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Broadband and Efficient Full Wave Rectenna for Wireless Energy

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Abstract: ***This paper presents a novel approach to realize a broadband full wave rectenna for wireless energy transfer at 2.45 GHz ISM band. The full wave rectenna structure is designed using a center shorted dual edge feed microstrip patch antenna and two Schottky diodes. This antenna is inherently broadband in nature and can provide differential voltage at its two feed points. An optimized full wave rectenna is fabricated and tested. The proposed rectenna provides more conversion efficiency than a rectenna with similar antenna and conventional half wave rectifier.***

Keywords: Dual feed antenna, Full wave rectenna, Wireless energy transfer.

I. INTRODUCTION

A rectenna is a rectifying antenna system and it normally consists of single or multiple receiving antennas and rectifiers. Sometimes voltage multipliers are also included in rectenna systems to increase the voltage output [1−3]. The rectifier part of rectenna can be either half wave or full wave. The half wave rectifier is simple and can be constructed using single series or shunt diodes, but it can utilize only one half cycle of the AC signal. Several rectenna systems consist of half wave rectifier have been investigated so far [4−7]. On the other hand, full wave rectifier can take advantages of both half cycles of the AC signal. Rectenna with full-wave rectifier consist of two diodes or four diodes are also studied by researchers [8−12].

In this paper, we focus on developing a rectenna system that utilizes full wave rectification to increase RF to DC conversion efficiency using differential voltage output from dual feed antennas. The proposed rectenna system consists of dual edge feed broadband antenna and two-diode full wave rectifier. Dual feed antennas with differential voltage output are already reported for efficient rectenna with half wave rectifier [13] but here similar antenna is used for full wave rectifications. The working principle of the proposed configuration is similar to the traditional AC to DC conversion using a center tapped transfer and full wave rectifier consists of two-diodes. The proposed system has been analyzed theoretically using commercially available IE3D and ADS software [14], [15]. An optimized rectenna system is fabricated for experimental verification and the measured results agree with the theoretical results.

II. CENTER SHORTED DUAL EDGE FED BROADBAND MICROSTRIP ANTENNA

The proposed rectenna consists of a broadband dual edge fed microstrip antenna and full wave rectifier circuit. The broadband dual edge fed center shorted microstrip antenna geometry is shown in Fig 1. A dual edge fed center shorted antenna is optimized at 2.45 GHz considering low cost glass epoxy FR¬4 substrate with dielectric constant εr = 4.4, height h = 1.59 mm and dielectric loss tan δ = 0.01. The dimensions of the optimized antenna geometry are: patch length Lp = 29.84 mm, patch width Wp = 34 mm, ground plane length Lg = 75 mm and width Wg = 7 mm. The width of 50 Ω microstrip feed line d is 3.036 mm, lengths a = 13.85 mm, b = 31 mm and c = 10.56 mm, respectively.

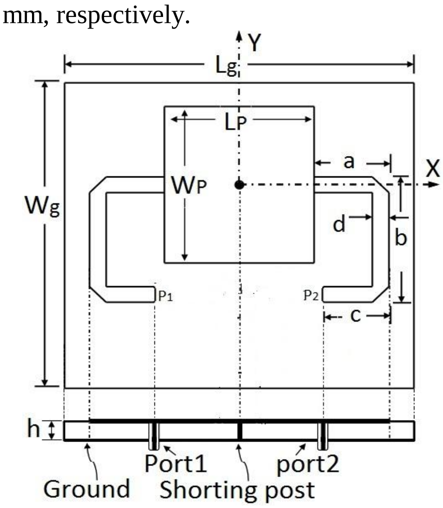

Fig. 1. The geometry of dual edge feed center shorted microstrip antenna top view and side view.

The antenna operates at the fundamental TM_{10} mode during power conversion and in this mode of operation; the voltage is maximum at the patch edges and minimum (zero) at the center of the patch. Two edge-fed microstrip lines are placed at two edges of the rectangular radiating patch where the voltages are maximum and out of phase with respect to each other. The center of the patch antenna is shorted to ground where the voltage is zero.

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The simulated variation of S-parameters with a frequency for the two edge feeds placed at optimized antenna edges are shown in Fig. 2 and corresponding Smith chart plot is shown in Fig 3. The value of S_{11} is close to -50 dB at 2.45 GHz and the antenna exhibits impedance bandwidth of 500 MHz (20%). This bandwidth is much larger than the bandwidth of a similar single feed microstrip antenna.

Gain and efficiency of this antenna are 5.6 dBi and 46%, respectively. The value of S_{21} is -1.53 dB at resonating frequency.

