Wireless Power Transfer Using Rectenna

Mrs.S. Keerthana¹, Mr.C.Uthranarayan², Ms. V. Rajalakshmi³, Ms. A. Ramya⁴

¹Assistant Professor, Electronics and Communication Engineering, Mepco Schlenk Engineering College, Sivakasi, India
²Assistant Professor, Mechanical Engineering, Mepco Schlenk Engineering College, Sivakasi, India
³,⁴UG Student, Electronics and Communication Engineering, Mepco Schlenk Engineering College, Sivakasi, India

¹Keerthana.viswa@gmail.com, ²uthranarayan@mepcoeng.ac.in, ³rajivsk2298@gmail.com, ⁴ramyaasok98@gmail.com

Abstract — Radio frequency (RF) harvesting technologies are bewitching a huge number of people as they are enormously available in the atmosphere. These energies are received and converted to useful DC energy which can be used to charge electrical devices which need low power consumption. Here, in this paper a microstrip square patch antenna operating at 2.45 GHz is proposed having a dimension of 29.2 mm X 29.2 mm, which is fabricated on a low-cost FR4 substrate having a dielectric constant of 4.4 with a thickness of about 1.2 mm. L-shaped matching network is designed for maximum power transfer between the antenna and the rectifier. HSMS-2850 zero bias Schottky diode is used as a rectifier. The RF-DC rectification is done with an efficiency of 42.8% at -7dBm at 2.45 GHz.

Keywords — Square patch antenna, BPF, matching circuit, Schottky diode, LPF, RF energy harvesting

1. INTRODUCTION

In this emerging world, self-powered electronics devices are used in various applications which include wireless sensor networks, smart applications, health care etc. All these devices need battery charging/maintenance need. So, the wireless power transfer is very important for many self-charging devices. In medical industry, many sensors and pacemakers are in the need of power supply and also, they are in need of battery replacement after a particular period. So, there is a need to go for alternate method to harvest these energies from various energy sources available in the atmosphere.

In harvesting energy, technologies like solar, kinetic, thermal or electro-magnetic (EM) energy can be used to recharge the batteries. Since last decade RF energy harvesting is mostly used because the maximum energy from the atmosphere can be obtained from RF energies. So, there is a need to harvest the readily available RF energy present in our atmosphere and convert it into DC voltage to charge our devices. The tele-communication bands that are available are 2.4 GHz, 5.1 GHz, 5.8 GHz (Bluetooth/Wi-Fi), 2.3 GHz, 2.5 GHz, 3.5 GHz, 5 GHz (WiMAX), 3.4-3.6 GHz. ISM band of frequencies were approved by Federal Communication Commission (FCC). Scientific band is 2.4 – 2.4835 GHz with the center frequency of 2.45 GHz. Today large number of Wi-Fi devices are used everywhere, so the RF energy is the readily available one. Many studies have been conducted and several methods are adopted to harvest these RF energies and it is utilized to power-up the electronic devices with low-power consumption. The methodology to implement this concept is by using a rectenna circuit which comprises of antenna and rectifier circuit. The antenna receives the RF energy and converts it into AC voltage. Then the rectifier is used to convert this AC voltage into DC voltage. This available DC voltage is used to charge the devices. The concept of rectenna was proposed in 1975 in which a microwave beam was transmitted through an RF-DC conversion at a distance of 1.6 km and 85% efficiency is obtained. Then a new demonstration is proposed to eliminate the use of power cables. Here reduction in the cost of implementation.
In this work, the rectenna is designed to harvest the available RF signals and convert it into voltage to charge the devices. The ISM band of frequencies 2.4-2.4835 GHz is used. The rectenna circuit consists of antenna, band pass filter (BPF), matching circuit, rectifier and a low pass filter (LPF). Here a microstrip square patch antenna is designed with inset feed operating at the centre frequency of 2.45 GHz.

The antenna is designed and simulated using Agilent advanced design system (ADS) Momentum, a simulator that works on full-wave analysis method-of-moment (MoM) technique. The output from the antenna is passed through the band pass filter (BPF). A Schottky diode is used as a rectifier since it has high speed switching at higher frequencies and low voltage drop characteristics. The output from the Schottky diode is given to the low pass filter (LPF). For maximum power transfer, a matching circuit is introduced between band pass filter and the rectifier.

