Chapter 6: High-efficiency harmonic harvester rectenna for energy storage application

6.1. Introduction

Recently, Rectenna devices are gaining a lot of attention by both academia and industry [96-98]. In the Rectenna, RF-DC power conversion efficiency depends on the load connected to the output terminal; at the matching load resistance, the output power is maximal [99-102]. Unfortunately, the energy storage units like a rechargeable battery or supercapacitor do not have voltage/ current characteristics of a resistor. And the purpose of Rectenna for battery charging or energy storage application with maximal power transfer is a challenging task. For example, Photovoltaic and wind power system also require a matching load resistance, and their maximum power point tracking (MPPT) techniques are used for solving load matching problem[103-109]. However, Rectenna operates at very low power levels (typically Rectenna output power in mill watts). Therefore such MPPT techniques are not suitable in Rectenna, which is due to the high-power overhead of complex control circuitry. There is requirement of rectenna power management control technique that is compatible, cost-effective and adaptive. Also, it must be as simple as possible so that the control circuit consumption can be reduced to a few microwatts [110]. Resistance emulation technique provided in [111] proposed low burden control circuit and found suitable for energy harvesting from different low power sources; this technique was first proposed in [112] using a buck converter and in [113] using a flyback converter. Earlier this technique has been used for power factor correction; it involves DC-DC converter with a simple control switch operating in discontinuous current mode (DCM). In this technique switching will control average input resistance, therefore with the proper switching; a matching load resistance can be realized by the storage element at the output terminal.

In this chapter, a technique is proposed that is useful for collecting power from the two rectifiers (fundamental and harmonics) also deliver the combined maximal power into energy storage cell. The harmonics harvester Rectenna, which has fundamental rectifier output and harmonics rectifier output terminals, the two terminals are interfaced through switches to connect with the buck-boost converter. The two switches will be controlled such that the emulated resistance for both circuits is equal to their matching load resistance at the output terminal to ensure maximal power transfer.

6.2. Requirement of Harmonics harvester Rectenna

Typically conversion efficiency of RF rectifier is (50-70%); there are losses due to diode ohmic loss and non- rectified signal harmonics. Due to single phase operation and diode nonlinearity, the rectified signals contain harmonics in addition to desired DC signal [114]. Therefore a harmonics harvesting circuit that will re-rectify harmonics as proposed in [115-116] will improve RF-DC conversion efficiency. Rectenna utilizing harmonics harvester will have two output terminals, one for fundamental signal rectifier output and other is harmonics rectifier output [117]. Harmonics harvester Rectenna with fundamental rectifier output voltage (V1) and harmonic rectifier output voltage (VHH) is presented in Figure 6. 1. Here it is to keep in mind that both rectifier output terminals have their individual matching load resistance. Here each rectifier is individually connected to its matching load resistances; this condition is critically needed for associated maximal output power transfer. Complementary Pulsed Mode Controller is utilized to achieve the goal of replacing Individual rectifier's matching load resistance with a single load that is a rechargeable battery or supercapacitor. Here, the system turns into dual input power source with different voltage/current characteristics [118]. If the two terminals are connected to a common load, only the higher voltage terminal will supply power, and another terminal will behave as a load (there are also chances of source terminal oscillation) [118-122]. Thus in harmonics harvester Rectenna case, a cost-effective technique is required so that the maximum output power from two rectifiers can be fed to a common load for energy storage application.

