Chapter 4: Design of differential source fed circularly polarized rectenna with embedded slots for harmonics suppression

4.1. Introduction

In the previous chapter, rectenna analysis is presented which is more focused on impedance matching component. However, for a conventional rectenna, the interface between antenna and rectifier circuit has a harmonic suppression filter which leads to circuit complexity and occupies extra space. Hence it is not suitable for compact rectenna design [83-85].

High frequency (HF) Schottky diodes are utilized for rectifying RF signal into DC power [86]. For low-level RF signal, the rectifier’s efficiency is very poor. Thus energy harvesting may fail. A Rectenna Using Differentially-Fed Rectifier for WPT has been proposed in [87], but it requires a differential antenna with coaxial probe feeding and a rectifier that is placed on a separate board. The rectenna device which is easy in fabrication and onboard integration with other components is highly preferable [88]. In another work, a differential rectenna scheme has been proposed in [89, 90] with improved efficiency at low signal level. However, the designed differential rectenna is linearly polarized and thus highly sensitive to the device or source movement. Therefore an onboard CP rectenna with single microstrip feed is preferable for RF energy harvesting

[90]. The Schottky diode rectifier has nonlinear property, and it produces signal harmonics when connected to antenna [91]. Therefore, there is a requirement of the bandpass filter (BPF) between them to eliminate signal harmonics. A coaxial feed CP antenna with harmonics suppression capability has been proposed in [92]. Here, the patch with loaded slots provides higher-order resonance frequency shift which is different from operating frequency harmonics. Therefore the proposed scheme eliminates the requirement of BPF; it is due to the mismatch of the signal harmonics and higher-order resonance mode. However, the proposed work is not suitable for compact rectenna application as it requires coaxial feed.

In this chapter, a new rectenna is provided with differential source feeding scheme for the low cost and efficient RF energy harvesting. First, a microstrip antenna with a diametrically opposite peripheral projection of isosceles right triangle shape which provides CP is designed. The antenna has four internal slots that are deliberately made to suppress higher order harmonics and enhance fundamental resonance mode. To show it's harmonics rejection capacity, a conventional linearly polarized (LP) circular patch antenna without slots [93] is also designed and fabricated at 2.45 GHz, and their return loss results are compared. The performance of the proposed antenna is verified by the measurement results, such as radiation pattern and return loss. The designed antenna is then tested for RF energy harvesting in two ways. One is conventional SSFR, and other is new DSFR. In the DSFR, the designed antennas are differentially operated by making a difference of $\lambda g/2$ path length; and the ports are then connected to a differentially driven optimized rectifier circuit. For the comparison, an SSFR and a DSFR are fabricated and tested. The experimental results verify the performance of the proposed rectenna.

4.2. Antenna design

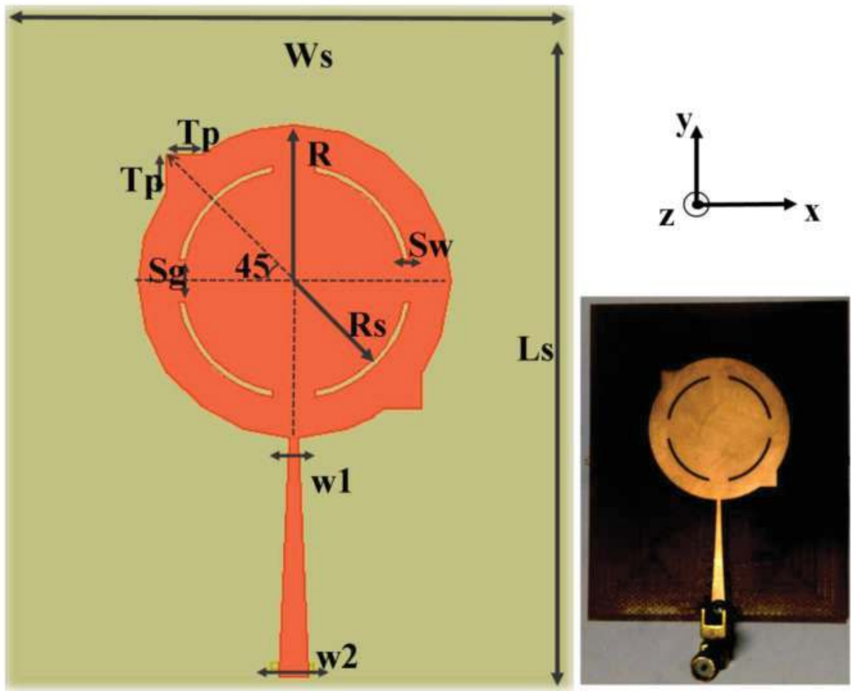


Figure 4. 1 Geometry of proposed circular polarization antenna with harmonics suppression, the parameters (values in mm) are, Ws = 60, Ls = 80, R = 16.3, Rs = 11.7, Tp = 4.1, Sw = 4, Sg = 4.5, W1 = 0.7, W2 = 3.02.

The geometry of the proposed antenna is shown in Figure 4. 1. The substrate top conductor layer has a copper thickness of 35 µm, it has a circular microstrip patch of radius *R*, and it has two diametrically opposite peripheral projection of isosceles right triangle shape. The right angle triangular shape is selected to excite CP. Also, the top patch has four radial slots, slot width *Sw* and the gap between them is *Sg*. Slots are equidistance from the center with radial distance *Rs*. Here, slots are made purposely to block harmonic signals that are produced due to connection with the nonlinear load. The structure is designed on the substrate with length *Ls*, and width *Ws* and the bottom layer is covered with copper. The bottom conductor can work either as the RF ground or the reflection plane. A tapered microstrip single feed is used to match antenna element with 50-ohm impedance at *w2* as depicted in Figure 4. 1.

The proposed antenna is designed on FR4 substrate thickness (*h)* 1.6 mm, dielectric constant (*εr)* 4.4, and a loss tangent of 0.02. The circular patch has two peripheral isosceles right triangle projection that is diametrically opposite at 45 degrees from the X-axis, and feed is connected at the lowest Y- axis point. This arrangement can excite the near-degenerate orthogonal resonant modes which provide CP. The isosceles right triangle projection has a dimension of length *Tp*. The antenna is simulated and designed in Agilent ADS 2011. The ADS has two solvers, by the methods of the moment and finite element method (FEM) solver and ADS FEM simulation have been used.

