Design of Rectifying Circuit and Harmonic Suppression Antenna for RF Energy Harvesting

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***Abstract*— In this paper a rectifying circuit and antenna designs at frequency of 2.45 GHz are presented. The antenna has a form of two-layer through which high gain and harmonic rejection property are embedded. The rectifying circuit consists of two stages with four fast switching diodes to provide high output DC voltage. The power combiner is used to combine the two stages and maximize the output DC voltage. The equivalent circuits of both antenna and rectifying circuit that are derived from lumped components, are presented. From measurement, the proposed rectifying circuit can achieve 78.7 % with load resistance 4 KΩ and input power of 20 dBm. The advantages of the proposed rectifying antenna are that the harmonic rejection filter is not needed and the cost of the overall rectifying antenna design is low. These benefits make it suitable for RF energy harvesting applications.**

***Index Terms*—Antenna Design, Enhanced Gain, Harmonic Suppression, Rectifiying Circuit, RF Energy Harvesting.**

I. INTRODUCTION

The need for new free and green energy source is vital to avoid limitations associated with current energy sources such as oil and gas. The idea of obtaining such energy is originated based on utilization of RF signals that are collected and converted to DC voltage by the mean of the rectifying antenna or rectenna. The idea behind rectenna function was first proposed and tested by Nicolas Tesla. RF energy harvesting system can capture ambient RF signals and converts them into DC voltage [1]. The receiver side of the RF energy harvesting system consists of receiving antenna, matching network, rectifier and load resistance, as shown in figure 1. This system is called as a rectifying antenna or rectenna [2].

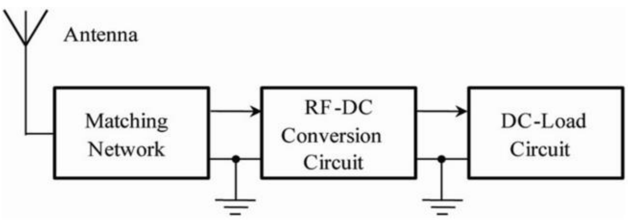


Figure 1: Basic Block diagram of RF energy harvesting receiver

The antenna is used to capture RF surrounding signals. The rectifying circuit can convert the captured signals into DC voltage by the mean of the diodes. However, due to nonlinear behavior of the diodes unwanted harmonics are generated which reduces the overall rectenna efficiency.

Some researchers have used low pass filter (LPF) or Harmonic rejection filter (HRF) to block unwanted harmonics [3]- [6], but the use of harmonic rejection filter (HRF) has increased the size and cost of the rectenna.

In [7]- [9] the antennas used, for rectenna application, has the capability of harmonic rejection so that the harmonic rejection filter (HRF) is not required. Although these rectennas have small size and low cost, due to the elimination of harmonic rejection filter (HRF), the antennas have low gain which results in low conversion efficiency of the overall rectenna.

Many rectenna designs have been proposed [10]-[17]. Some designs used single microstrip patch antenna and others used array antenna to collect as many as possible of the surrounding RF signals. However, these designs have a RF to DC conversion efficiency.

In this paper, an efficient rectenna design with harmonic suppression capability is presented. The antenna consists of two-layer low-cost FR-4 substrates with an air gap which improves the antenna gain. The antenna has the capability of suppressing high-order harmonics which replaces the low pass filter (LPF). The rectifying circuit consists of two stages combined by a power combiner to increase the output DC voltage. The high output DC voltage beside the elimination of the insertion loss, occurs with the low pass filter (LPF), have resulted in a high RF-DC conversion efficiency of the proposed rectenna.

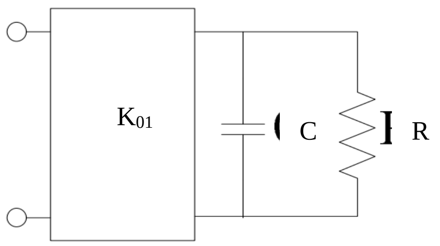
Based on study and results presented in this paper, the proposed rectenna can be compared with past research proposed rectennas as shown in Table 1 The comparison is conducted in terms of the type of antenna, harmonic rejection capability, substrate used and RF-DC conversion efficiency. From comparison, it can be noted that the proposed rectenna used single patch antenna design with harmonic rejection capability. The harmonic rejection capability is embedded within the antenna design without harmonic rejection filter. The RF-DC conversion efficiency of the proposed rectenna can reach 78.7 %. The proposed rectenna uses low cost FR-4 substrate which makes the design cost effective.