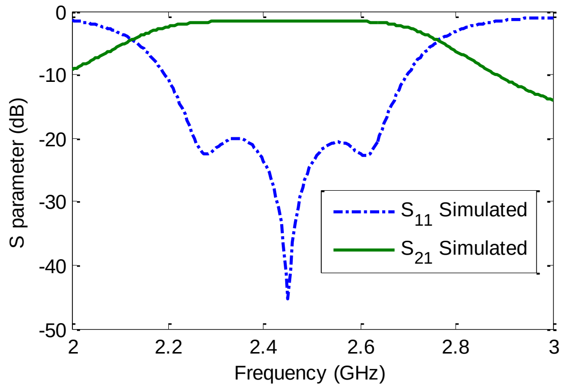

Fig. 2. Simulation of frequency v/s S-parameter results for broadband dual edge feed microstrip antenna.

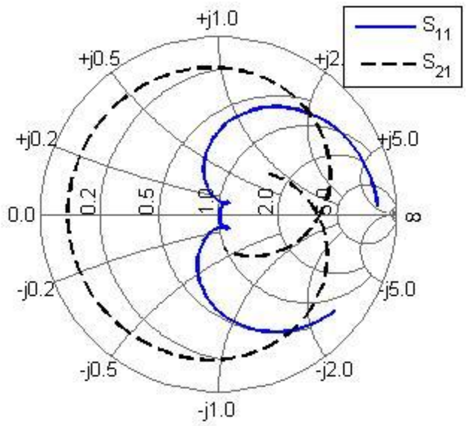

Fig. 3. Simulated input impedance of the broadband dial edge feed antenna on the smith chart.

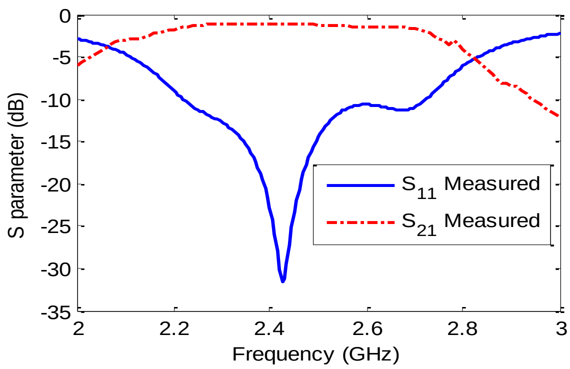

Fig. 4. The measured S-parameter of broadband dual edge feed microstrip antenna.

The optimized dual fed antenna is fabricated for measurement and the simulated and measured S-parameters of dual feed antenna as a function of frequency is shown in Fig. 4. S_{11} for the port 1 of the dual feed antenna is measured using a two port network analyzer (Agilent NA E5071B series) keeping another port matched with 50 Ohm. Since the antenna is symmetric, $S_{11} = S_{22}$. Hence, only S_{11} is measured. A little shift in the center frequency is observed, but the measured operating band (S_{11} < - 10dB) agrees with simulations.

III. DESIGN OF RECTENNA USING FULL WAVE RECTIFIER

The proposed full wave rectenna system consists of a center shorted dual edge fed microstrip antenna and two Schottky diodes are shown in Fig. 5. Two quarter wavelength impedance transformers are used for impedance matching. Edge feed ports P1 and P2 are used for connecting diodes and capacitors. During receiving mode this antenna acts like a center tap transformer and voltages induced at its two opposite feed locations are of equal amplitudes with 180 degree phase difference.

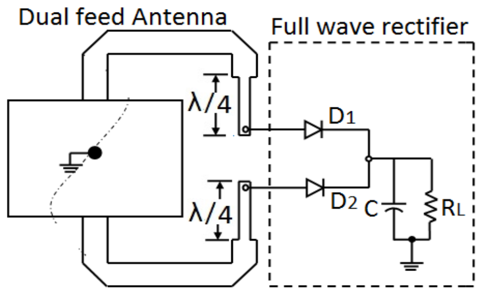

Fig. 5. Proposed full wave rectenna consists of dual feed center short microstrip antenna and full wave rectifier circuit.

For rectification two HSMS 2820 Schottky diodes are used. The generated rippled DC voltage is filtered using RC filter where the R is basically the load RL = 50 Ω and the value of the capacitor (c) is 1nF. The impedance matching quarter wavelength transformers is used to transform 50 Ω to 100 Ω such that at combining junction the impedance becomes 50 Ω. The rectenna shown in Fig. 5 can be modeled like two-diode full wave rectifier connected to a dependent RF source as shown in Fig. 6. In the positive half cycle diode D1 conducts and D2 remains in OFF state as shown in Fig. 6 (a). During the negative half cycle, D2 conducts and D1 remains in OFF state as shown in Fig. 6(b).