4.2.1. Circular polarization

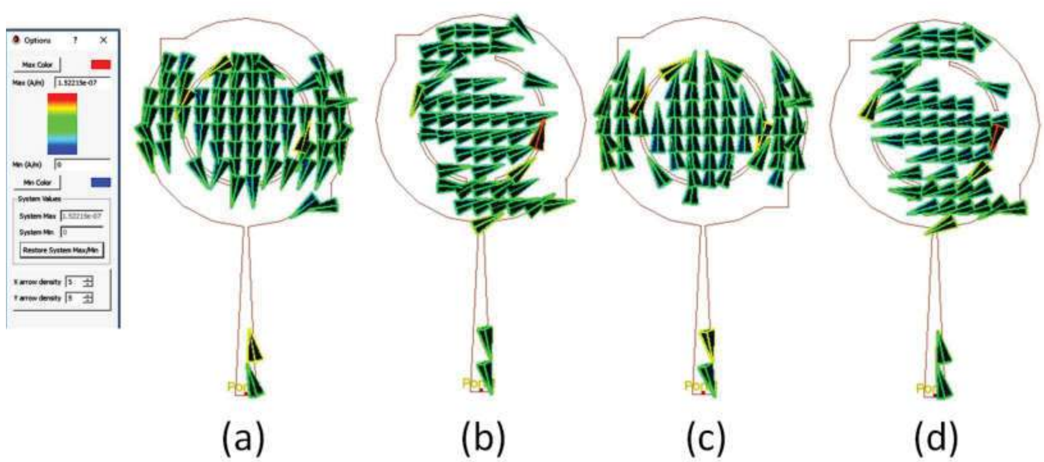


Figure 4. 2 Surface current orientation at (a) 0. (b) 90. (c) 180. (d) 270 degrees, here degree means time progress in one period.

To verify the CP behavior of the proposed antenna, the surface current distribution on the top patch at 2.45 GHz at 0^{o}, 90^{o}, 180^{o}, and 270^{o} are depicted in Figure 4. 2 (a), (b), (c), and (d) respectively. From these Figures, one can easily predict that the surface current rotates synchronously with phase making it CP. At the desired resonant frequency, two orthogonal modes with the 90-degree phase difference for CP can be optimized by adjusting *Tp* size. It is also observed that if only one isosceles right triangle projection is used, it will generate left-hand circular polarization, and a diagonal mirror projection will generate right-hand circular polarization.

4.2.2. Harmonics blocking

An antenna or any AC signal source when connected with nonlinear elements produces signal harmonics; these harmonics can re-resonate antenna and efficiency is highly reduced. Therefore a bandpass filter (BPF) is required in-between to eliminate such undesired harmonics. However, there is an alternative which can also eliminate undesired harmonics without using a BPF. In this design four radial slots in the patch are used instead of using BPF, they are equidistance from the center, and there are four equal gaps in between. The slots dimension and gap lengths are optimized or adjusted in such a way that fundamental mode of resonant is increased, but higher order resonant modes are reduced. The slots help to shift antenna's higher order resonant modes at different frequencies that is without disturbing it's fundamental resonant mode. In this way, due to slots arrangement and optimization the operating frequency signal harmonics and antenna's higher order resonant modes are highly mismatched, and as result antenna's re-resonation and efficiency loss problem is eliminated now. Thus a BPF can be removed.

The return loss for an LP circular patch antenna (without slots) has been compared with the proposed CP antenna (with slots); their simulated and measured return loss are shown in Figure 4. 3.

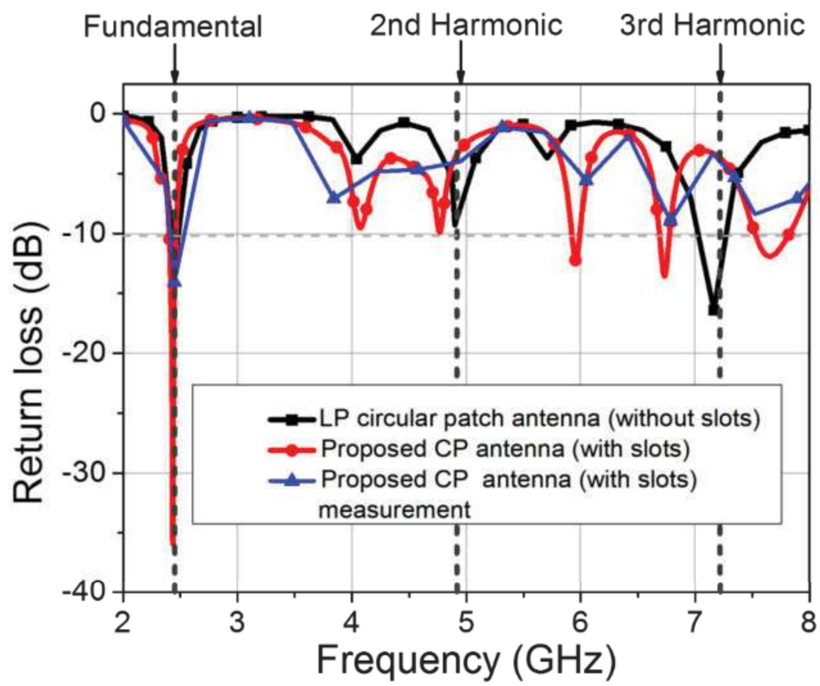


Figure 4. 3 Simulated and measured return loss

The LP circular patch antenna (without slots) has a fundamental resonant frequency at 2.45 GHz with a return loss of 14 dB. It's 2nd order resonant, and 3rd order resonant are at 4.9 GHz (9.56 dB) and 7.35 GHz (14.6 dB) respectively. It is to be noticed here that higher-order resonant modes and signal harmonics are similar to the LP circular patch antenna. Whereas the proposed CP antenna has an improved return loss of 37.2 dB at a fundamental resonant frequency, i.e., 2.45 GHz. But It's 2nd order resonant, and 3rd order resonant are now shifted from 4.9 GHz to 4.75 GHz with 9.13 dB return loss and from 7.35 GHz to 6.75 GHz with 12.6 dB return loss respectively. The proposed CP antenna's simulated return loss decreased to 1.89 dB at 4.9 GHz, and 2.31 dB at 7.35 GHz and signal harmonics due to nonlinear elements are now suppressed. Figure 4. 4 (a), 4 (b), 4 (c) shows the surface current densities of the proposed CP antenna resonance at fundamental, 2nd order and 3rd order respectively. Due to embedded slots, higher order current paths have been increased, and higher order harmonics are now shifted to a different frequency. Here it is observed that variation of slot's radial distance and the gap between slots, the higher-order mode current path can be adjusted, and it can be optimized as per the requirement.

