Chapter 5: Design of an improved differentially fed antenna array for RF energy harvesting

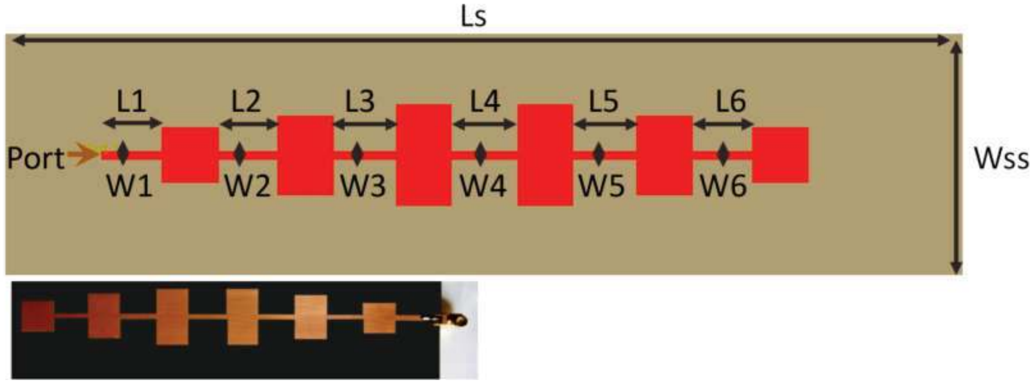
5.1. Introduction

Antenna with high gain and directivity is required to collect more RF power, for this purpose an antenna array is needed [92]. A planar antenna array with amplitude tapering is preferred as it provides high directivity with low side lobes. In the amplitude tapered planar antenna array, the excitation amplitude of each element decreases with distance from the center while keeping the same phase for each element [95]. In the non-uniform, Dolph-Tchebyscheff array pattern, the excitation amplitude of individual elements can be found to obtain the desired sidelobe level.

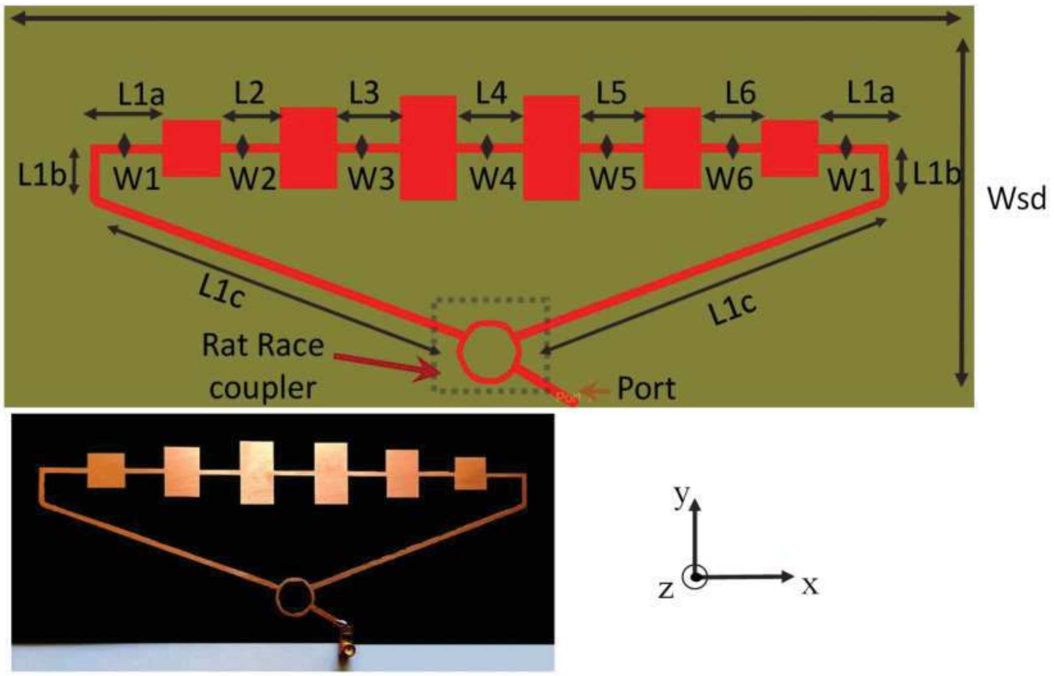
The microstrip antenna with differential feed technique is proposed in [87], the method is effective in reducing the cross polarization, and it also suppresses the higher order modes. Due to this antenna radiation efficiency increases and therefore gain may be improved [87]. This scheme proposed a differentially driven rectifier which eliminates the requirement of a differential power coupler (rat race), and the overall size is reduced. However, there is a requirement of coaxial cable differential feeds that is making it more complicated. The microstrip line feed is desirable as it can be easily fabricated and easily integrated with onboard components, and it is compact in design. It also provides easy connection with different onboard elements or single and differential driven rectifiers without holes or vias. In the other work, the series and parallel connection of the differential rectenna units proposed in [89]. Here it has been stated that the differential rectenna unit provides high expandability of rectenna arrays due to its balanced structure. However, this scheme requires wide bandwidth microstrip antenna, and thus impedance matching with the rectifier is more challenging.

