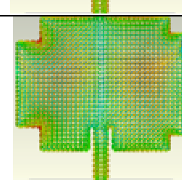
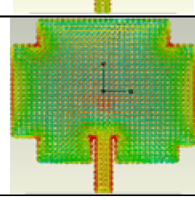
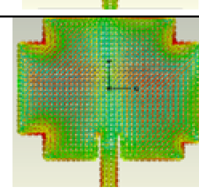
Iteration No.	Surface current (f=2.49 GHz)	Surface current (f=3.73 GHz)
Iteration_0		
Iteration_1		
Iteration_2		
Iteration_3		
Iteration_4		

Fig 6. Surface current distribution at 2.49 GHz and 3.73 GHz

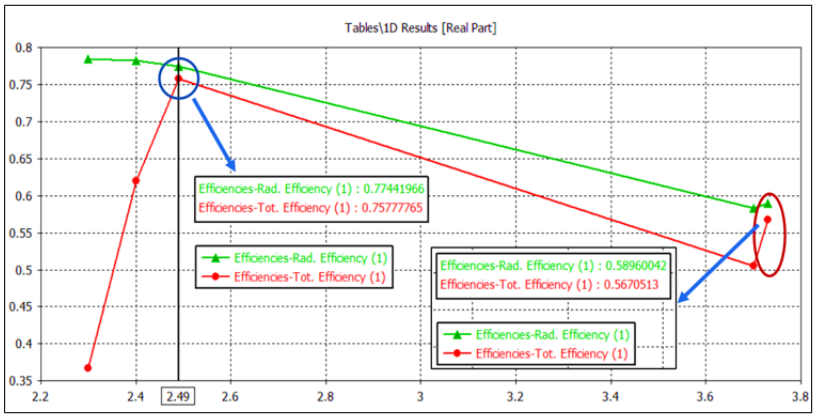


Fig 7. Antenna radiation and total efficiency at 2.49 GHz and 3.73 GHz

Table 3. Antenna gain and directivity at 2.49 GHz and 3.73 GHz

Iteration No.	Gain (dBi) at 2.49 GHz	Gain (dBi) at 3.73 GHz	Directivity (dBi) at 2.49 GHz	Directivity (dBi) at 3.73 GHz
Iteration_0	4.69	3.20	6.02	5.34
Iteration_1	4.79	3.35	5.91	5.69
Iteration_2	4.77	3.50	5.89	5.91
Iteration_3	4.75	3.55	5.87	5.78
Iteration_4	4.74	3.62	5.85	5.92

slots on the four corners of the proposed rectangular microstrip antenna were introduced, the surface current was more evenly distributed on edges of the slots, as well as on antenna edges, which resulted in a significantly enhanced reflection-coefficient (S1,1), Impedance (Z1,1) and VSWR at iteration_4. As a result of enhanced current distribution, the iteration_4 shows that the gain and directivity is improved at 3.73 GHz, without affecting the performance of first band at 2.49 GHz as shown in Table 4, showing that iteration_4 is a suitable choice for RFEH.

[Figure 7] shows the antenna radiation efficiency and total efficiency at 2.49 GHz and 3.73 GHz. The maximum radiation efficiency of 77.44% and total efficiency of 75.77% are observed at 2.49 GHz and at 3.73 GHz the maximum radiation efficiency of 58.96% and total efficiency of 56.70 are observed. As the antenna radiation efficiency and total efficiency are high at 2.49 GHz compared with the 3.73 GHz, 2.49 GHz is selected for the rectenna design and simulation in ADS software. The proposed antenna bandwidth at 2.49 GHz and 3.73 GHz can be enhanced with metamaterial structure/shapes[16].

The radiation pattern of the antenna shows the field strength of the radio frequency waves. [Figure 8] shows the farfield radiation pattern at 2.49 GHz. The main lobe direction in the radiation pattern is 8 degrees at frequency 2.49 GHz for the iteration_4. The angular width at 3 dB points of the main lobe is 100.2 degrees for 2. 49GHz.The value of side Lobe Levels (SLL) in the radiation pattern at 2.49 GHz is -12.1dB and it is below -15 dB which shows that the proposed antenna is suitable for RFEH.

2.1 Design of rectenna

[Figure 9] shows the RF rectenna circuit which converts RF energy/power to dc. To transfer maximum input RF harvested energy to load, a L-type impedance matching network comprising of the series inductor and shunt capacitor is placed between input (Antenna) and load. The optimized inductor and capacitor values are shown in [Figure 9]. To avoid the effect of diode junction capacitance (Cjo) on impedance matching network, a smoothing capacitor value should be higher than that of diode junction capacitance[17]. The Friis Transmission Equation (FTE) can be used to calculate RF power received by the receiving antenna[4].