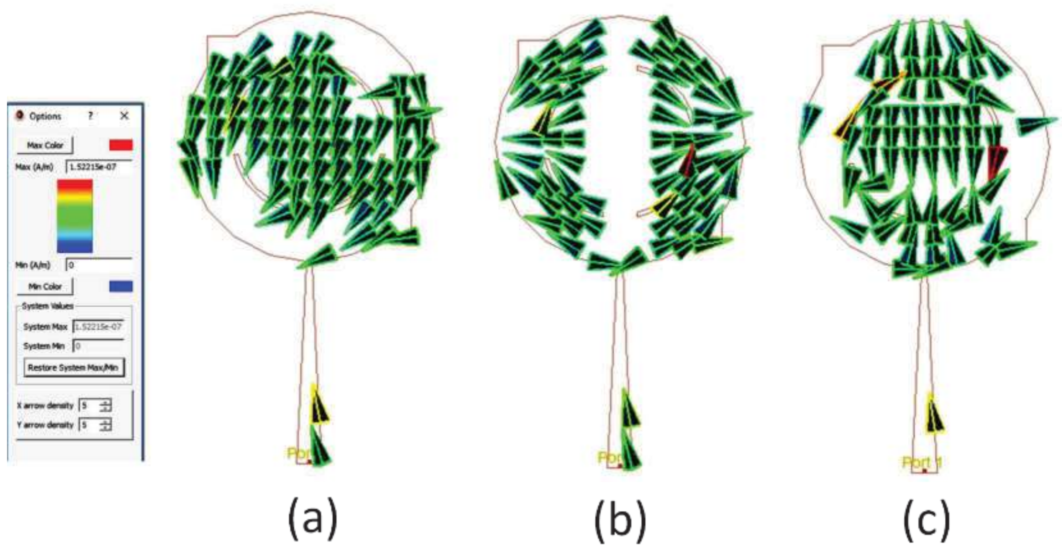


Figure 4. 4 Surface current densities of the proposed antenna's resonance at (a) Fundamental (2.45 GHz). (b) Second order (4.75 GHz). (c) Third order (6.75 GHz).

4.3. Parametric study

Various parameters may influence the performance of the proposed antenna structure. The dimension of isosceles right triangle peripheral projection is affecting the circular polarization axial ratio bandwidth, and slots arrangement are affecting the higher order resonant mode. The parametric analysis is performed in Agilent ADS 2011 electromagnetic simulation to show their effects.

4.3.1. Effect of isosceles right triangle projection

In the FEM simulation, the isosceles right triangle projection diagonals *Tp* is varied from 3.6 mm to 4.2 mm. The return loss variation with different *Tp* is illustrated in Figure 4. 5. Here With the increase in *Tp* size, the resonant frequency decreases, and the optimized value is obtained at 3.9 mm at which the structure has highest CP axial ratio bandwidth and 2.45 GHz resonant frequency.

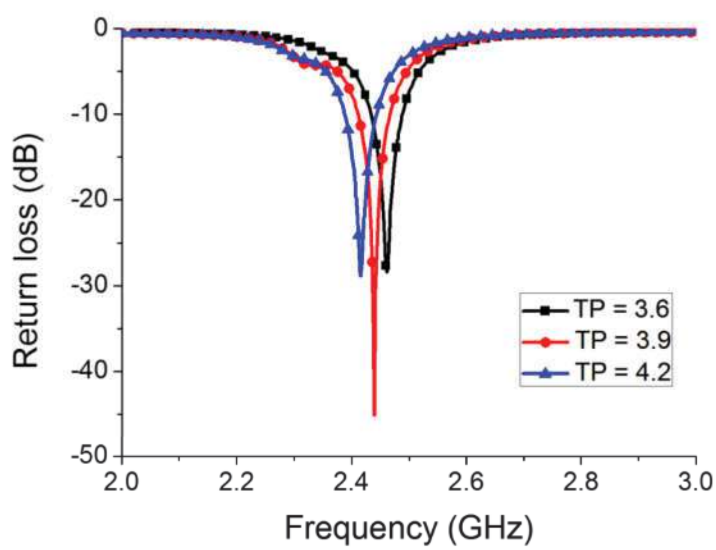


Figure 4. 5 Simulation of proposed antenna with varying Tp (values in mm)

4.3.2. Effect of the radial slot

The radial slots distance from the center *Rs* is varied from 11.1 mm to 12.3 mm. The return loss variation with different *Rs* is shown in Figure 4. 6. It has been found that higher-order resonant modes depend on the *Rs*, here resonant modes are shifting toward lower frequency while increasing the *Rs*. At the optimized *Rs* value, i.e., 11.7 mm, the antenna 2nd and 3rd resonant modes are shifted far below from the nonlinear operating signal (2.45 GHz) harmonics.

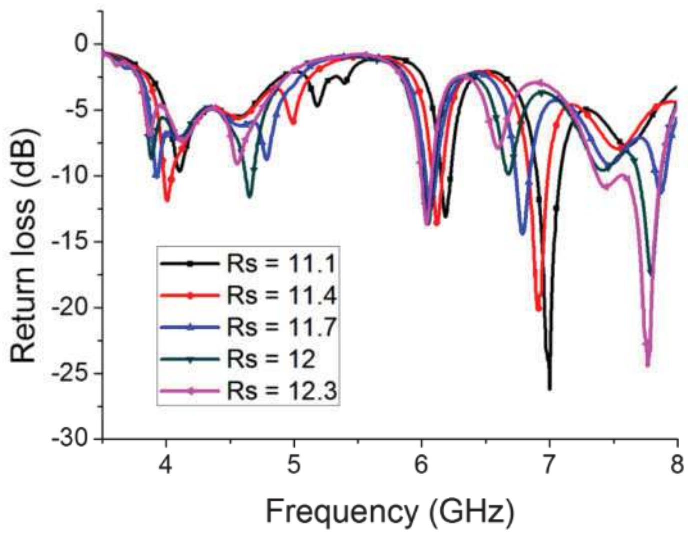


Figure 4. 6 Simulation of proposed antenna with varying Rs (values in mm)

4.3.3. Effect of slot gap

The radial slots have a gap between *Sg*; its value is varied from 3.3 mm to 4.5 mm as shown in Figure 4. 7. The variation of *Sg* highly influences the higher-order resonant mode bandwidth. However, the lower bandwidth is preferred because there is a requirement to block nonlinear signal harmonics. The optimized value is found at *Sg* equals to 3.9 mm.

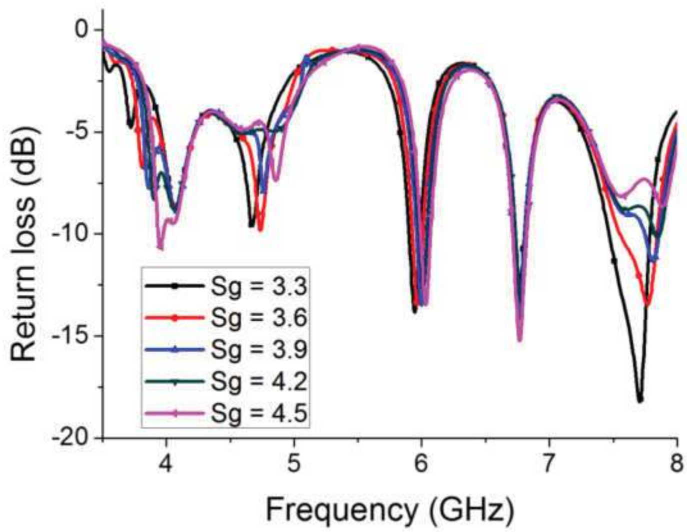


Figure 4. 7 Simulation of proposed antenna with varying Sg (values in mm)

4.3.4. Results and Discussion

The prototype of the proposed antenna is designed, fabricated and tested to validate simulation results. Simulated and measured results show good agreement. The proposed antenna's measured return loss at 4.9 GHz, and 7.35 GHz is 2.46 dB and 2.91 dB respectively. Thus the proposed antenna effectively eliminates operating signal harmonics, and it can be connected to a nonlinear element without BPF. The radiation pattern in E- Plane and H- Plane has been shown in Figure 4. 8.