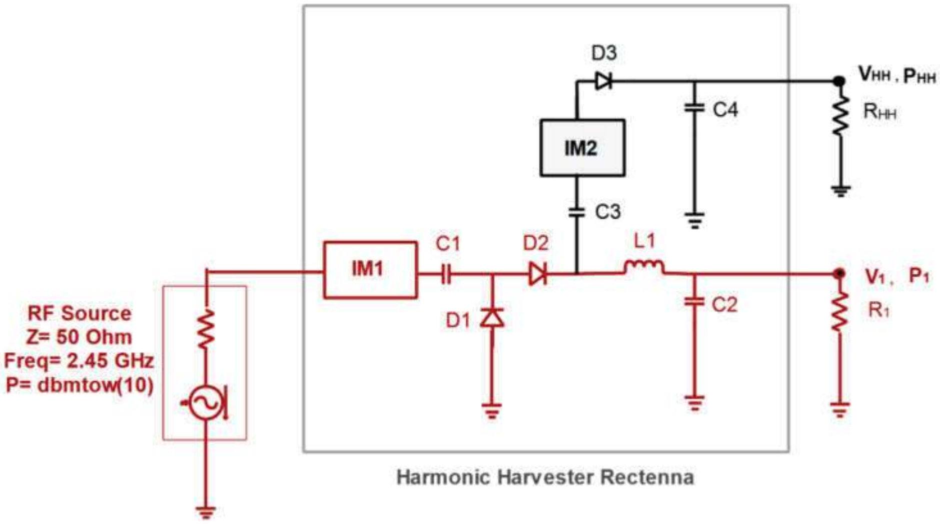


Figure 6. 1 Harmonics harvester Rectenna at 2.45 GHz with fundamental rectifier output voltage (V_1) and harmonic rectifier output voltage (V_{HH}), circuit with individual matching load resistance

6.3. Harmonic harvester rectenna

Harmonics harvester Rectenna at 2.45 GHz, circuit with individual matching load resistance is presented in Figure 6. 1. A proper impedance matching network IM1 is required to match rectifier's impedance with 50 Ohm transmission line. As the rectified signal has DC components and harmonics, a low inductor L_1 is introduced in the path that will prevent harmonics and only allows DC signal. In the way, rectified pure DC output of the fundamental signal is available at V_1. A secondary circuit is utilized for re-rectifying harmonics signal with impedance matching block represented as IM2. The re-rectification is performed with single diode D2 to implement low component count and vias, The DC output after re-rectification of harmonics signal is available at V_{HH}.

Rectenna with harmonics harvester is simulated in Agilent's Advance Design System. RF Source of power 10 dBm, frequency at 2.45 GHz, and source impedance 50 Ohm used. It represents antenna elements in association considering 10 dBm balanced array condition and each of them is energized with identical RF input power. For rectification, single stage voltage doubler configuration using HSMS-2860 Schottky diode is selected. ADS 2011 Smith Chart Utility for Impedance Matching with source impedance 50 Ohm and rectifier's found impedance for fundamental is used for IM1. For IM2 source and load impedances, each calculated and matching was performed. The fundamental rectifier terminal and harmonics harvester terminal are connected to two different load resistances R_1 and R_{HH} respectively. Here, P_1 and P_{HH} represent power delivered to load resistances R_1 and R_{HH} respectively. The corresponding Power curve varying with load resistance has shown in Figure 6. 2. P1 has a maximum power point, i.e. m2; at the load of 1002.34 Ω, and P_{HH} has a maximum power point, i.e. m1; at the load of 666.7 Ω. In this chapter, first, the harmonics harvester rectenna is simulated considering resistive load condition to find matching load resistance. Further, the resistance will be replaced by a battery and in between power management circuitry to realize maximal power supply in the battery or energy storage cell.

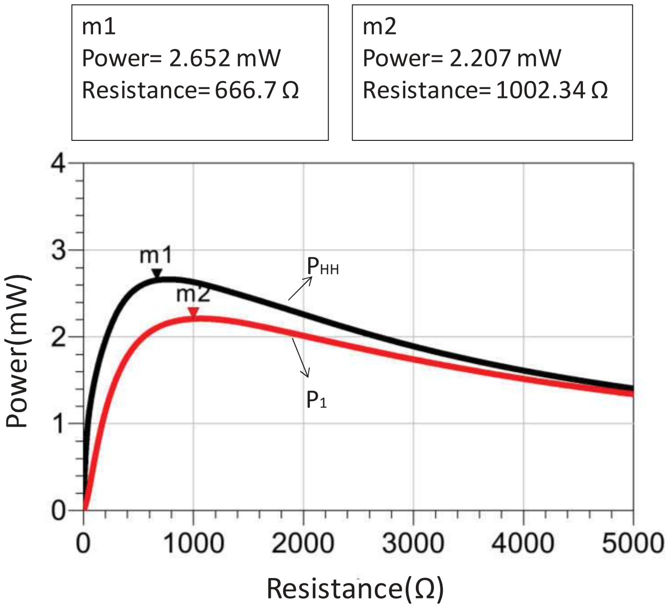


Figure 6. 2 Power versus Resistive load for the fundamental rectifier (P_1) and harmonics rectifier (P_{HH})