2. LITERATURE SURVEY

A novel co-planar waveguide fed rectenna [1] with high efficiency is proposed and implemented for 2.45GHz Bluetooth/Wireless LAN applications. The design process starts with the CPW design guiding principles and then further optimized with commercially available software package Ansoft HFSS. The rectenna is well matched for 2.37 GHz to 2.52GHz. A method [2] of recycling RF frequency energy at 2.4GHz and converting them to DC power was suggested. In order to avoid human intervention, IOT (Internet of Things) concept is used. Antenna was modelled and optimized using ADS (Advanced Design System). Received measured power is -64.4 dBm.

The rectenna operates at GSM 900 GHz frequency band [4]. This frequency is selected because it has large amount of power. It is suitable for Radio Frequency (RF) energy harvesting applications. Energizing the sensor nodes and reduce battery requirements. The array antenna uses a ground stub and reduces the size about 50% without affecting the gain and bandwidth. An integrated rectifier [6] which is a voltage quadrupling circuit that provides RF–DC rectification with efficiency of 40% at 0 dBm is proposed. A real-time actuation of a medical drug pump is demonstrated using only wirelessly transmitted power with no additional power storage elements. It produces an efficiency of 47.7% at 2.45GHz frequency. Using a transmitting antenna/source located in the radiated near-field zone of the rectenna, a total of 1.2 mW was delivered across 42 cm. A misalignment analysis was performed showing a maximum of 7.5 dB when offset by 15 cm.

The rectenna circuit comprises of an antenna, a band pass filter (BPF), matching circuit, a rectifier and a low pass filter (LPF). Advance Design System (ADS) 2009 software package is used for the simulation of the rectenna. ADS is the world’s leading electronic design automation software. It is for RF, microwave and high-speed digital applications. There are two windows in ADS namely, Schematic and Layout. The antenna was designed in the Layout window and the rectifier was designed in the Schematic window.

3. ANTENNA DESIGN

First, a microstrip square patch antenna operating at 2.45 GHz is designed. The antenna is fabricated on a FR4 substrate with a thickness of about 1.2 mm with dielectric constant of 4.4 and a loss tangent
of 0.02. The dimensions of the square patch were calculated. Since it is a square patch the dimensions of the length and the width are the same as 29.2 mm. Here, the inset feed method is used in order to increase the return loss. The designed microstrip patch antenna is shown in the Fig. 2. Since it is a microstrip patch antenna with inset feed, it shows a narrow bandwidth of about 14 MHz.

Fig. 2: Design of the proposed antenna

Design equations for the antenna:

\[ L = W = \frac{c}{2 \times f \times \sqrt{\varepsilon_r}} \]  \hspace{1cm} (1)

\[ Y = \frac{W}{5} \]  \hspace{1cm} (2)

\[ U = \frac{2W}{5} \]  \hspace{1cm} (3)

Where,

L is the length of the patch,
W is the width of the patch,
P is the width of the inset feed,
X is the length of the feed,
Y is the width of the inset feed and gap value,
U is the width of the patch before the feed.

The calculated values are tabulated below in the Table 1.
The proposed antenna was designed using Advanced design system (ADS) 2009 as shown in Fig. 3. ADS provide an integrated simulation and verification environment to design high-performance hardware compliant with the latest wireless, high speed digital and military standards. The return loss $S_{11}$, radiation pattern, directivity, gain was observed. The simulated results are shown in the Fig. 4. The antenna’s radiated power is about 0.248673 W. The impedance of the antenna is $Z_{\text{antenna}} = 50*(1.040 - j0.284)$. It is omnidirectional with the gain of about 5.16588 dB and the directivity of about 6.30203 dB.
B. Simulated reflection coefficient ($S_{11}$) of the designed antenna:

An S-parameter indicates the amount of power leaving one port of the network. In the RF technologies, these parameters are measured using a 50Ω system. $S_{11}$ represents how much power is reflected from the antenna and hence it is known as reflection coefficient. If $S_{11} = 0$ dB, then all the power is reflected from the antenna and nothing is radiated. Return loss is a measure of how good the devices or lines are matched. The reflection coefficient is also known as return loss. The return loss should be low so that the maximum power is delivered to the load. The designed microstrip square patch antenna has a return loss of about -17.128 dB for the frequency of 2.45 GHz. The $S_{11}$ parameter of the antenna is shown in the Fig. 5.