In this chapter, an improved rectenna with a differentially fed antenna array is proposed for efficient RF energy harvesting. A linear, non-uniform, Dolph-Tchebyscheff antenna array with 6 elements is selected. The spacing between elements is provided in a manner such that each element is excited in the same phase. The arrangement is designed with a consideration of side lobes level, i.e. less than -20 dB. For comparison, two antenna array, one with a single feed and other with differential feed is designed and fabricated to operate at 5.8 GHz. The performances of the proposed antennas are verified by the measurement results, such as radiation pattern and return loss. For providing the differential feed, a rat race coupler is also designed and fabricated in Agilent ADS 2011. Then both antennas are tested for RF energy harvesting. The performance of the proposed rectenna is verified by measurement results, such as conversion efficiency, output DC power and also compared with single fed rectenna.

5.2. Differentially fed antenna design



(a)



(b)

Figure 5. 1 Detailed geometry of microstrip antenna array (a) single fed antenna array, (b) differentially fed antenna array, the parameters are, L1=L2=L3=L4=L5=L6=18.69, & W1=W2=W3=W4=W5=W6= 2.39 L1a= 19.23, L1B= 14.65, L1c= 110.34

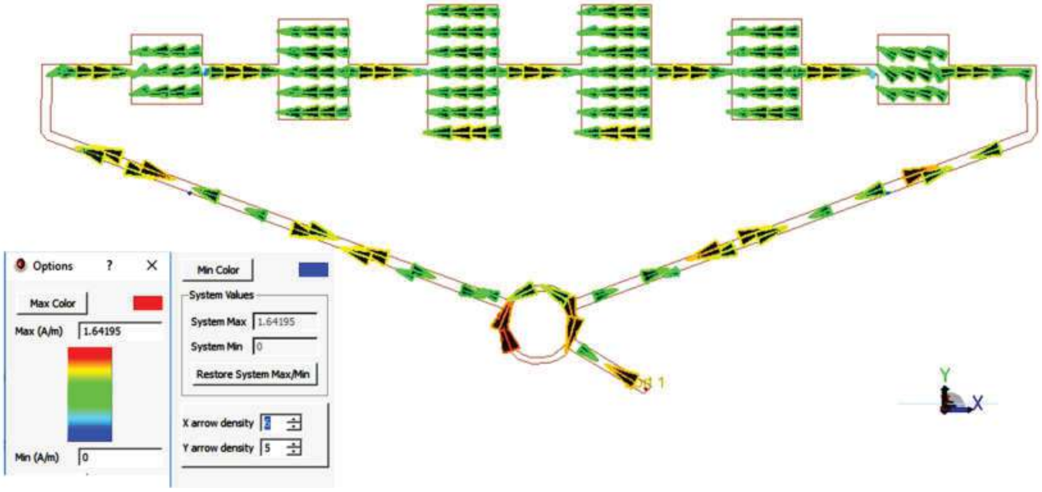
The geometry of the proposed antenna array with single and differential feed is shown in Figure 5. 1(a) and 1(b) respectively. The proposed antenna is designed on RT-Duroid substrate thickness h=31 mil, dielectric constant ε_r =2.2, and loss tangent 0.004. The substrate top and bottom conductor layer have a copper thickness of 18 µm. The bottom conductor can work either as RF ground or reflection plane. A linear, non-uniform, Dolph-Tchebyscheff antenna array with 6 elements is selected. The spacing between elements is λg/2 (λg Guided wavelength), and it is selected such that individual antenna elements are excited in the same phase. In Figure 5. 1 (a), 6 patch elements with series feed are shown, and a single port is connected at feed 1. The array is mirror about the center, i.e., mid-point of line L4, W4, and patches are decreasing in size with distance from the center. The calculated normalized total excitation coefficients are 1 for 3rd and 4th patch, 0.7768 for 2nd and 5th patch, and 0.5406 for 1st and 6th patch. The arrangement has a simulated side lobes level less than -20 dB. A similar antenna array with differential feed is also designed to operate at 5.8 GHz. Accordingly antenna parameters are optimized with feed lines.

Table 5. 1 geometric parameters of array elements

Patch	Width (mm)	Length (mm)
3rd & 4th	30.80	16.87
2nd & 5th	24.27	16.95
1st & 6th	16.75	17.10

The optimized patch element's parameters are listed in Table 5. 1. A microstrip feed is used to match single feed antenna with 50-ohm impedance. For the differential feed, there are two ports, and a rat race coupler is required for converting two ports into a single port. For this purpose, a rat race coupler at 5.8 GHz is also produced in Agilent ADS 2011. Differentially fed antenna array using rat race coupler is shown in Figure 5. 1 (b). The antennae are simulated and designed in Agilent ADS 2011. The ADS has two solvers, by the methods of moment and FEM solver. FEM solver found to be more accurate for planar antenna design. Therefore, this chapter used ADS FEM simulation.