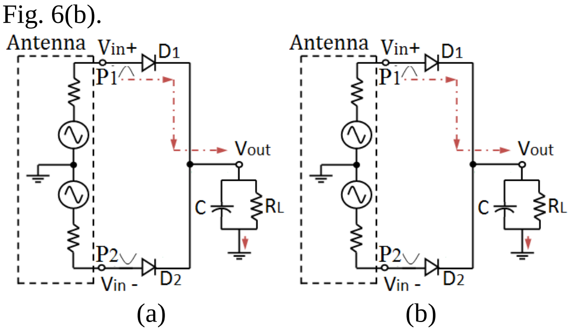

Fig. 6. Equivalent schematic of the proposed full wave rectenna showing the direction of the dc signal path (a) positive and (b) negative half cycles.

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IV. SIMULATION AND MEASUREMENT OF THE PROPOSED RECTENNA SYSTEM

A complete EM and circuit co-simulation setup for RF energy harvesting is as shown in Fig. 7. ADS simulator is used for complete EM and circuit co-simulation. A suspended radiating patch antenna with 9.7 dBi gain (at 2.45 GHz) is considered as transmitter [16].

The dual feed receiver antenna (Rx) is placed at 10 cm, 15 cm and 20 cm apart from transmitter (Tx) antenna for wireless RF energy transfer investigations. In the co-simulation setup, the three port model SNP1 represents the S-parameters in touchstone format generated from IE3D for single port Tx and two port Rx antennas placed at 10 cm to 20 cm apart from each other. The variable input power source is connected to transmitter antenna at port 1 and the ports 2 and 3 of dual fed receiver antenna are connected with full wave rectifier consists of Schottky diodes. The received power is observed across port 2 and port 3 of the Rx antenna and the DC output voltage (Vout) is observed at the load for varying input power for various distances between transmitter and receiver antenna.

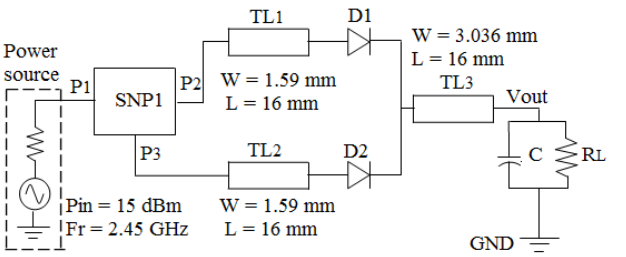

Fig. 7. EM and circuit co-simulation setup for the proposed full wave rectenna.

The variation of S-parameters with frequency for the entire transmitter-receiver system for 15 cm distance between them is shown in Fig.8. It can be seen that in the presence of transmitter antenna the receiver antenna property is changed slightly. The value of S_{11} for transmitter antenna is -20 dB and S_{22} and S_{33} for receiver antenna are also close to -20 dB at 2.45 GHz. The mutual coupling between transmitter and receiver antenna is better than -27 dB at operating frequency. The receiver antenna bandwidth is still more than 500 MHz. The transmitter antenna shows a bandwidth of 140 MHz (2.381 GHz to 2.521 GHz).

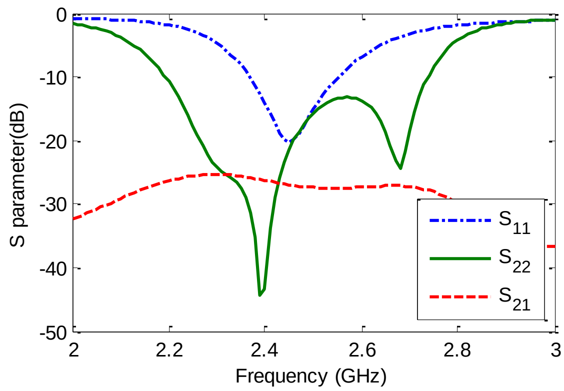

Fig. 8. The simulated S-parameters for the transmitter and receiver antennas placed at 15 cm apart.

The simulated gains of the transmitter and receiver antenna as a function of frequency are shown in Fig. 9. From the figure, the receiver dual feed antenna gain varies from 3.6 dBi to 4 dBi within frequency range from 2 to 3 GHz and the gain is 5.6 dBi at 2.45 GHz frequency. On the other hand, the transmitter antenna gain is 9.7 dBi at 2.45GHz.