![Fig. 5: $S_{11}$ parameter of our antenna](image)

C. Testing of fabricated antenna:

The simulated antenna is fabricated on the FR4 substrate. The fabricated antenna is tested in the Vector Network Analyzer. The observed readings are shown in the Fig.6 and Fig.7. It shows the $S_{11}$ parameter of the fabricated antenna, and the VSWR of the antenna. VSWR is the Voltage Standing Wave Ratio, it denotes how effectively the power is transferred from the source to the load through the transmission line. For the antenna, the VSWR should be real and positive value and less than 2 for the maximum power transfer. The fabricated antenna resonates at 2.3989835 GHz frequency for the return loss of -20.136 dB and the VSWR is about 1.2326 which is less than 2.

![Fig. 6: $S_{11}$ of the fabricated antenna](image)
Fig. 7: VSWR measurement of fabricated antenna

4. BAND PASS FILTER
Band-pass filter allows only certain range of frequencies and eliminates or attenuates the remaining frequencies. The output ac voltage from the antenna is given to the band pass filter to filter out the undesired frequency components and noise. There are two BPF model namely T-model and Pi-model. Here the BPF can be implemented in π network as given in Fig. 8. It is selected to reduce the cost, size and it improves the performance of the circuit. This π model network provides more output voltage and noise free output as compared to other filter models.

Fig. 8: π model of the BPF

Some mathematical equations are used to determine the value of the capacitors and the inductors.

\[ L_1 = \frac{Z_0}{\pi(f_2 - f_1)} \]  \hspace{1cm} (4)

\[ L_2 = \frac{Z_0(f_2 - f_1)}{4\pi f_1 f_2} \]  \hspace{1cm} (5)

\[ C_1 = \frac{(f_2 - f_1)}{4\pi f_2 f_1 Z_0} \]  \hspace{1cm} (6)

\[ C_2 = \frac{1}{\pi Z_0(f_2 - f_1)} \]  \hspace{1cm} (7)

From the above equations, the characteristic impedance (\(Z_0\)) is 50Ω and the cut-off frequencies (\(f_2\) and \(f_1\)) are 2.4 and 2.4835 GHz respectively. The calculated values of \(L_1\), \(L_2\), \(C_1\) and \(C_2\) are 190.6 nH, 55.74 pH, 0.022 pF, 76.24 pF respectively.

5. RECTIFIER
Rectifier is used to convert AC voltage into DC voltage. So, here the ac voltage from the antenna is converted into DC voltage by the help of rectifier. RF energies are mostly available at low power
densities normally from -50dBm to -20dBm. The efficiency of the rectifier plays an important role in obtaining the maximum output power from the rectenna circuit. Normally the RF voltage level fluctuates from 0.1 V to 1 V. A HSMS-2850 diode is used as a rectifier. It is a zero bias Schottky detector diode. The diode consists of a metal-semiconductor barrier which is created by the deposition of a metal layer on a semiconductor. The non-linear response of these diodes is capable of producing a DC energy. These diodes have fast switching capabilities at high frequencies. So, it is most suitable for RF applications which need low power. The additional advantages include low flicker noise, low failure in time (FIT) rate, better thermal conductivity for higher power dissipation. These diodes are mostly used in signal processing applications.

![Fig. 9: Spice model for HSMS-2850 Schottky diode](image)

\[ R_s = 25 \Omega \text{ (series resistance)} \]

\[ R_f = \frac{8.33 \times 10^{-5} nT}{I_b + I_s} \]  

(8)

Where,

- \( I_b = \) Externally applied bias current in amps
- \( I_s = 3 \times 10^{-6} \text{ A (saturation current)} \)
- \( T = \) Temperature, °K
- \( n = 1.06 \) (identity factor).

**TABLE 2: Spice Parameters**

| Parameter                     | Value      |
|-------------------------------|------------|
| Single Reverse Voltage, \( V_T \) | 2 V        |
| Forward Current, \( I_F Max \) | 1 mA       |
| Forward Voltage, \( V_F Max \) | 250 mV     |
| Capacitance, \( C_t \)        | 0.3 pF     |
| Diode Case Style              | SOT-23     |
| No. of Pins                   | 3          |

6. MATCHING CIRCUIT

For maximum power transfer, it is necessary to design a matching circuit. Matching circuit is placed between band pass filter and the rectifier. In designing a matching circuit, it is important to find the input impedance (\( Z_{in} \)) and output impedance (\( Z_0 \)). \( Z_{in} \) is the sum of the output impedance of the antenna and the band pass filter impedance. \( Z_0 \) is the sum of the impedances of the rectifier, low pass filter and the load. The impedance of the antenna is calculated by using the smith chart and found to be 52-j14.2\( \Omega \). The impedance of the Schottky diode is found to be 290.209\( \Omega \).

\[ Z_{\text{antenna}} = 50 \times (1.040-j0.284) \Omega \]

The impedance of the BPF is calculated by using the following equations,
The values of $X_{L1}$, $X_{L2}$, $X_{C1}$, $X_{C2}$ are found to be 2934.059 $\Omega$, 0.85805 $\Omega$, 2913.581 $\Omega$, 0.852061 $\Omega$. The impedance of the Band pass filter is 0.4275 $\Omega$. By using the Smith Chart Utility in ADS 2009, the LC matching circuit was designed and implemented. The designed matching circuit is shown in the Fig. 10.