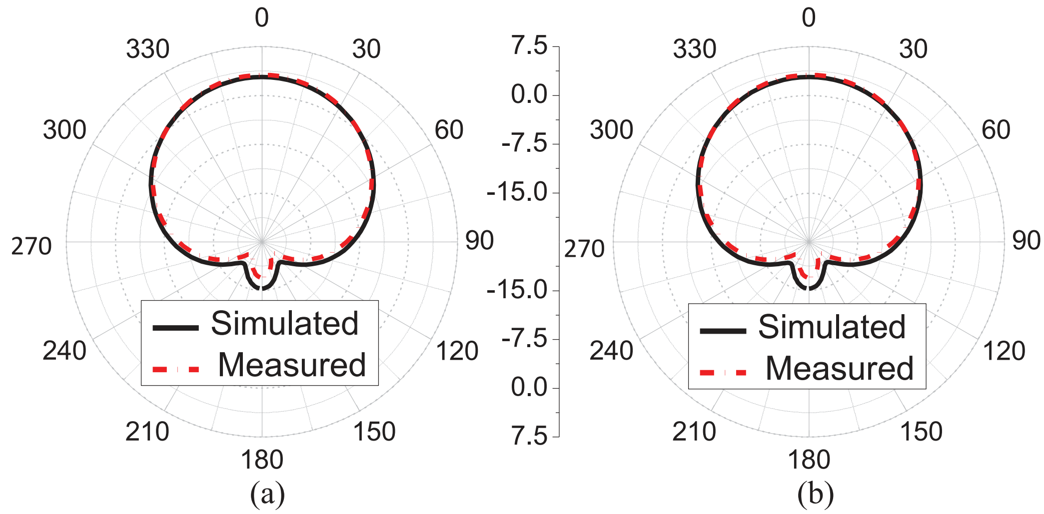


Figure 4. 8 Simulated and measured radiation pattern of the proposed antenna (a) E-plane (b) H- plane

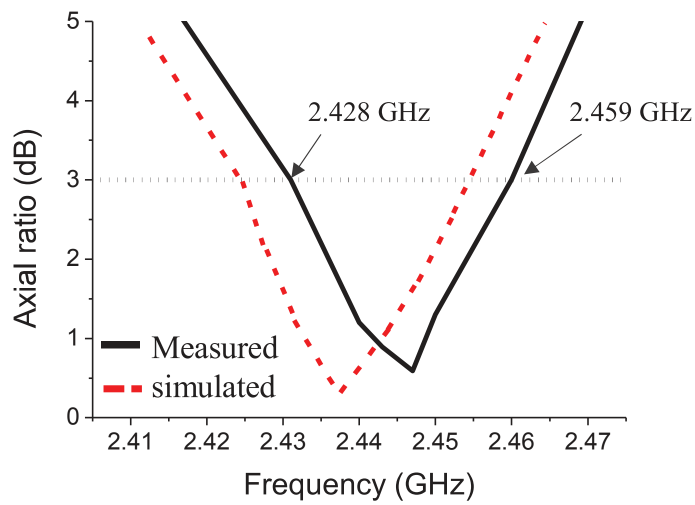


Figure 4. 9 Simulated and measured axial ratio

The radiation pattern is identical in both planes, confirming good circular polarization property. The antenna has a maximum gain of 3.16 dBi at the fundamental resonant frequency, i.e., 2.45 GHz. Simulated and measured axial ratio is shown in Figure 4. 9.

The circular polarization 3 dB axial ratio bandwidth is from 2.428 GHz to 2.459 GHz frequency that is found to be 31 MHz, with the minimum axial ratio of 0.68 dB.

4.4. RF-DC conversion

4.4.1. SSFR

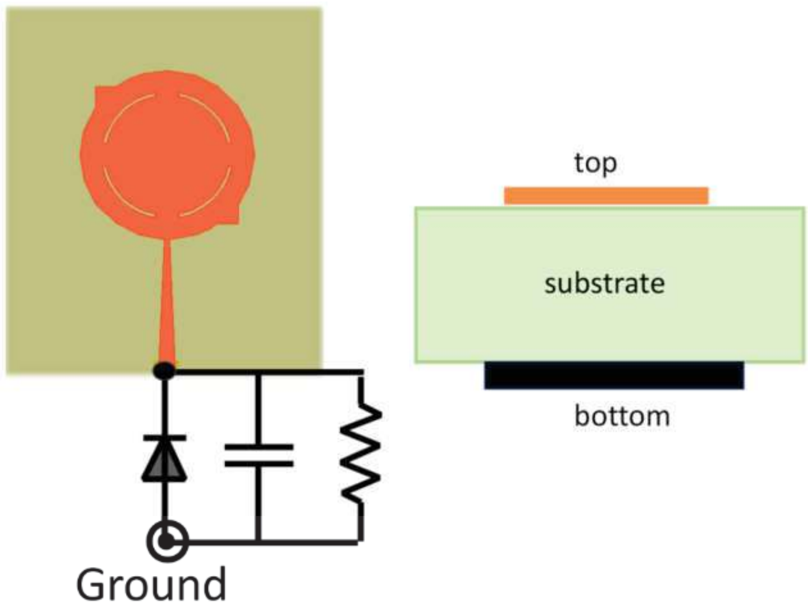


Figure 4. 10 Single source antenna connected to a rectifier circuit

The configuration of conventional SSFR is shown in Figure 4. 10. A single source antenna that is presented in Figure 4. 1 has been used for RF energy harvesting. The rectifier with matching circuit is connected to the top microstrip feed at *w2* and the ground. Here, the rectifier is designed on a separate board such that the RF-ground and DC- ground are isolated.

4.4.1.1. Single driven rectifier for SSRF

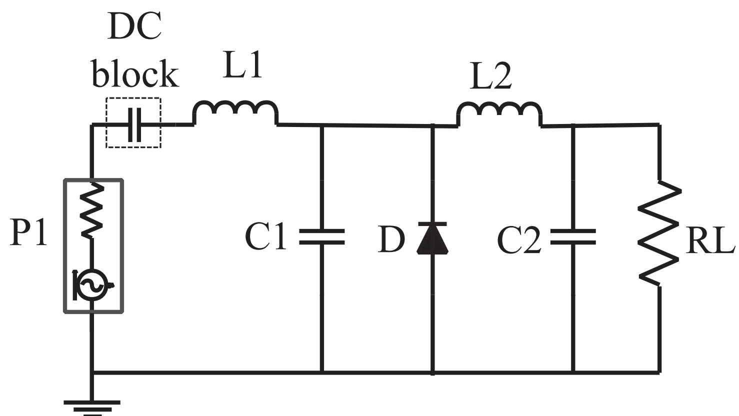


Figure 4. 11 Circuit diagram of a Single driven rectifier

The single source antenna connected with rectifier circuit topology is shown in Figure 4. 11. An RF source with P1 is applied here. 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 D 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 proper optimization goal settings is used. Here optimization type genetic and iteration 500 is used. After optimization the parameters are L1 = 7.5 mH, C1 = 0.37 pF, L2 = 7.88 mH, C2 = 280 pF, and RL = 200 ohm. The circuit schematic of the proposed single driven rectifier with detailed parameters has been provided in Figure 4. 12.