The surface current density of the proposed differentially fed antenna has been shown in Figure 5. 2. Here phase of each array elements are equal, and it can provide high directivity.



Max (A/m) 1.64195

Min (A/m) 0

System Max 1.64195

System Min 0

X arrow density 5

Y arrow density 5

Figure 5. 2 Surface current densities of the proposed antenna at 5.8 GHz

5.3. Results and discussion

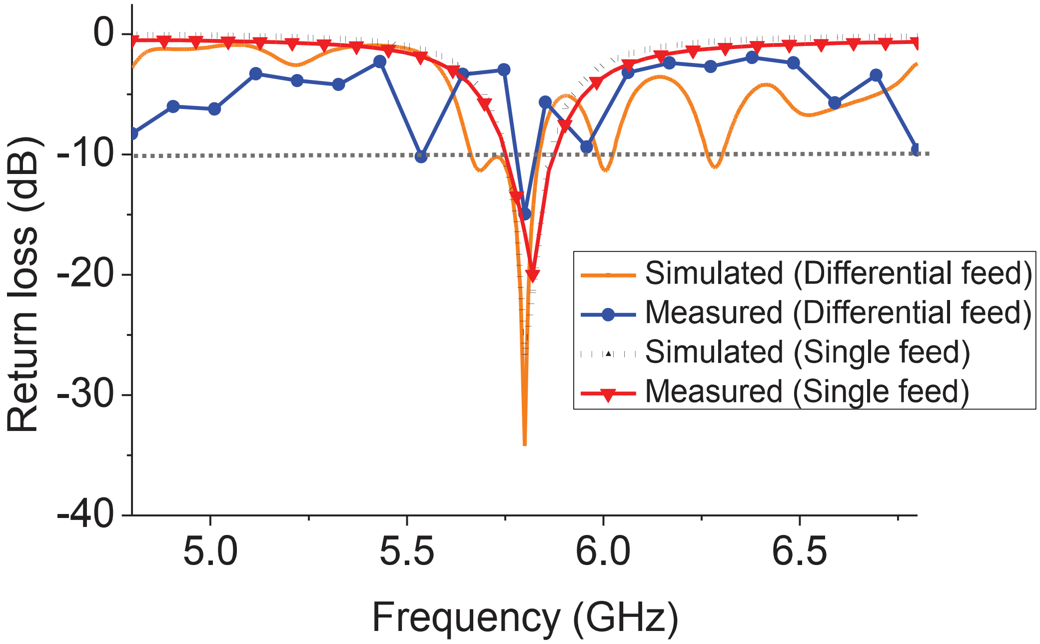
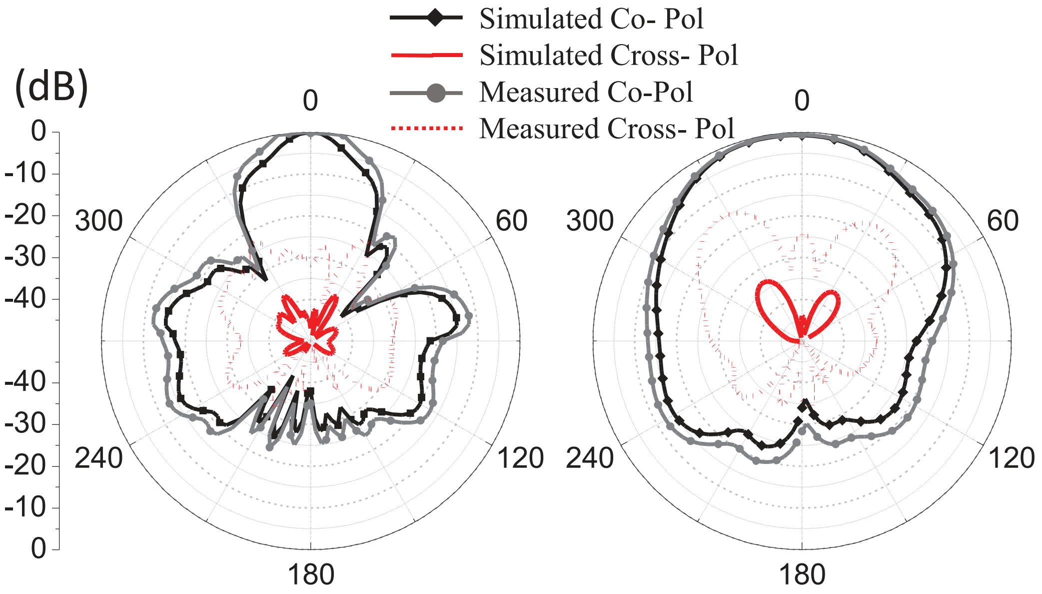


Figure 5. 3 Simulated and measured return loss

The simulated and measured return loss of single fed and differentially fed antenna array is shown in Figure 5. 3. The measured -10 dB bandwidth for a single fed antenna array is from 5.75 GHz to 5.88 GHz, and for the differentially fed antenna array is from 5.77 GHz to 5.84 GHz. The Simulated and measured radiation pattern of single fed antenna array's E- plane and H- plane is shown in Figure 5. 4 (a) and 4 (b) respectively. The Simulated and measured radiation pattern of the proposed differentially fed antenna array's E- plane and H- plane is shown in Figure 5. 5 (a) and 5 (b) respectively. At 5.8 GHz, the measured peak gain of the single fed antenna array is 13.38 dBi while the simulated peak gain is 14.42 dBi.