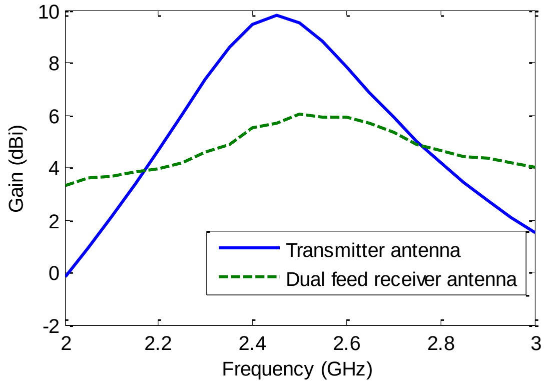

Fig. 9. Simulated gain with frequency of the transmitter and receiver antenna.

A complete RF energy transfer system comprising of a center grounded dual feed antenna and Schottky diodes based full wave rectifier is designed and fabricated. The fabricated dual edge feed center short full-wave rectenna is shown in Fig. 10.

The measurement setup for RF wireless energy transfer is shown in Fig.11. The transmitter as a suspended patch antenna is fixed and receiver dual feed full wave rectenna are placed at a different distance of 10 cm, 15 cm and 20 cm apart respectively from each other for measurement of output DC voltage. A signal generator Rhode & Schwarz SMR20 was used as a source. Measurements are carried out for varying distances, incident power, and frequencies.

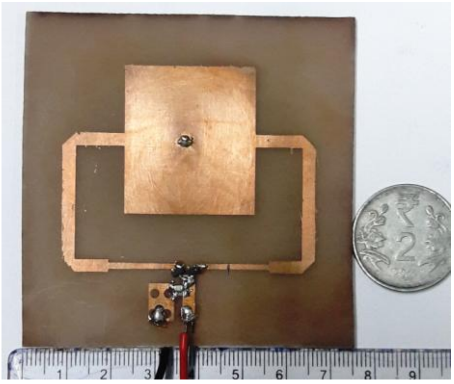

Fig. 10. The Fabricated broadband dual feed microstrip rectenna.

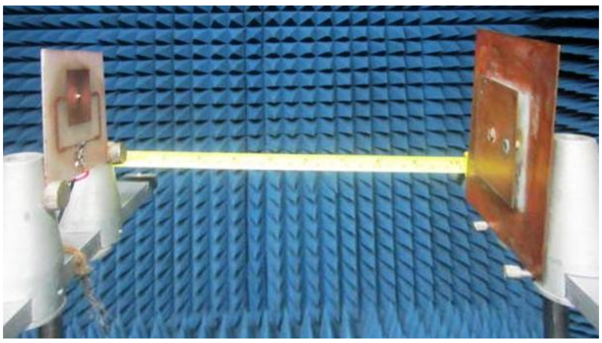

Fig. 11. Measurement setup for RF wireless energy transfer.

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When the transmitting and receiver antennas are placed at 10 cm, 15 cm, and 20 cm apart respectively from each other, the simulated and measured output DC voltages vary with variation of input transmitted power.
The variation of output voltages for changing input power from -10 dBm to +15 dBm at 2.45 GHz is shown in Fig. 12.

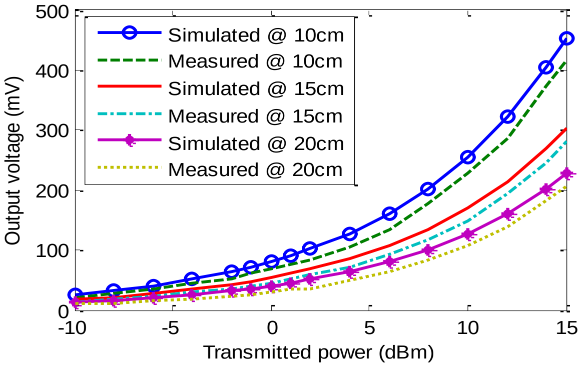

Fig. 12. Simulated and measured output voltage with transmitted power.

For 10 cm distance between transmitter and receiver, the simulated and measured output voltages vary from 25 mV to 451 mV and 20 mV to 406 mV, respectively. For 15 cm distance between transmitter and receiver, the simulated and measured output voltages vary from 17 mV to 277 mV and 14 mV to 251 mV, respectively. Similarly, for 20 cm distance, the measured and simulated output voltages vary from 12 mV to 206 mV, and 8 mV to 187 mV, respectively. The behaviors of measured and simulated output voltage curves are similar. But the measured voltage is always lower than the simulated result which is possibly due to some fabrication error and some extra losses from contacts.