II. EQUIVALENT CIRCUIT DESIGN

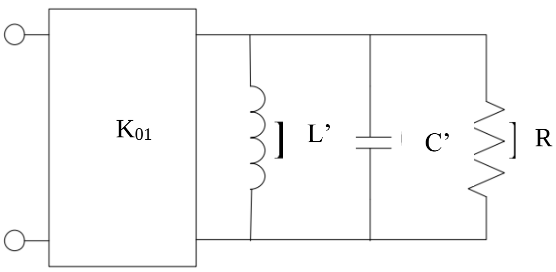
The equivalent circuit of the antenna can be created based on the low pass filter. The antenna can be single mode or dual mode which is determine based on the number of the response frequencies. The proposed design creates a single mode. Thus, a single mode equivalent circuit is applied. Figure 2 (a) shows the basic equivalent circuit where inverter, K_{01} refers to the coupling between the equivalent circuit and the input port [5]. Figure 2 (b) shows the antenna equivalent circuit based single mode low pass filter. Dual mode antenna that have more than one response frequency can be produce by combining single-mode antennas' equivalent circuit or by using low-pass circuit with second order.

Table 1
Comparison of the Proposed Rectenna and Past Research Work

Ref.	Author	Antenna Type	Harmonic rejection capability	Type of Substrate	Efficiency (η) (%)
10	(Nie et al., 2015)	GCPW Broadband slot antenna	Not achieved	F4B-2	72.5 %
11	(Falkenstein et al., 2012)	Microstrip antenna	Not achieved	Rogers 4003c	54 %
12	(Sennouni et al. 2014)	3×3 array antenna	low pass filter	FR-4	65.8 %
13	(Olgun et al., 2011)	2 ×2 planar array antenna	Not achieved	A 10.2 permittivity substrate	68 %
14	(Vera et al., 2010)	antenna with across shaped slot	Not achieved	Arlon A25N	42.1 %
15	(Huang et al., 2012)	Microstrip antenna	Achieved	FR-4	37.8 %
16	(Takhedmit et al., 2012)	Annular ring slot Antenna	Achieved	Arlon 25N	50 %
17	(Takhedmit et al., 2010)	patch antenna	Achieved	Rogers Duroid 5880	52 %
This work	(Sharif et al, 2017)	Single patch antenna	Achieved	FR-4	78.7 %



(a)



(b)

Figure 2: (a) General block diagram of the Equivalent circuit based on K_{01} inverter (b) Equivalent circuit of the top radiated patch antenna of the proposed structure.

The K_{01} inverter and the capacitance C_r are determined for equivalent circuit design using the following equations. The order number is referred to as N as presented in reference [18]. The insertion loss ripple is presented as ƹ. The equivalent circuit components in terms of are derived using the following equations [18]. Where, α refers to the bandwidth scaling factor, the load resistance is represented as R, η is the efficiency, and r is order number.

$$C_r = \frac{2}{\eta} sin\left[\frac{(2r-1)\pi}{2N}\right] \quad (1)$$

$$K_{r,r+1} = \frac{\left[\eta^2 + sin^2\left(r\pi/N\right)\right]^{1/2}}{\eta} \quad (2)$$

$$L_r^{'} = \frac{1}{\alpha Cr\omega_o} \quad (3)$$

$$C_r^{'} = \frac{\alpha C_r}{\omega_o} \quad (4)$$

In RF energy harvesting system, the rectifying circuit can take a form of doubler rectifier or bridge rectifier. In this paper, a bride rectifier that have four rectifying diodes is used as it has the advantage of providing high output DC voltage. the lumped circuit of the bridge rectifier is shown in figure 3(a). The rectifying circuit rectifies the input AC signals and the rectified signals are stored in the output capacitor. The equivalent circuit of the proposed bridge rectifier is shown in figure 3(b) [19].