6.4. Harmonic harvester rectenna power management circuit for battery charging

Harmonic Harvester Rectenna for Battery Charging or energy storage application is presented in Figure 6. 3. A rectenna will deliver maximum power only if a matching load resistance is connected. Therefore, rectenna for battery charging critically needed a power management circuit in between to control average load current. For battery charging near maximum power transfer, the average load current is controlled such that it resembles a matching resistive load situation.

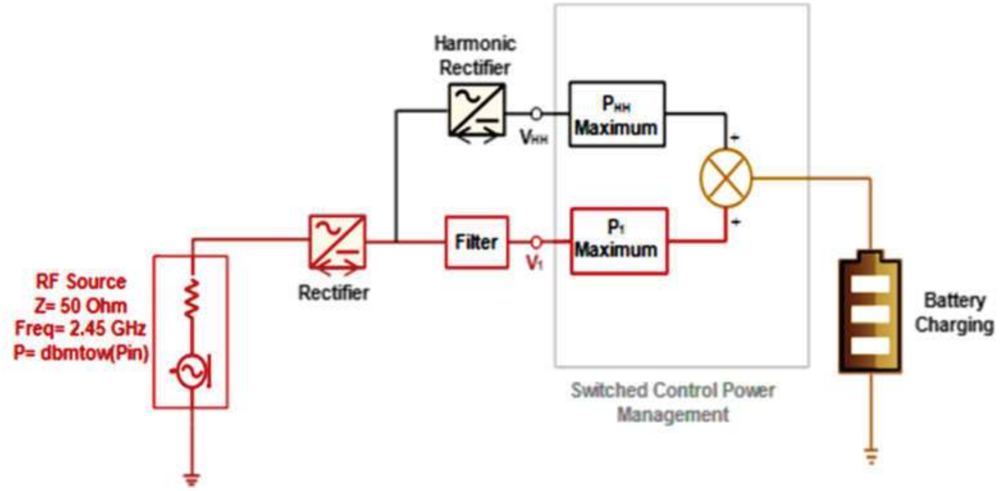
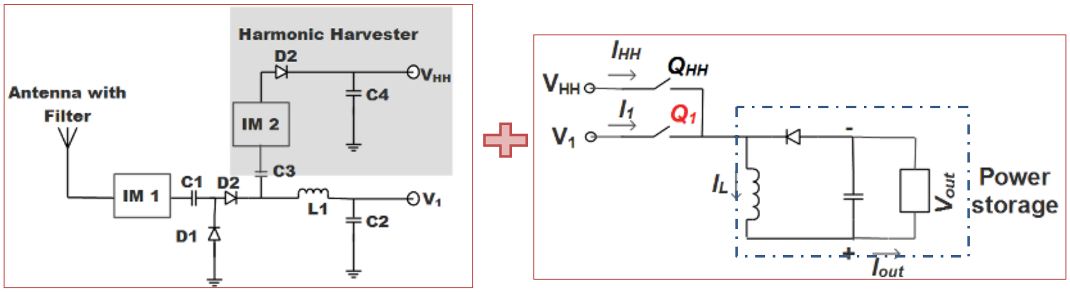


Figure 6. 3 Harmonic Harvester Rectenna for Battery Charging

It is called Resistance Emulation technique, and with simple discontinuous current mode (DCM) control, the load resistance of the desired value can be realized. The system efficiency is further improved by utilizing harmonics re-rectifier. Here, the fundamental rectifier and Harmonic Harvester are feeding P1 maximum and PHH maximum respectively, and the collective maximum power from the two rectifiers supplying to the battery needed. The technique proposed here utilized, the two rectifiers interfaced through switches and each switch is pulsed mode controlled with a different frequency such that their individual average load current is maximum. An integrated Buck-Boost converter will increase chargeable battery voltage range.