The simulated and measured output voltages are studied for 2 GHz to 3 GHz frequency range, keeping 10 cm distance between the transmitter and receiver antennas and 15 dBm transmitted power. The variations of output voltages with the varying frequency are shown in Fig. 13. Measured output voltages agree with the simulated results. The simulated and measured maximum output voltages are 451 mV and 406 mV, respectively at 2.45 GHz. The graph shows that the simulated and measured output DC voltages follow cumulative effect of transmitter antenna gain and reflection coefficients. It is expected that this rectenna will be able to collect energy from any energy sources with narrower bandwidth which is covered by the rectenna bandwidth.

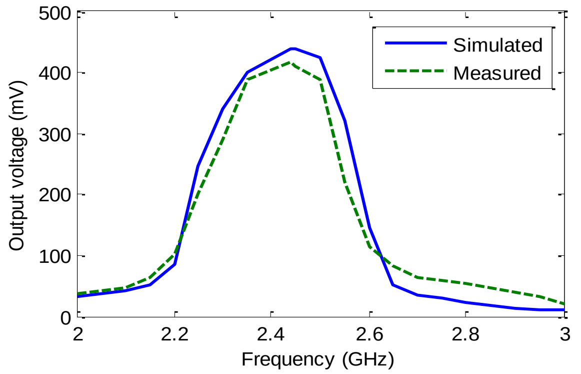

Fig. 13. The variation of simulated and measured output voltages with frequency.

The received output voltages and efficiencies for the full wave rectenna system for 10 cm, 15 cm and 20 cm distances between transmitter and receiver are verified. Output DC voltages and efficiencies for 15 dBm transmitted power at 2.45 GHz are shown in Tab. I. The received output voltages from the receiver rectenna are obtained using EM and circuit co-simulations. The efficiency of the rectenna is calculated using equation (1).

$$\eta = \frac{\text{Power delivered to the load}}{\text{Power received by the antenna}} \qquad (1)$$

When the transmitter and receiver are placed at 10 cm distance, the output simulated and measured voltages are 0.451 V and 0.406 V, respectively. For 15 cm distance, the output simulated and measured voltages are 0.277 V and 0.251 V, respectively. Similarly, for 20 cm distance, the output voltages are 0.206 V and 0.187 V, respectively. Thus, the simulated efficiencies for 10 cm, 15 cm and 20 cm distances are 24.7%, 21.8%, and 21.7%, respectively. Corresponding measured efficiencies are 20.00%, 17.92% and 17.89 %, respectively.

Table- I: The simulated and measured results of the dual feed full wave rectenna at 2.45 GHz (Transmitted power = 15 dBm and load R_L = 50 Ω).

Distance (cm)	Simulated		Measured	Efficiency %	
	Received power (dBm)	Output voltage (V)	Output voltage (V)	Simulated (%)	Measured (%)
10	12.17	0.451	0.406	24.7	20.00
15	8.47	0.277	0.251	21.8	17.92
20	5.92	0.206	0.187	21.7	17.89

The output voltages and efficiencies of the proposed full wave rectenna is also compared theoretically with conventional half wave rectenna constructed using the same antenna as shown in Tab. II. It is observed that simulated output voltages for the full wave rectenna are always higher than output voltages for half wave rectenna. Simulated full wave rectenna efficiencies for 10 cm, 15 cm and 20 cm distances between transmitter and receiver antennas are 24.7 %, 21.8% and 21.7 %, respectively. Similarly, half wave rectenna efficiencies are 17.3 %, 16.7 % and 15.8 %, respectively. Thus, the full wave dual feed rectenna efficiency is better than half wave dual feed rectenna.

Table- II: Comparison between full wave rectenna with half wave rectenna simulation results at 2.45 GHz (Transmitted power = 15 dBm and load R_L = 50 Ω).

Distance (cm)	Simulated			Efficiency %	
	Received power (dBm)	Full wave Output voltage (V)	Half wave Output voltage (V)	Full wave (%)	Half wave (%)
10	12.17	0.451	0.378	24.7	17.3
15	8.47	0.277	0.242	21.8	16.7
20	5.92	0.206	0.176	21.7	15.8

V. CONCLUSION

In this paper, a broadband dual feed full wave rectenna. This rectenna can be useful for broadband wireless energy transfer for ISM band.

The proposed full wave rectenna configuration provides better efficiency than conventional half wave rectenna constructed using same antenna. An optimized rectenna system is fabricated for experimental verification and the measured results agree with the theoretical results.

It is expected that this rectenna will be able to collect energy from any single or multiple narrow band energy sources where individual source bands are covered by the rectenna bandwidth.

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