![Matching circuit in ADS Schematic window](image)

**Fig. 10:** Matching circuit in ADS Schematic window

7. LOW PASS FILTER

Low pass filter is the last circuit in the design of the rectenna circuit. It is used to remove the ripples from the signal and pass only the useful frequencies. It filters out the entire noise component from the signal. A simple shunt capacitor is used as a low pass filter (LPF). It is done to improve the power factor of the network and reduces the power loss. It also increases the voltage stability. The capacitor exhibits reactance and it is high at low frequencies and blocks the current and made it to pass through the load. The value of the capacitor is found by using the equation and found to be 0.20 pF

$$C = \frac{1}{2\pi f R}$$

The impedance of the capacitor is found by using the equation and found to be 24.806$\Omega$. Now, all the parts of the rectenna circuit are connected together by using a matching circuit for maximum power transfer. The simulated rectifier is shown in the Fig. 11.

8. RECTIFIER DESIGN

The rectifier is designed in a schematic window in ADS. The components are placed from the component panel available in the left side of the window and simulation is performed.
9. SIMULATED RESULTS FOR DESIGNED RECTIFIER

The simulation is done by using S-parameter simulator and Harmonic Balance (HB) simulation in Agilent ADS. The $P_{in}$ value is set as the input power in dBm to the rectifier, as the value was obtained from the $S_{11}$ response of the designed square patch antenna. The start and the stop frequencies were set as 1 GHz and 4 GHz respectively in the S-parameter and Harmonic simulations. From the HB simulation, the efficiency for various input power is calculated by using sweep analysis in harmonic balance simulator. The input voltage, output voltage, input power, output power and power efficiency are calculated by using following equations. The obtained results are shown in the figure below.

\[ P_{in} = I^2 R \]  \hspace{1cm} (14)

Where,
I is the current measured at the input of the rectenna circuit using I_PROBE1.
R is the resistance (50 Ω).

\[ P_{out} = I^2 R \]  \hspace{1cm} (15)

Where,
I is the current measured at the output of the rectenna circuit using I_PROBE2.
R is the load resistance (50 Ω).

\[ PCE = \frac{P_{out}}{P_{in}} \times 100 \]  \hspace{1cm} (16)

Where,
PCE is the power conversion efficiency.
$P_{in}$ is the input power given to the rectenna circuit.
$P_{out}$ is the output power from the rectenna circuit.
The input and output voltages of the rectenna circuit is given in the Fig. 12 and Fig. 13.
Fig. 12: Input voltage to the rectenna

Fig. 13: Output voltage from the rectenna

Fig. 14: Input Power to the rectenna circuit

Fig. 15: Output power from the rectenna circuit

The input and output voltages of the rectenna circuit is measured as 207 mV and 54 mV respectively. The input and output power of the rectenna circuit is given in the Figure 14 and 15. The input and
output power of the rectenna circuit is measured at 2.45 GHz as \(1.375 \times 10^{-4}\) W and \(5.899 \times 10^{-5}\) W respectively. The power conversion efficiency of the rectenna circuit obtained is shown in Fig. 16.

![Fig. 16: Power conversion efficiency of the rectenna circuit](image)

The power conversion efficiency of the rectenna circuit is 42.89%. The power conversion efficiency is plotted for various input power levels and they are obtained as shown in Fig. 17.