6.4.1. Circuit topology

The matching load resistance for individual rectifiers would decide the resistor emulation control scheme. Now circuitry operation has discussed, it is capable of transferring maximum energy from RF source to the battery. The circuit topology of Fundamental rectifier output and a harmonic rectifier output, the two terminals are interfaced through switches integrated with the buck-boost converter is shown in Figure 6. 4. There are two input voltages V_1, V_{HH} and currents I_1, I_{HH}. For fast switching and cost-effective operation, Mosfet with low on-resistance is suitable. The two inputs are interfaced through forward conducting switches will share common inductor and an output capacitor. The output voltage and currents are V_{out} and I_{out}.



Two outputs of Harmonic Harvester rectenna

Buck-Boost Converter

Figure 6. 4 Fundamental rectifier output and harmonic rectifier output are interfaced through switches integrated with buck-boost converter

6.4.2. Buck-Boost converter switching (DCM mode) and analysis

Dual input buck-boost topology switching scheme is shown in Figure 6. 5. Switches Q_1 and Q_{HH} are working in a complementary pulsed mode with a low-frequency pulsed duty cycle ‘k’ and ‘1-k’ respectively for period ‘T_{LF}.’ The inductor current waveform is operating in DCM with on time t_1 and constant frequency ‘$1/T_{HF}$’. In this case, the average load resistance realized (emulated resistance) for the fundamental rectifier is V_1 divided by the average value of current I_I and for the harmonic rectifier is V_{HH} divided by the average value of current I_{HH}, given by equation (6.3) and (6.6) respectively.

$$\langle I_1 \rangle = \frac{I_{Peak1} t_1}{2T_{HF}} \times (1-K) \tag{6.1}$$

$$I_{Peak1} = \frac{V_1 . t_1}{L} \tag{6.2}$$

$$R(1)_{emulated} = \frac{V_1}{\langle I_1 \rangle} = \frac{2LT_{HF}}{{t_1}^2(1-k)} \tag{6.3}$$

$$\langle I_{HH} \rangle = \frac{I_{Peak\_HH} t_1}{2T_{HF}} \times (K) \tag{6.4}$$

$$I_{Peak\_HH} = \frac{V_{HH} . t_1}{L} \tag{6.5}$$

$$R(HH)_{emulated} = \frac{V_{HH}}{\langle I_{HH} \rangle} = \frac{2LT_{HF}}{{t_1}^2 k} \tag{6.6}$$

From the emulated resistance equation, it can be noticed there are two variable parameters, t_1 and k can be controlled by the desired value of average current. The two variable parameters are not linked and useful by users in tuning condition for matching load, and it is also promote operating range.