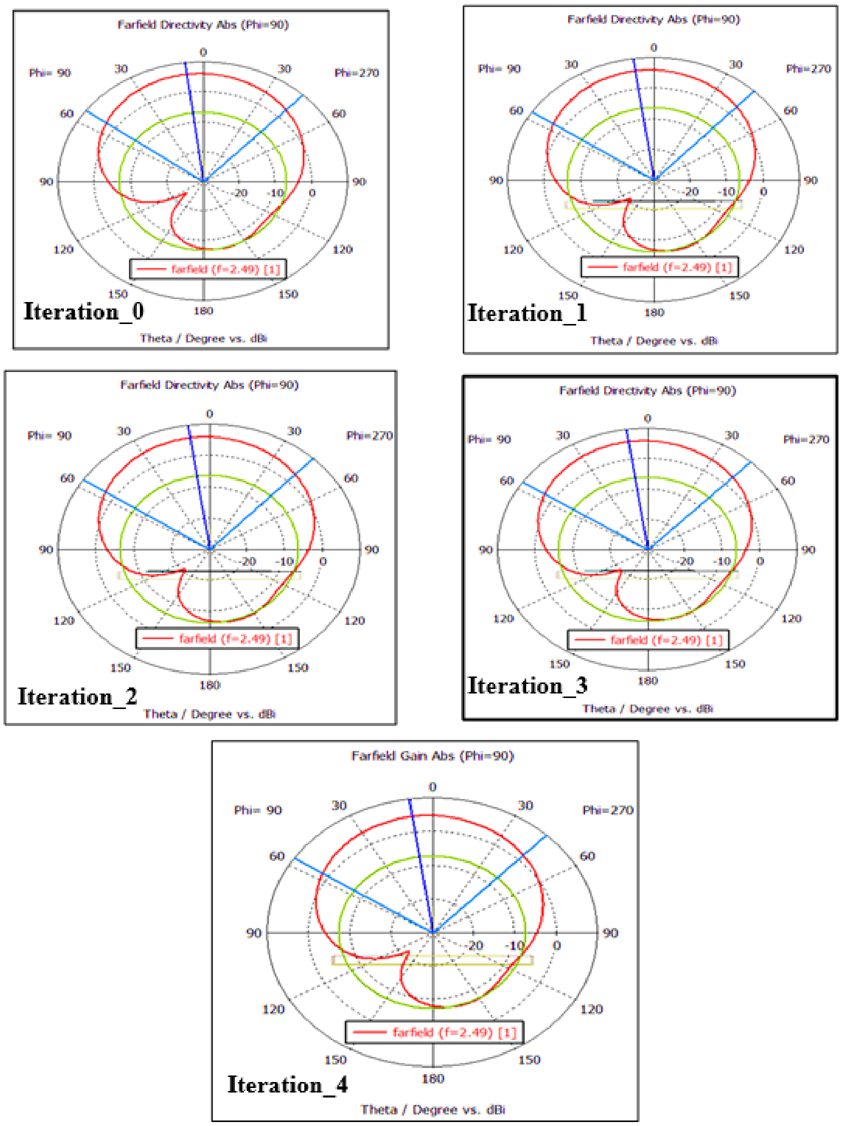


Fig 8. Farfield radiation pattern at 2.49 GHz for Iteration_0 to Itration_4

2.2 Diode selection

As ambient RF levels are lower than those that can be provided by a dedicated RF source, the diode must be able to "switch on" for a very low input RF power levels. Therefore, in the proposed work, a microwave Schottky detector HSMS-2852 is selected, because of its low series resistance (Rs), low junction capacitance (Cj), and low threshold voltage, (Cj = 0.18 pF, Rs = 25 Ω, Is = 3e-6 A). Schottky diodeHSMS-2852 with its low threshold voltage (150 mV) supports rectification at low ambient energy levels. To reduce the circuit/Printed Circuit Board (PCB) size, HSMS-2852, 2862 Schottky diode packages were used since the single package comprises two diodes that are connected in series. The single HSMS-2852 package is equal to two HSMS-2850 packages. The HSMS-285X and HSMS-286X are originally designed and optimized for use from 915 MHz to 5.8 GHz.

3 Simulation Result and Discussion

The S1,1 at 2.45 GHz and its input-output voltage waveforms are shown in [Figure 9] and [Figure 10]. From [Figure 9] it is observed that, the return loss (S1,1) is -25 dB at 2.4 GHz. The output voltage at Pin=1dbm is 1.37 V and at Pin=10 dBm is 3.35V. The output DC voltage and input are taken on a time function scale. Table 5 shows that the proposed antenna gives better