![Fig. 17: PCE for various input power levels](image)

The input voltage, output voltage, input power, output power and power conversion efficiency of the rectenna circuit is tabulated in Table 3

| TABLE 3: Observations obtained from the rectenna circuit |
|-----------------|-----------------|
| Frequency       | 2.45 GHz        |
| \(V_{in}\)      | 0.207 V         |
| \(V_{out}\)     | 0.054 V         |
| \(P_{in}\)      | 0.0001375 W     |
| \(P_{out}\)     | 0.00005899 W    |
| PCE             | 42.888 %        |

10. HARDWARE IMPLEMENTATION OF RECTENNA

The simulated rectenna was implemented practically. The fabricated patch antenna is shown in the Fig. 18. The microstrip square patch antenna is tested in the vector network analyzer. Similarly, the tested antenna is connected to the Agilent N5182A (100 KHz-3GHz) Vector Signal Generator which generates the frequency of 2.45GHz for various input power. The transmitting antenna was analyzed with the EXA Signal Analyzer N9010A (10Hz – 26.5GHz) shown in the Fig. 19. It acts as a
transmitting antenna. On the receiving side, another square patch antenna is connected to the rectifier circuit with lumped components. The output voltage is measured across the low pass filter using multimeter.

![Fabricated square patch antenna](image1.png)

**Fig. 18: Fabricated square patch antenna**

![Hardware implementation of the designed Rectenna](image2.png)

**Fig. 19: Hardware implementation of the designed Rectenna**

Table 4 depicts the voltage measured for various input power at various distance between the transmitting and the receiver antenna.

| $P_{\text{radiated}}$(watts) | $P_{\text{in}}$(watts) | $V_{\text{out}}$(mV) | Simulated Conversion efficiency |
|-----------------------------|------------------------|----------------------|-------------------------------|
| $1.140\times10^{-5}$       | $4.57\times10^{-6}$    | 1                    | 74.16%                        |
| $6.081\times10^{-6}$       | $2.479\times10^{-6}$   | 0.7                  | 76.7%                         |
| $5.623\times10^{-6}$       | $2.295\times10^{-6}$   | 0.4                  | 76.87%                        |
| $4.5289\times10^{-7}$      | $1.871\times10^{-7}$   | 0.4                  | 78.73%                        |
| $8.6696\times10^{-8}$      | $3.585\times10^{-8}$   | 0.3                  | 78.84%                        |
| $9.638\times10^{-10}$      | $3.986\times10^{-10}$  | 0.2                  | 78.86%                        |

The transmitting antenna is connected to the signal generator and the spectrum analyzer is used to calculate the amount of power radiated from the transmitting antenna. The rectenna circuit consists of receiving antenna, band pass filter, matching circuit, diode and the low pass filter are connected together in a bread board and it is placed near the transmitting antenna. The output voltage is measured across the low pass filter using multi-meter by varying the distance between the transmitting antenna and the receiving antenna.
11. RESULTS AND DISCUSSION:

In this paper, an antenna operating at 2.45 GHz is designed to harvest the RF energies available in the atmosphere. It is designed using Advanced Design System (ADS) and fabricated on a FR4 substrate having a dielectric constant of 4.4 having a thickness of about 1.2 mm. The proposed rectenna circuit comprises of microstrip square patch antenna, band pass filter (BPF), matching circuit, rectifier and a low pass filter (LPF). Antenna is used to receive the energy from the atmosphere and it is rectified by using the rectifier which performs RF-DC rectification which can be used to charge the electronic devices with low power consumption. The radiated power from the transmitting antenna for various input power levels are measured using spectrum analyzer and they are obtained as shown in Fig. 20 (a) – (c).

![Fig. 20. (a): Radiated power at the input power level of 17 dBm](image)

![Fig. 20. (b): Radiated power at the input power level of 15 dBm](image)
The voltage is measured for various input power at various distances and plotted in the graph shown in the Fig. 21. It is inferred from the graph (Fig. 21) that if the input power is set as 17 dBm, the radiated power from the antenna is -19.43 dBm and the output voltage is measured for different distances. Then output voltage of 1 mV is obtained at a distance of 5 cm. For 30 cm, an output voltage of 0.8 mV is obtained. These measured values are plotted as graph. As the distance increases the output voltage gets reduced.

12. CONCLUSION

Here an antenna operating at 2.45 GHz to harvest the RF energies available in the atmosphere has been designed using Advanced Design System (ADS) and the designed antenna has been fabricated on a FR4 substrate having a dielectric constant of 4.4 with thickness of about 1.2 mm. The designed rectenna circuit comprises of microstrip square patch antenna, band pass filter (BPF), matching circuit, rectifier and a low pass filter (LPF). The designed antenna receives the energy from the atmosphere and rectifies it by using the rectifier that performs RF-DC rectification which can be used to charge the electronic devices with low power consumption. The efficiency of the fabricated rectenna circuit is obtained as 42.9%. The circuit is also implemented in hardware and the output voltages are measured and plotted.

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