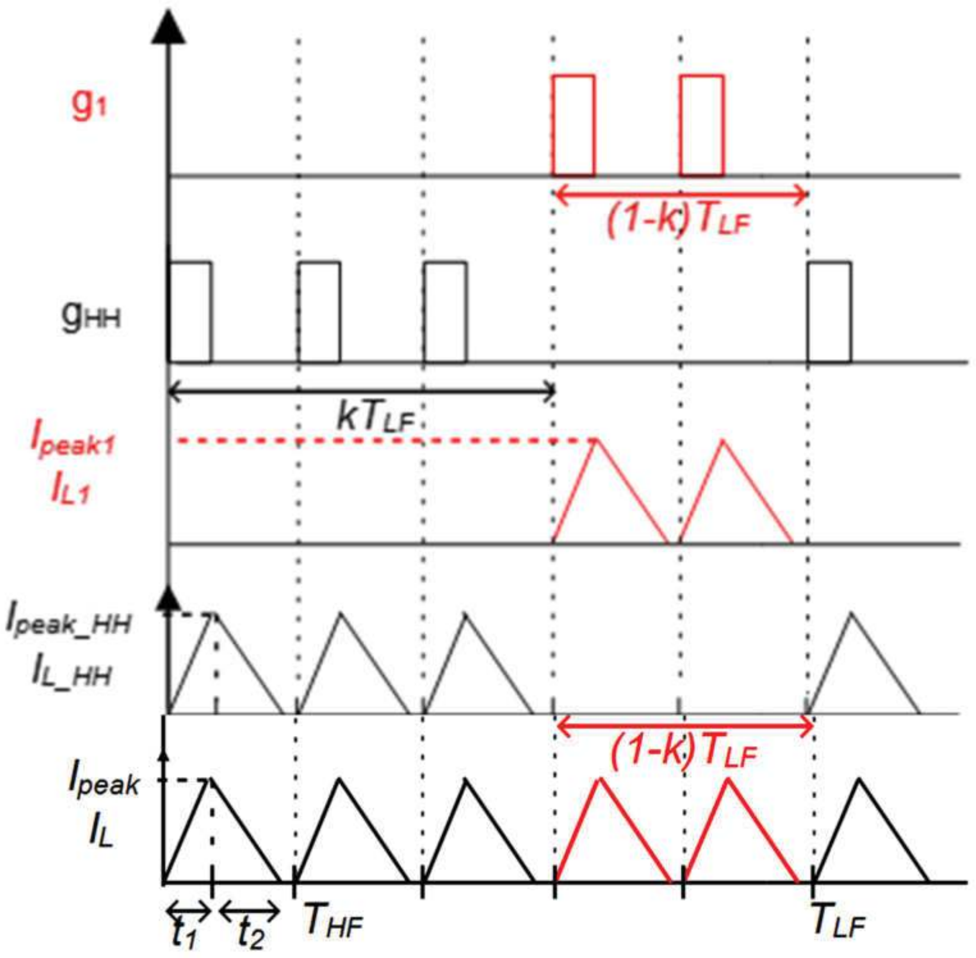


Figure 6. 5 High-frequency period (T_{HF}) and low-frequency period (T_{LF}), Duration of pulsed operation of switch Q1 is $kT_{LF,}$ and Q_{HH} is (1-k) TLF, inductor current waveform in fixed frequency DCM with on time t_1 and off time t_2

For the battery charging application, the benefit of using two frequency controlled switch is that multiple average load resistance can be realized by simply varying control parameters as given in equation (6.3) and (6.6), and complementary pulsed mode switching is suitable for maximal energy harvesting from the fundamental rectifier as well as a Harmonic rectifier.

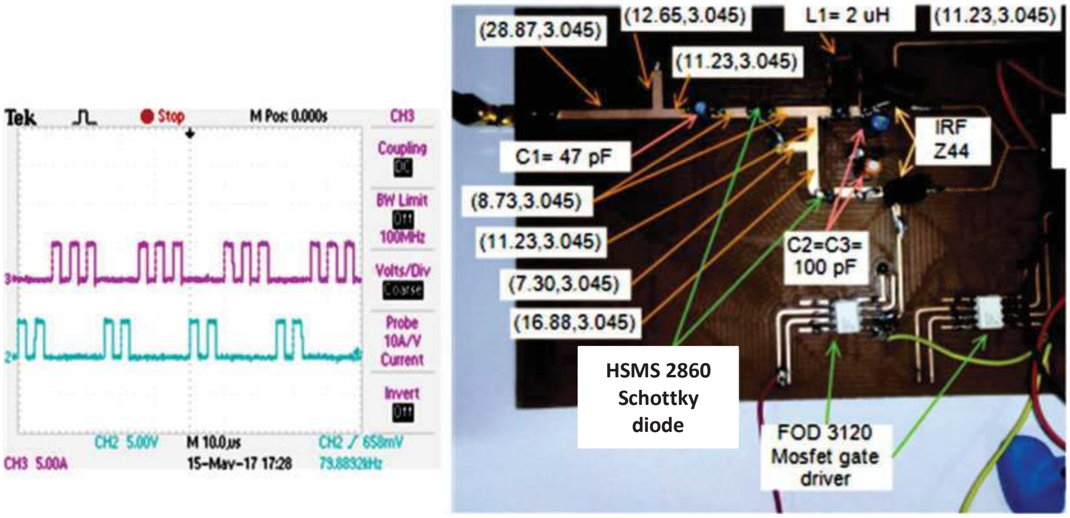
The output power from the two rectifiers is tuned up to near maximum output power and the results from optimized simulation in ADS environment. At 10 dBm input power RF source, the found values of matching load resistance for the fundamental and harmonics rectifiers are $R(1)_{match=}$1002.34 Ω and $R(HH)_{match}$=666.7 Ω respectively. These values are critically needed for practical circuit design.