(a) (b)

Figure 5. 4 Simulated and measured radiation pattern of the single fed antenna array at 5.8 GHz (a) E- plane (b) H- plane

The differentially fed antenna has measured, and simulated peak gain is 14.29 dBi and 14.95 dBi respectively. It is observed here that the differentially fed antenna array has higher peak gain than the single fed antenna array by 0.90 dBi at 5.8 GHz. The enhancement in the peak gain of the differentially fed array over single fed can be explained by the radiation pattern of two arrangement. From the Figures, one can notice that the cross polarization of the differentially fed antenna array is much lower than the single feed antenna array, both in the E-plane and H-plane. Mainly in the H-plane, the difference is more significant. As a result, the radiation efficiency of the differential feed antenna has been enhanced and producing superior gain. Here it is also observed that the measured cross polarization is higher than simulated results. This difference might be produced from the design tolerance and due to practical testing set up condition.

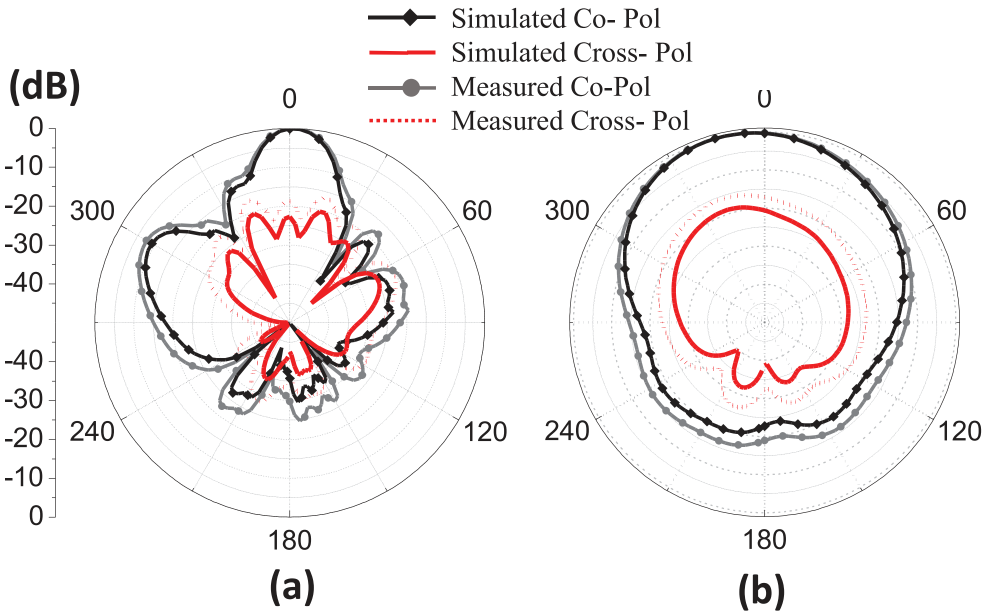


Figure 5. 5 Simulated and measured radiation pattern of the proposed differentially fed antenna array at 5.8 GHz (a) E- plane (b) H- plane

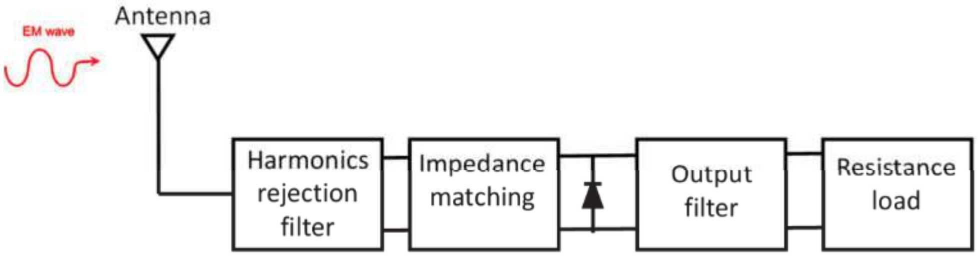


Figure 5. 6 Rectenna components

5.4. RF energy harvesting

High frequency (HF) Schottky diodes are utilized for rectifying RF signal into DC power. To match antenna output impedance with a rectifier, a matching circuit is required in between. To suppress harmonics, there is also a requirement of a band pass filter. Rectenna block diagram with components is shown in Figure 5. 6. In the load side, an output filter is also required.