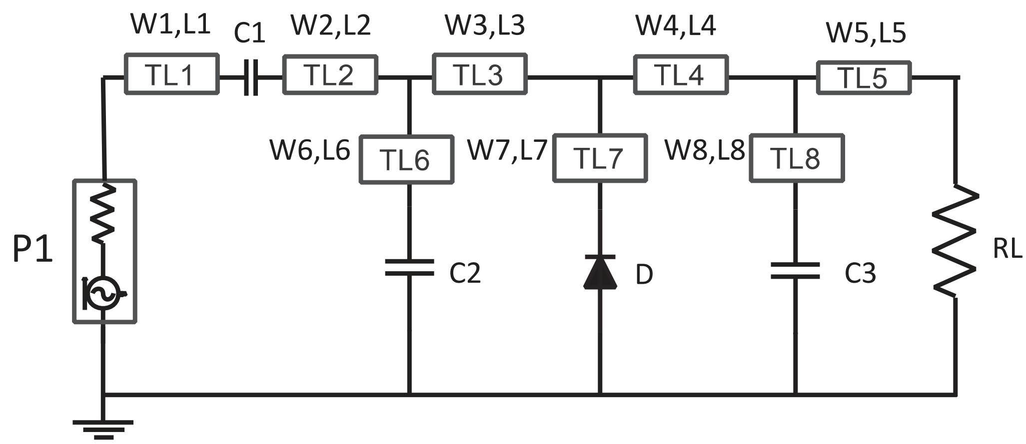
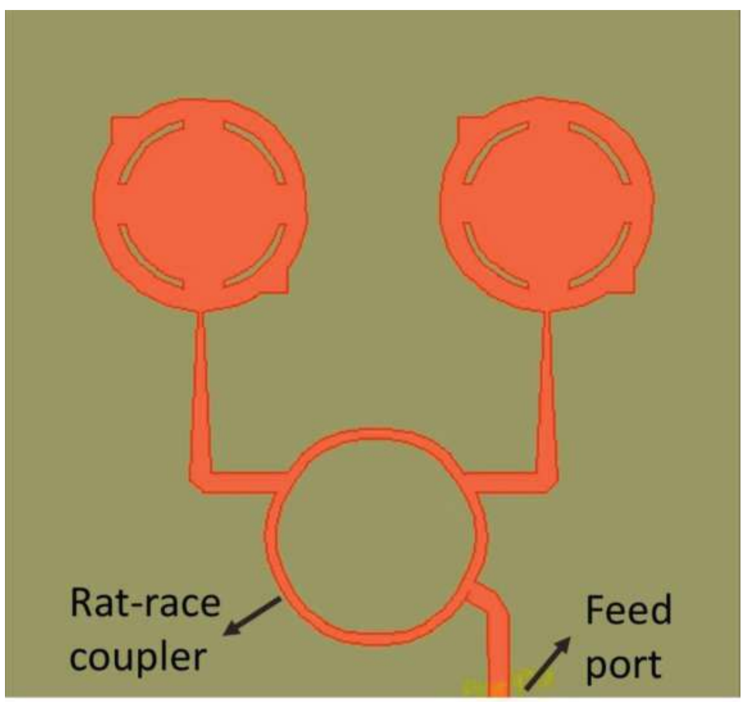
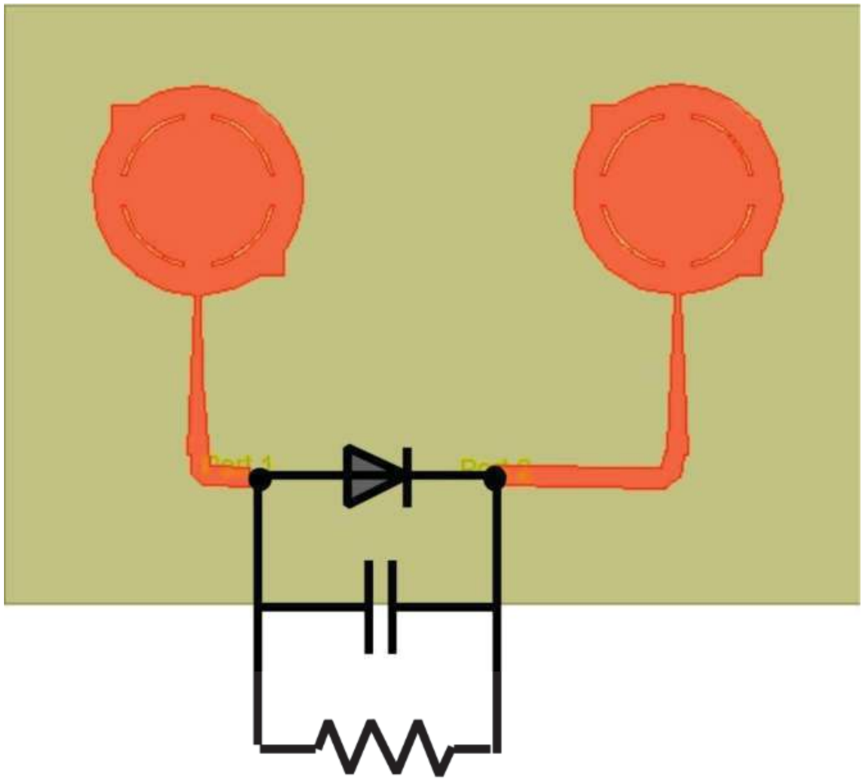


Figure 4. 12 Circuit schematics of the proposed single-driven rectifier, the parameters are, L1= L2= 2.5 mm, L3= 8.2 mm, L4= 8.2 mm, L5= 3 mm, L6= 7.1 mm, L7= 9.7 mm, L8= 7.4 mm and W1=W2=W3=W4= 1.12 mm,W5= 2.4 mm, W6= 5.1 mm, W7= 3.8 mm, W8 = 3.5 mm, C1= 1 pF, C2= 4 pF, C3= 4 pF, RL= 1200 ohm