6.5. Hardware fabrication

Table 6. 1 Components Model and Specification

component	Model	specification
MOSFET (N-channel)	IRFZ44	$R_{DS(on)} = 0.028\ \Omega$ $Q_g = 67$ nC $C_{oss} = 920$pF
Surface Mount Microwave Schottky Mixer Diodes	HSMS-2860, SOT 23 Package	$V_F = 350$ mV $V_{BR} = 7$ V
High Speed MOSFET Gate Drive Optocouplers	FOD 3120	$I_{CCH} = 3.8\ \mu A$ $I_{CCL} = 3.8\ \mu A$
Inductor	Toroidal Inductor	L = 180 µH

At 2.45 GHz, Harmonic Harvester Rectenna battery charging circuit has simulated in ADS schematic. Then the optimized circuit layout is constructed in ADS layout window. The layout circuit performance in a simulation environment is significant and more accurate, for this purpose ADS co-simulation with layout model is performed in the schematic, the layout performance found suitable. The designed layout fabricated on FR4 substrate, with the specification, the height of substrate 1.6 mm, dielectric constant 4.4, and the conductor material is 35 µm thick copper



(a) **(b)**

Figure 6. 6 (a) Channel 3- QHH gate drive voltage, channel 2- Q1 gate drive voltage (b) Fabricated harmonics harvester Rectenna circuit. The numbers in parenthesis are the length and width of transmission lines (l, w) in millimeters

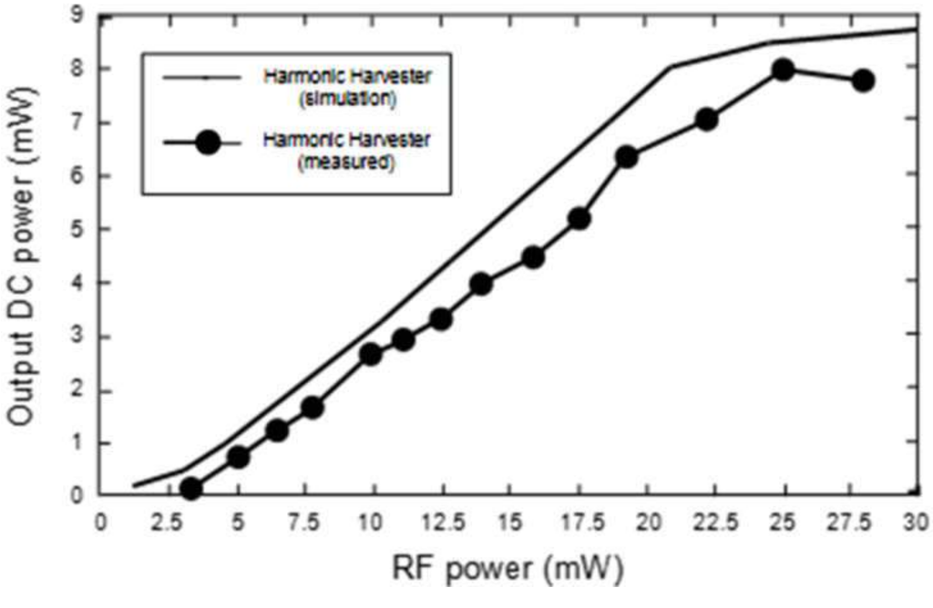


Figure 6. 7 Output DC power versus input RF power

. In the components connection, one should take care in soldering SOT-23, HSMS-2860 Schottky diode. For RF source, APLAB 2130 Series Signal Generator with 9 kHz~3002 MHz frequency coverage with 50 Ohm VNA output port used. Here, VNA to SMA connector needed to connect RF source with the fabricated circuit. The fabricated circuit with RF source has presented in Figure 6. 6.