5.4.1. Rectifier design

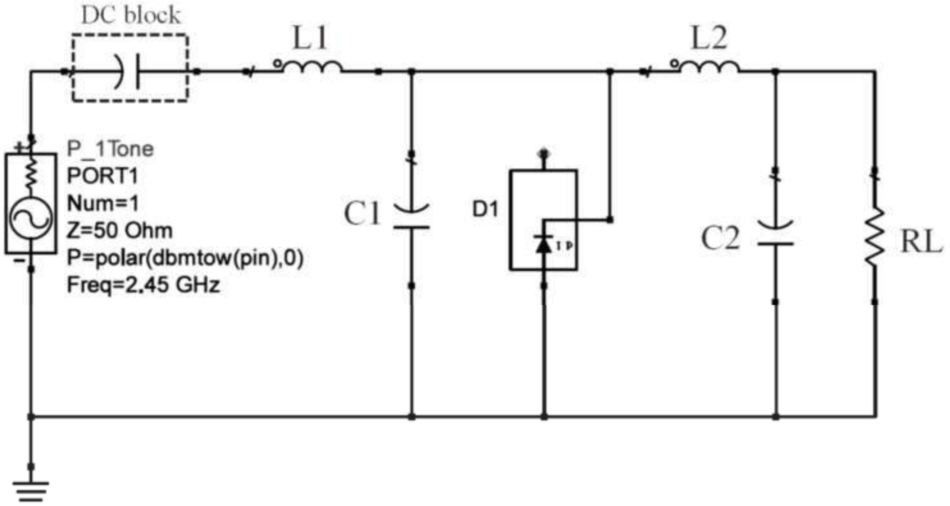


Figure 5. 7 Rectifier schematic

The rectifier topology is shown in Figure 5. 7. In this inductor L1, capacitor C1 acts as low pass filter, while inductor L2, capacitor C2 acts as output DC pass filter. Schottky diode HSMS-2860 (threshold voltage 350 mv & break down voltage 7 V) is used as D1 here. The circuit parameters L1, C1, L2, C2, and RL, can be first calculated; then the software ADS can be utilized to optimized those parameters. For this ADS optim toolbox with optimization type genetic and iteration 500 is used with proper optimization goal settings. After optimization the found parameters are L1 = 7.5 mH, C1 = 0.37 pF, L2 = 7.88 mH, C2 = 280 pF, and RL = 200 ohm.