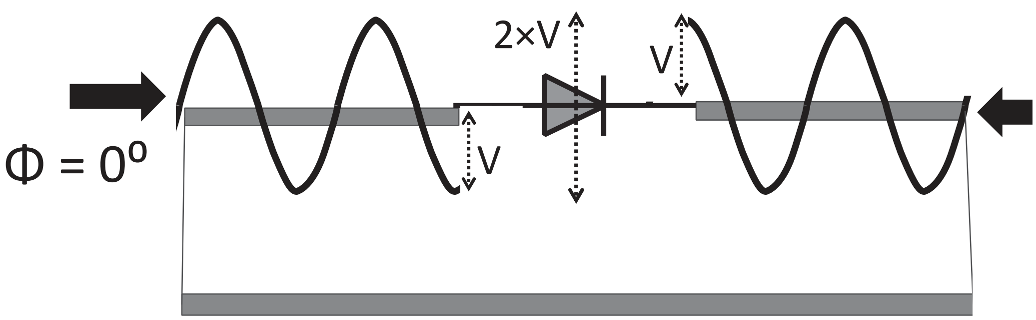
4.4.2. Proposed DSFR



(a)



(b)



(c)

Figure 4. 13 (a) direct measurement of differential source fed antennas using rat race coupler to transform two ports into single port (b) Differential source fed rectenna (b) RF voltage applied to the diode in differential source fed condition

Two top patches from Figure 4. 1 is placed as in Figure 4. 13 (a), and differential input power is provided. For testing, this differential source fed antenna in a real situation; a rat race coupler has been used to transform two ports into single port as shown in Figure 4. 13 (a). Here, a rat race coupler is designed in ADS at 2.45 GHz to provide differential power input, and the measured return loss of 14.6 dB is found at 2.45 GHz. In the differential structure with rat-race coupler, two patches are symmetrical, and their feed lengths are equal. Now, the differential ports in Figure 4. 13 (a) is transformed into a single port. Thus the single driven rectifier that is designed for SSRF can be easily connected, and rectenna performance can be tested.

Here, DSFR configuration that is presented in Figure 4. 13 (b) is used. It is an alternate rectenna design without rat-race coupler, and it is also compact design. Here two symmetrical patches from Figure 4. 1 is used, but now their feed lengths have a path difference of λ/2 to provide differential source fed mode, and port's connection has been shown in Figure 4. 13 (b). At any instant, the voltage at port 1 and port 2 is 180^{o} out of phase; this is because of the two feeds have a path difference of length L = 33.127 mm, i.e., λg/2 (simulated and calculated at 2.45 GHz in ADS software). In this mode, the voltage applied to rectifier is shown in Figure 4. 13 (c). The geometry of differential source fed rectenna is shown in Figure 4. 14. In the construction, two proposed top patches from Figure 4. 1are connected as shown in Figure 4. 14.

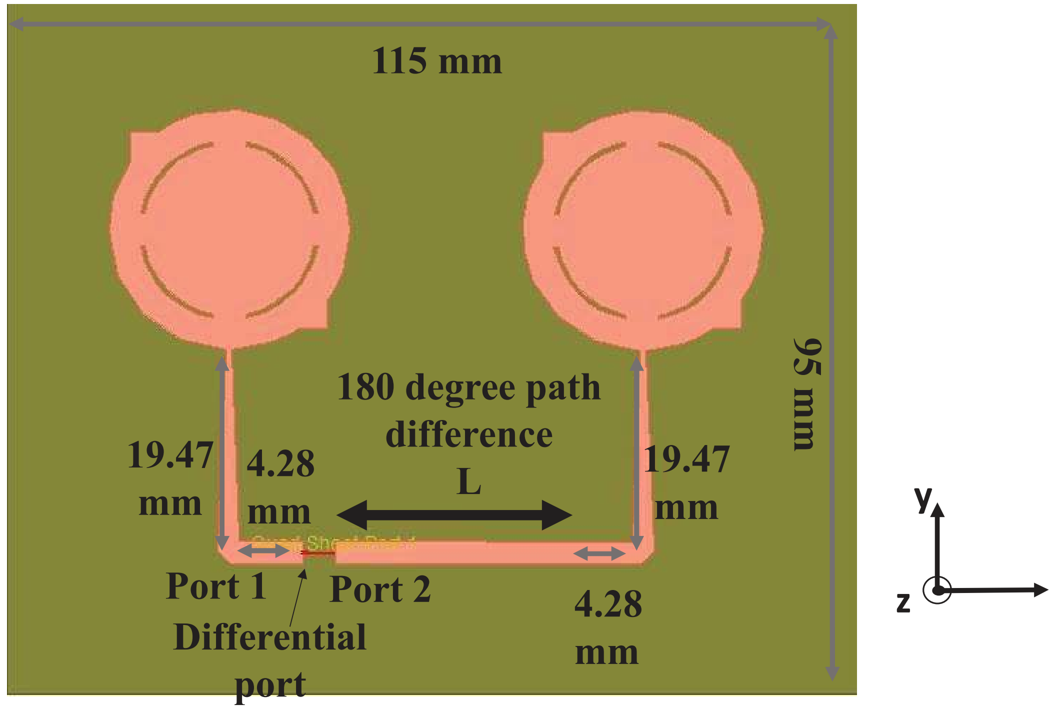
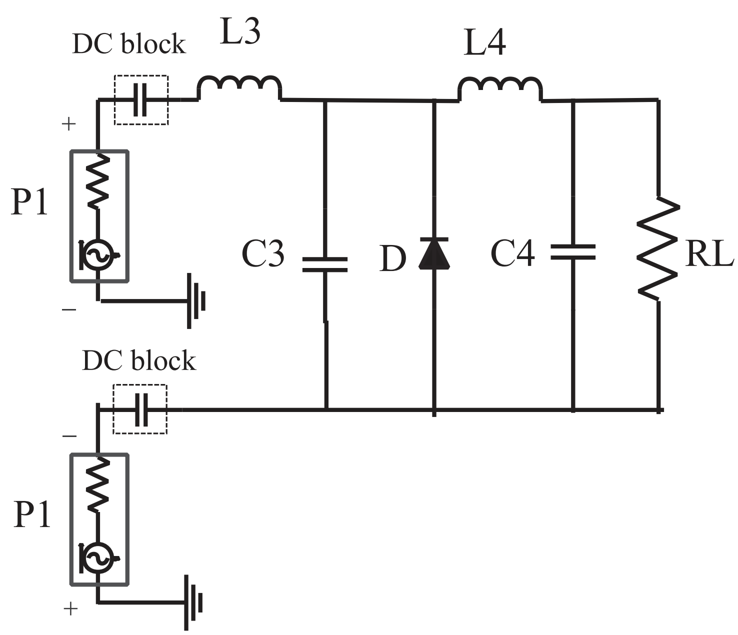


Figure 4. 14 Differentially operated antenna

4.4.2.1. Differentially driven rectifier for DSFR



(a)