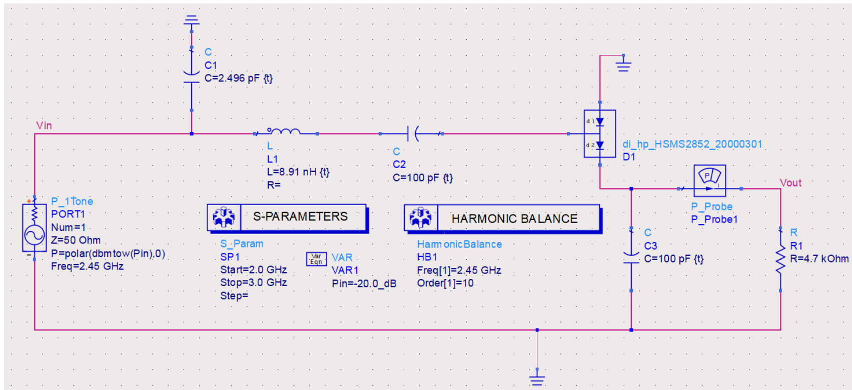


Fig 9. Proposedrectenna topology

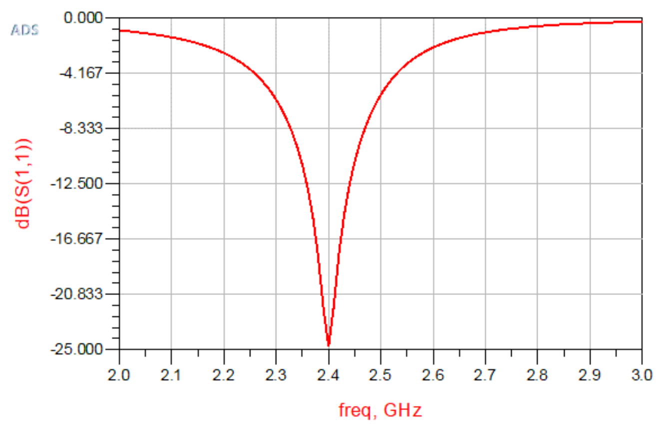


Fig 10. Simulated S1, 1of the rectenna at 2.45 GHz

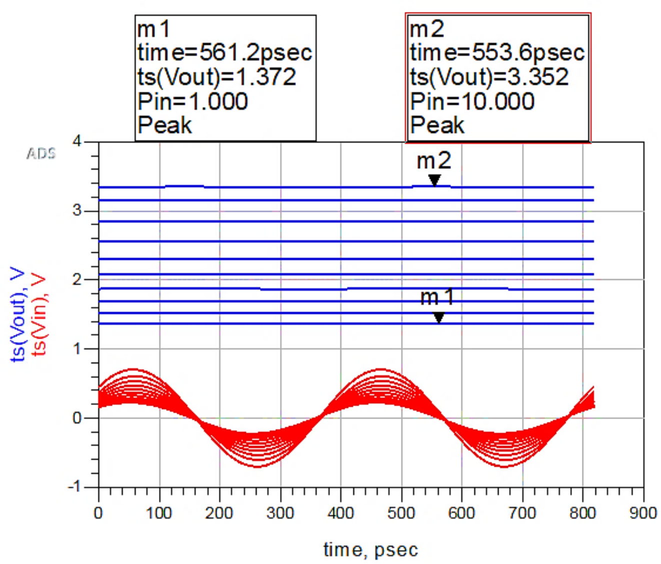


Fig 11. Simulated Vin and Vout

performance with the reduced size compare to the recent literatures [18,19]. The dual band characteristics provides the diversity to harvest the RF energy from both the bands.

Table 4. Comparison of proposed work with existing literature (Antenna)

Ref.	Resonance frequency (GHz)	|S1,1|	Gain (dBi)	Dimensions (mm)	Substrate Thicknesses/Height (mm)	Substrate Type
(5)	2.38 and 3.85	-18.00 -15.00	4.35 and 2.78	Lg=126.25 Wg=95.44	1.5	FR-4
(6)	2.4	−25.77	6.28	Lg=58.4* Wg=87.6*	1.6	FR-4
(8)	2.45	−52	3.48	Lg=47.5 Wg=40	1.6	FR-4
(11)	**2.4 and 5.4**	**-27.23 -30.477**	**2.03 and 3.23**	**Lg= 41.00Wg= 44.00**	**1.6**	**FR-4**
(18)	5.4	-21.00	4.35	Lg=92.00 Wg=73.5	0.8	FR-4
(20)	2.45 and 5.0	-22.42 -14.20	4.08 and 6.92	Lg=90.0 Wg=45	1.6	RT Duroid
(19)	0.9 and 2.4, 2.3	-21.27 and -12.34, -12.243	Not reported	Lg=77.0 Wg=96	Not reported	Not reported
Proposed Design	2.45 and 3.73	-35.47 -37.42	4.74 and 3.62	Lg=48.00 Wg=57.00	2.5	Rogers

* Microstrip patch length and Microstrip patch width.

4 Conclusion

As the gain of the proposed antenna are 4.62 dBi and 3.73 dBi at 2.49 GHz and 3.73 GHz, the proposed antenna with rectifier (rectenna) satisfies all the characteristics required for the RFEH system. It can be used for the RFEH system at 2.45 GHz and 3.73 GHz. The ADS simulation result shows the output voltage of 3.35V at Pin=10 dBm and frequency 2.45 GHz with a load resistance of 4.7 KΩ. The proposed antenna and rectifier circuit with load is operating at 2.49 GHz and can be directly integrated on a single substrate for practical validation of the RFEH system. In future work, the objective would be the design of a dual-band rectenna with enhanced performance, and practical validation of a dual-band RFEH system.

5 Acknowledgement

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