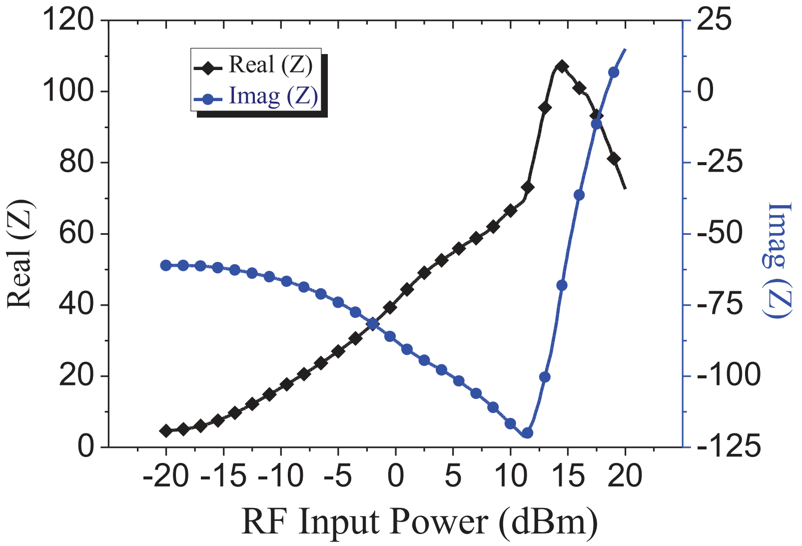
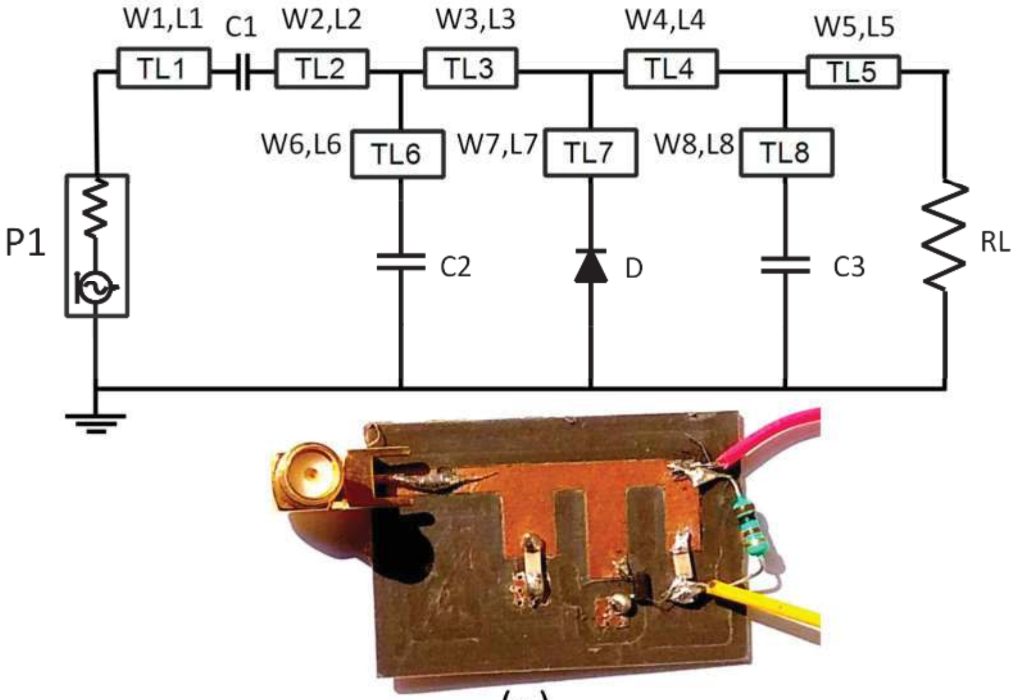
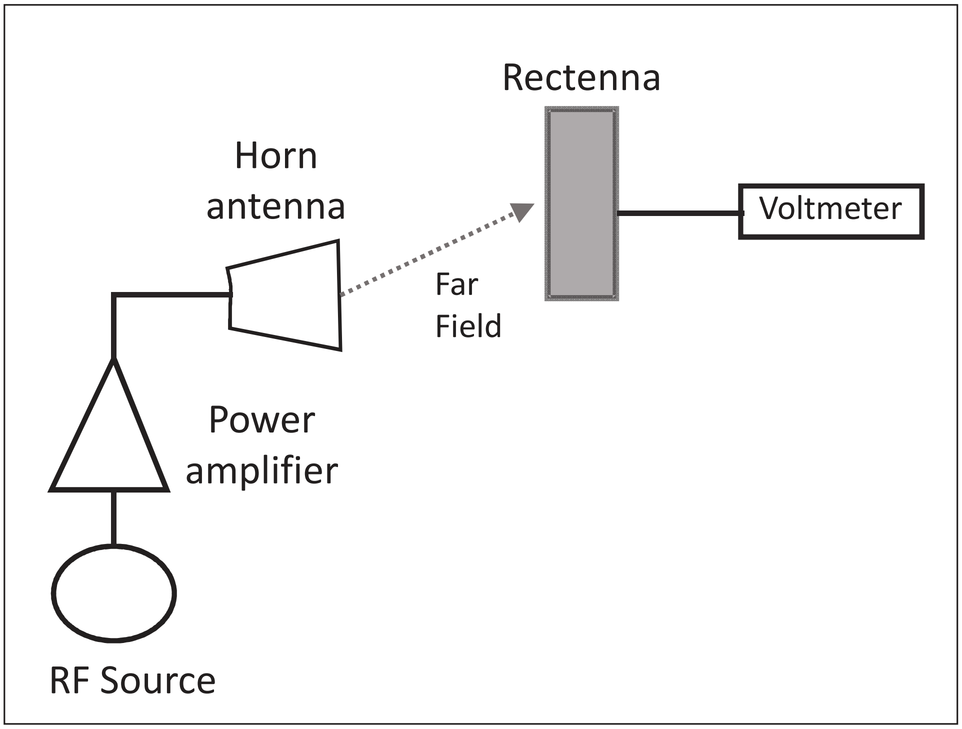


Figure 5. 8 Rectifier input impedance’s real and imaginary value variation with input power (dBm)



(a)



(b)

Figure 5. 9(a) Circuit schematics of the proposed single-driven rectifier, the parameters are, L1= 2.5, L2= 2.5, L3= 8.2, L4= 8.2, L5= 3, L6= 7.1, L7= 9.7, L8= 7.4 and W1=W2=W3=W4=W5= 1.2, W6= 5, W7= 3.9, W8 = 3.4, C1= 1 pF, C2= 4 pF, C3= 4 pF, RL= 1000 ohm (b) measurement setup

Also, the rectifiers input impedance is varying with RF input power and the load. Rectifier input impedance's real and imaginary value variation with input power (dBm) is provided in Figure 5. 8.

The rectifier's optimized circuit schematic with detailed parameters is provided in Figure 5. 9 (a). The variation of rectifier output DC power with different RL are plotted in Figure 5. 10. The variation of rectifier efficiency with different RL is plotted in Figure 5. 11.