Table 6. 1 provides components and specification for fabrication. The gate drives high-frequency switching performed at 100 kHz, i.e., T_{HF} equals to 10 µs with on time t_1 is 3 µs. The period T_{LF} is 50 µs with a low-frequency pulsed duty cycle ‘k,’ and ‘1-k’ are 0.6 and 0.4 respectively. Gate drive voltage for switches Q_1 and Q_{HH} is shown in Figure 7. The parameters t_1, T_{HF}, T_{LF}, k, L2, and C1 are selected such as emulated resistance R(1), and R(HH) have calculated values of 1002.4Ω and 666.7Ω respectively.

$$R(1)_{emulated} = \frac{V_1}{\langle I_1 \rangle} = \frac{2LT_{HF}}{{t_1}^2(1-k)} = 1002.4\ Ohm \tag{6.7}$$

$$R(HH)_{emulated} = \frac{V_{HH}}{\langle I_{HH} \rangle} = \frac{2LT_{HF}}{{t_1}^2 k} = 666.7\ Ohm \tag{6.8}$$

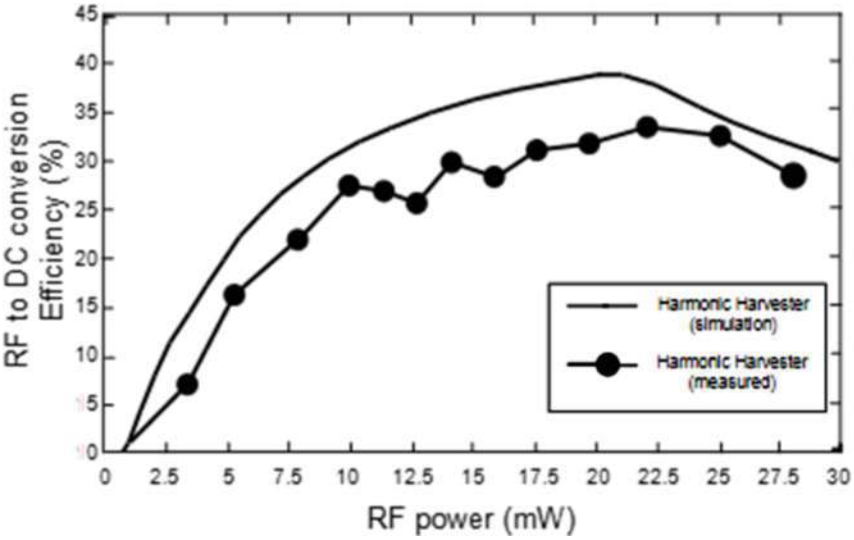


Figure 6. 8 Harmonic Harvester Rectifier Efficiency versus input RF power

The setup is operating at desired matching load resistance for 4 V battery charging application, Measured Rectenna output power versus multiple input power is shown in Figure 6. 7. RF to DC conversion efficiency for battery charging is shown in Figure 6. 8. The measured maximum conversion efficiency is 37.6 % at 20 mW.

Table 6. 2 Comparison among previous high-frequency rectifiers for energy storage application

Source	Operating frequency (GHz)	Required RF power (mW) for maximum efficiency	Maximum measured efficiency (%)
[110]	0.9-1.9	3.16	23.5
[111]	2.4	2.5	24.6
This paper	2.45	20	37.6

A comparison among previous high-frequency rectifiers for energy storage application is presented in Table 6. 2.

$$\text{Maximum measured efficiency } = \frac{Output\ DC\ power}{Input\ RF\ power} \qquad (6.9)$$

6.6. Summary

This chapter presents harmonic harvester Rectenna integrated power management circuitry for improving RF-DC power conversion efficiency. The circuitry is developed for battery charging or energy storage application; resistance emulation method is used to realize a matching load resistance at output terminals. The proposed technique is useful for harvesting near maximum output power from the dual rectifiers (fundamental and harmonics) independently. Also, it delivers the combined maximal power to the energy storage cell. The power management module based on dual input buck-boost converter with simple open-loop control is utilized.