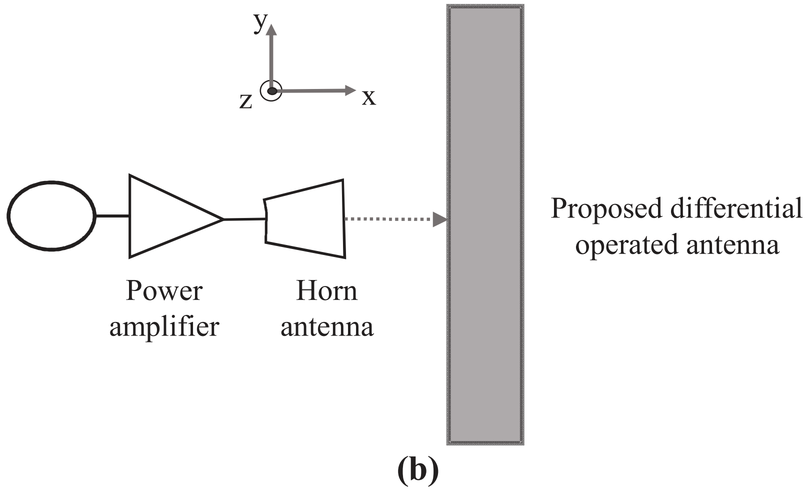


Figure 4. 15 A differentially driven (a) rectifier schematic with (b) measurement setup

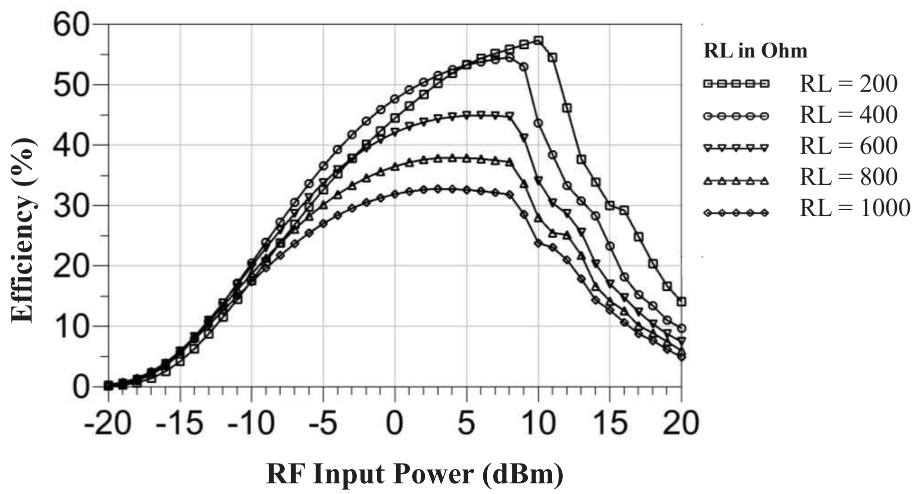


Figure 4. 16 Variation of efficiency (%) with different RF input power (dBm), simulated results

The differentially driven rectifier topology for DSFR is shown in Figure 4. 15 (a). Here two sources (individual power P1) connected at two terminals are 180° out of phase. In this circuit inductor L3, capacitor C3 acts as low pass filter, while inductor L4, capacitor

C4 acts as DC pass filter. The parameters L3, C3, L4, C4, and RL, can be first calculated; then the software ADS can be utilized to optimized those parameters with proper goal settings. Schottky diode HSMS-2860 is applied as D here. After optimization the parameters are L3 = 16.17 mH, C3 =0.37 pF, L4 =22.28 mH, C4 =120 pF, and RL =200 ohm. The variation of differential driven rectifier's efficiency with different RL is plotted in Figure 4. 16, and the variation of it's output DC power with different RL is plotted in Figure 4. 17. The circuit schematic of the proposed differentially driven rectifier with detailed parameters has been provided in Figure 4. 18.

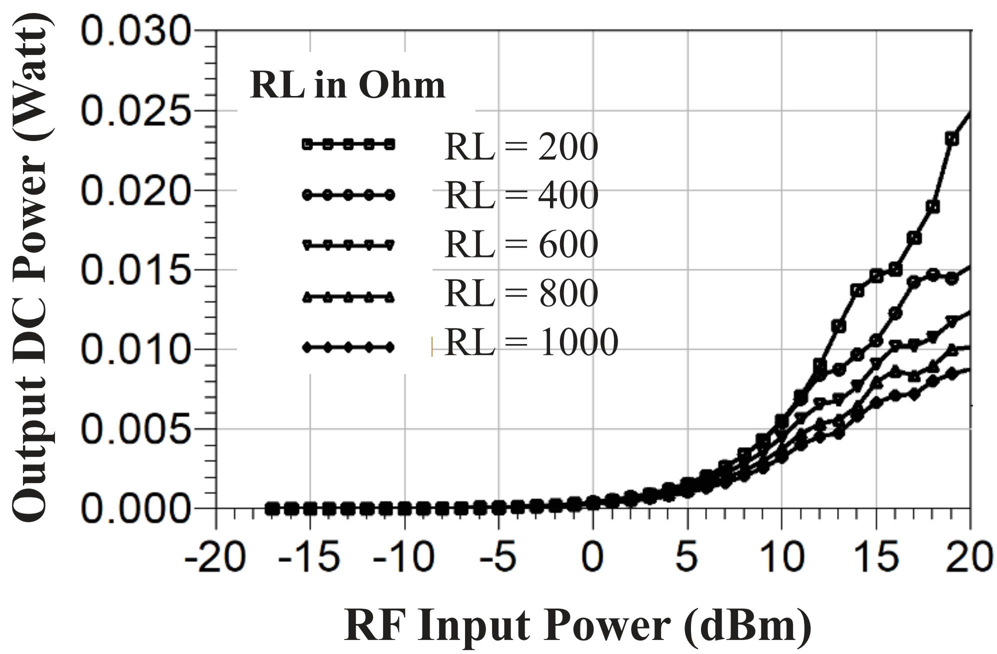


Figure 4. 17 Variation of Output DC power (Watt) with different RF input power (dBm), simulated results