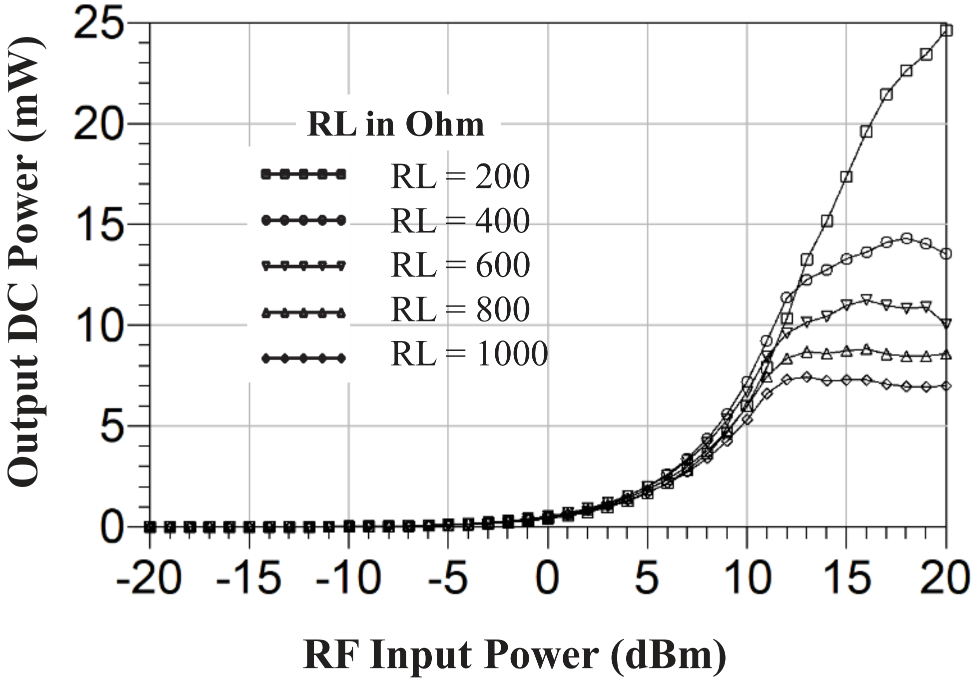


Figure 5. 10 Variation of Output DC power (Watt) with different RF input power (dBm)

5.5. Experimental results

The differentially fed antenna array (in Figure 5. 1 (b)) is connected to single-ended rectifier (in Figure 5.9 (a)), thus differentially fed rectenna is produced, and it is tested for RF energy harvesting. The differentially fed microstrip rectenna is designed at 5.8 GHz. The circuit schematic and detailed parameters are shown in Figure 5. 1 (b) and Figure 5. 8. A resistive load of 1000 Ohm is connected to the rectenna. For investigating the comparative performance, a single fed rectenna is also fabricated and tested. Both rectenna are printed on an RT-Duroid substrate of thickness h=31 mil, dielectric constant 2.2 and loss tangent 0.004.

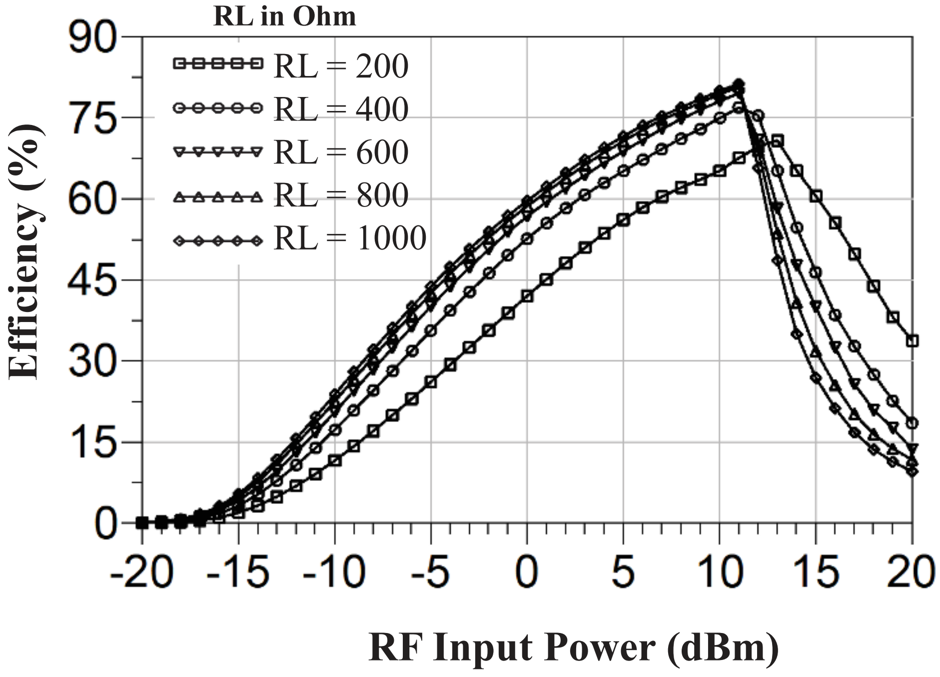


Figure 5. 11 Variation of efficiency (%) with different RF input power (dBm)

The proposed rectennas are measured in an anechoic chamber. An RF source with amplifier is used, it can excite RF power of 25 dBm. A high-directivity horn antenna (about 10 dBi gain at 5.8 GHz) is used, it has larger dimension D of 15 cm. Then rectennas under test is placed at a distance of 95 cm from transmitting horn antenna. The distance in between satisfies far field condition ($R > {2D^2}/{\lambda} \sim 87\ cm$) at 5.8 GHz. The measurement setup is shown in Figure 5. 9 (b). In the measurement, RF-DC conversion efficiency can be calculated as in equation (5.1).

$$\eta(\%) = \frac{Output\ DC\ power}{RF\ Input} \times 100 \tag{5.1}$$

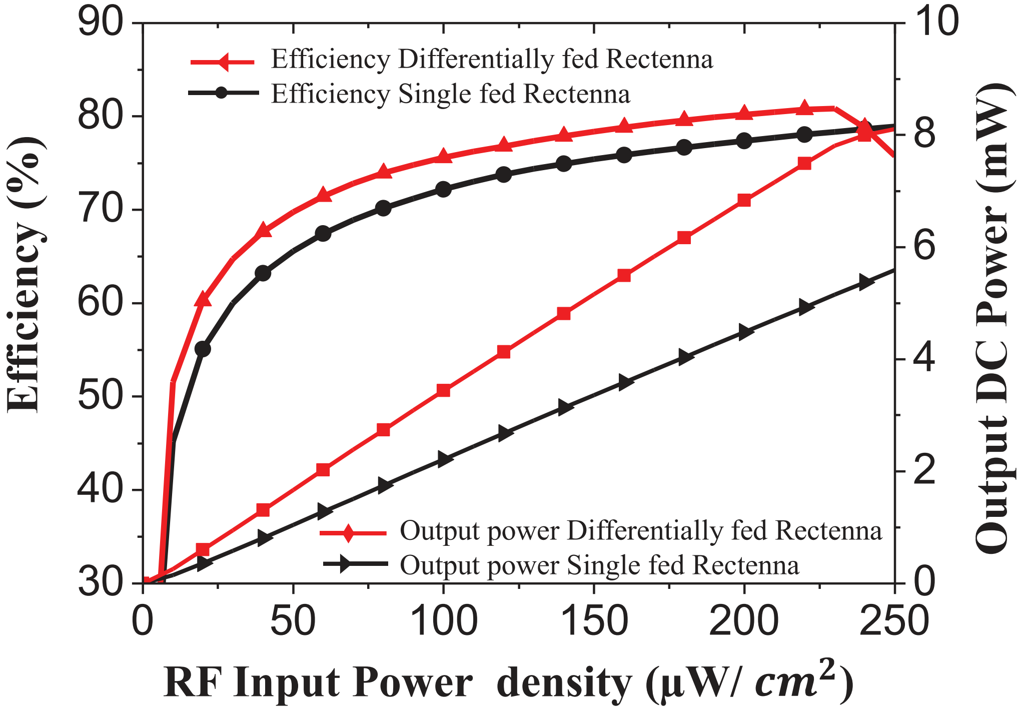


Figure 5. 12 measured efficiency and output power of single fed and the proposed differentially fed rectenna

Table 5. 2 Comparison of previous high-frequency rectifiers for energy harvesting application

Source	Operating frequency (GHz)	Feed type & Port type	Required RF power (μW/ cm^2) for maximum efficiency	Maximum measured efficiency (%)
[89]	5.8	Microstrip & differential	4.1	44.1
[93]	2.45	Coaxial & Single	300	51.5
[87]	5.8	Coaxial & differential	207	73.9
This paper	5.8	Microstrip & differential	232	82.4

The measured RF-DC conversion efficiency and the output power of the two rectenna versus RF input power density are shown in Figure 5. 12. From the Figure 5. 12, one can notice that the differentially fed rectenna has higher output DC power than the single fed antenna.

The Differentially fed rectenna has maximum RF-DC conversion efficiency of 238 μW/cm^2. It can be found that the differentially fed rectenna has a higher efficiency for the input power density from 5 μW/ cm^2 to 238 μW/cm^2, after this point the efficiency starts decreasing, and becoming lower than single feed rectenna. A comparison among previous high frequency rectifiers for energy harvesting application is presented in Table 5. 2.

5.6. Summary

In this chapter, an enhanced rectenna with differentially fed antenna array for RF to DC conversion is proposed. Firstly, a linear antenna array is designed considering its side lobes less than -20 dB. Two antenna array, one with a single feed and other with differential feed is designed to operate at 5.8 GHz. The measured peak gain of single fed and differentially fed are 13.38 dBi and 14.29 dBi respectively, at 5.8 GHz. The two antenna array, one with a single feed and other with differential feed is tested for RF energy harvesting. It is observed that the differentially fed rectenna has higher output DC power than the single fed rectenna. The Differentially fed rectenna has higher efficiency as compared with single fed rectenna for the power density variation from 5 μW/ cm^2 to 238 μW/cm^2, it has maximum efficiency (RF-DC) of 82.4 % at 232 μW/cm^2.