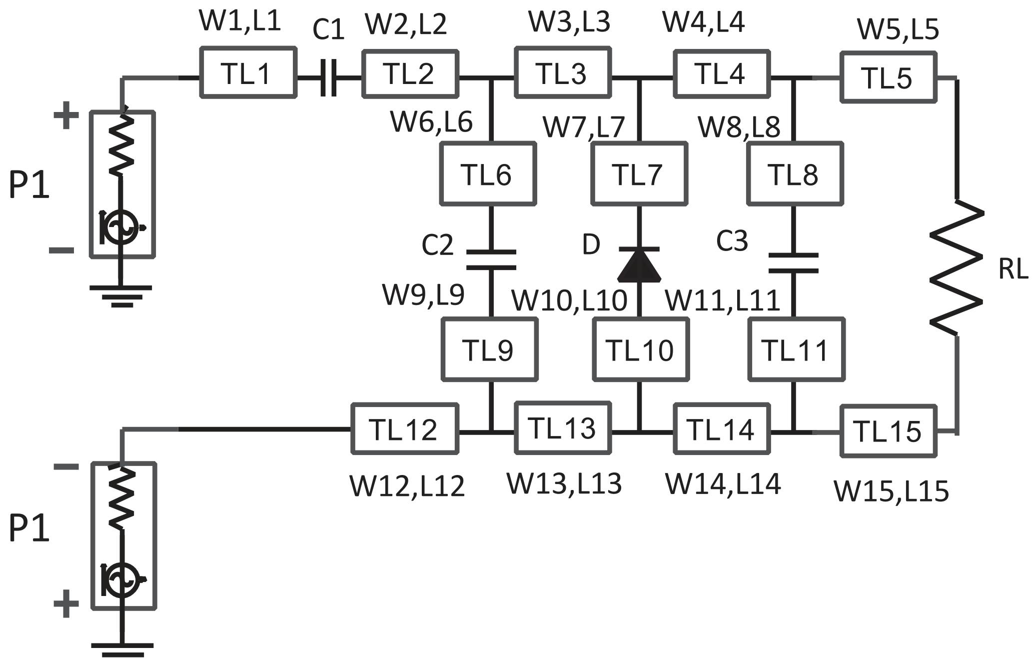


Figure 4. 18 Circuit schematics of the proposed differentially driven rectifier, the parameters are, W1=W2=W3=W4=W12=W13=W14= 1.2 mm, W5=W15= 3.4 mm, W6=W9= 1.3 mm, W7 = W10= 3 mm, W8=W11= 5.5 mm and L1= 6.5 mm, L2= 4.5 mm, L3=L13= 9.2 mm, L4=L14= 10.2 mm, L5=L15= 5.7 mm, L6= L9= 4.9 mm, L7=L10= 7.5 mm, L8=L11= 4.9 mm, C1= 32 pF, C2= 91 pF, C3= 4 pF, RL= 1800 ohm

4.4.3. Experimental results

A DSFR using microstrip is designed and fabricated at 2.45 GHz. The circuit schematic and detailed parameters are shown in Figure 4. 14 and Figure 4. 18. For investigating the comparative performance, an SSFR is also fabricated and tested. Both rectennas are printed on an FR4 substrate, 1.6 mm height, dielectric constant 4.4 and loss tangent 0.02. In the measurement, RF-DC conversion efficiency can be calculated as

$$\eta(\%) = \frac{Output\ DC\ power}{RF\ Input} \times 100 \tag{4.1}$$

It is noticeable that in equation (4.1), RF input for SSFR is (P1) while for the DSFR is (2×P1).

For the SSFR and DSFR measurements, APLAB 2130 Series Signal Generator with 9 kHz~3002 MHz frequency coverage with 50 Ohm VNA output port is used as RF source; it can excite RF power of 15 dBm. A high-directivity horn antenna (about 7 dBi gain at 2.45 GHz) is used, it has larger dimension D 20 cm. Then rectenna under test is placed at a distance of 70 cm from transmitting horn antenna. The distance in between satisfies far field condition ($R > {2D^2}/{\lambda} \sim 65\ cm$) at 2.45 GHz, and the measurement setup is shown in Figure 4. 15 (b). The simulated and measured RF-DC conversion efficiency of the two rectenna versus input power level are shown in Figure 4. 19. In the input power range from -20 dBm to 10 dBm, the DSFR has significantly higher efficiency over the SSFR. The DSFR has a maximum efficiency of 41.63 % at 10 dBm input power while the SSFR has a maximum efficiency of 37.88 % at 14 dBm input power. It is noticeable here that due to polarization mismatch loss, the received power of the SSFR and DSFR is decreased about by3 dB as both are CP rectennas. However, their efficiencies are stable irrespective of the rotation. A comparison among previous high-frequency rectifiers for energy harvesting application is also presented in Table 4. 1.

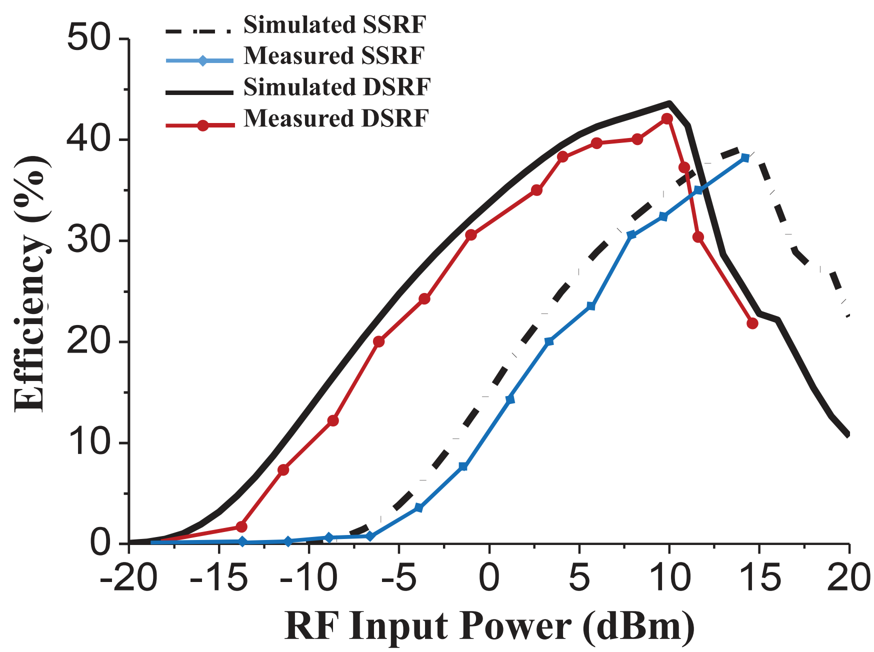


Figure 4. 19 The simulated and measured efficiency of single fed and differentially fed rectenna

Table 4. 1 Comparison of previous high-frequency rectifiers for energy harvesting application

Source	Operating frequency (GHz)	Feed type	Required RF power (mW) for maximum efficiency	Maximum measured efficiency (%)
[94]	0.9-1.9	(Coaxial feed)	3.16	23.5
[89]	5.8	(Microstrip feed)	10	23.3
[93]	2.4	(Coaxial feed)	2.5	51.5
This paper	2.45	(Microstrip tapered differential feed)	10	41.63 With 3dB polarization mismatch loss

4.5. Summary

In this chapter, an efficient differential source fed CP rectenna is proposed and designed. First, a circular patch antenna with a diametrically opposite peripheral projection of isosceles right triangle shape for circular polarization has been designed. It has internal radial slots for harmonics suppression up to third order that is suitable for rectifier connection for RF energy harvesting. The 2nd and 3rd harmonics return losses are suppressed to 2.46 and 2.91 respectively thus BPF can be eliminated. For RF energy harvesting, the proposed differential source antenna is connected with a differentially driven rectifier to perform higher efficiency and yields larger output power than the single source driven rectenna. In the DSFR, the RF-DC conversion efficiency reaches 41.63 % at 10 dBm while the SSFR has a maximum efficiency of 37.88 % at 14 dBm. Also In the input power range from -20 dBm to 10 dBm, DFSR has higher efficiency in comparison with SSFR. Therefore, this low profile rectenna strategy is suitable for cost-effective highly efficient and onboard rectenna for RF energy harvesting application.