$$\tau = \frac{C_L C_P\left(R_W + 2R_D\right)}{C_L + C_P} \quad (5)$$

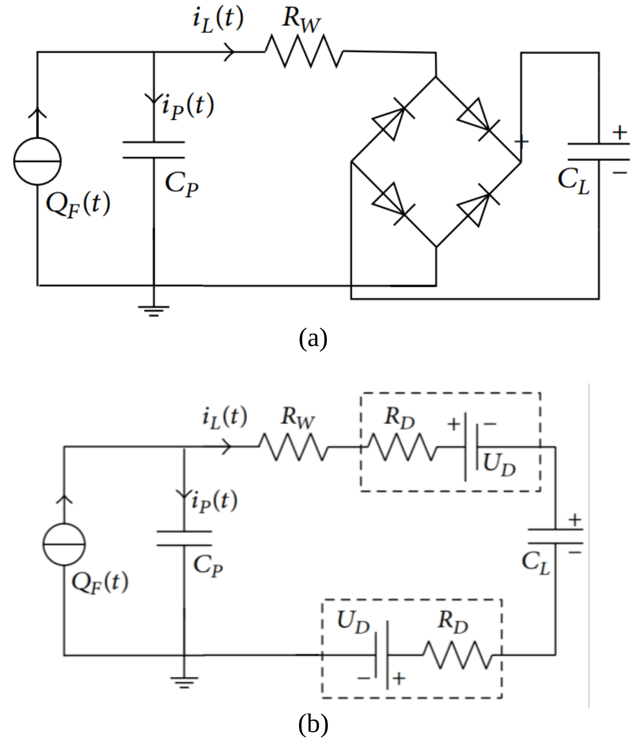
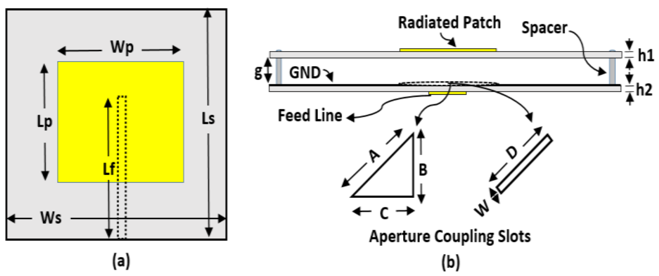


Figure 3: (a) Block diagram of the proposed bridge rectifier circuit (b) Equivalent circuit of the bridge rectifier circuit.

III. RECTIFYING ANTENNA DESIGN STRUCTURE

The proposed rectenna consists of an antenna and rectifier. The antenna is designed of two-layer 4.4 permittivity FR-4 substrates. An air gap separates the two layers to improve the antenna gain. The radiated patch is designed at the top layer as shown in figure 4 (a). The two layers are hold by using spacer of 5 mm as shown in fig. 4(b). Aperture coupling slot is etched on the ground plane to couple the feed line to the top radiated patch. Rectangular aperture coupling slot and right-angled triangular aperture coupling slot are designed to study the harmonic suppression capability of the antenna. A single-feed line with a 50 Ω impedance is designed at the bottom layer. The proposed antenna design is simulated using Computer Simulation Technology (CST) Studio Suite.

A double stage rectifier is designed with a power combiner. The detailed dimensions in mm unit of the proposed rectifier are shown in figure 4(c). The power combiner is first simulated with three ports to insure proper impedance matching. The lumped elements of the capacitors are replaced by Interdigital capacitors and stubs due to their advantages at high frequencies. HSMS286B Schottky diode is used as it has low breakdown voltage and fast switching capability. The proposed double stage rectifier is simulated using Advance Design System (ADS).



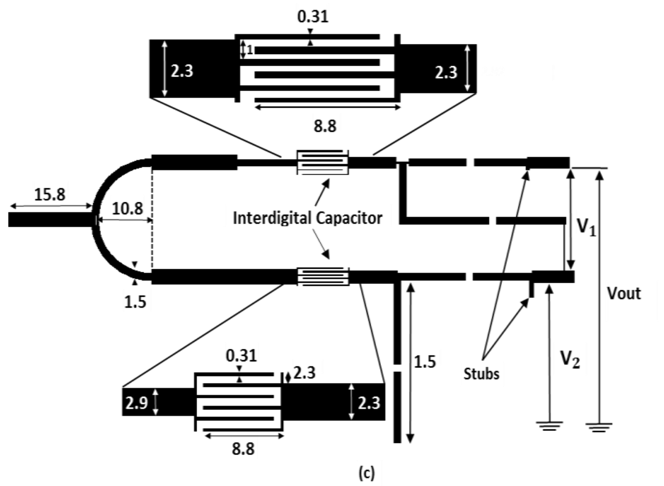


Figure. 4: The design geometry of the proposed rectenna. (a) Top view of antenna, (b) side view of the antenna, where Ws= 85 mm, Ls =100 mm, Wp= 38.9 mm, Lp= 37.2 mm, Lf= 52.1mm, W= 1.61 mm, D= 25.64 mm, B =C = 21 mm and A= 29.69 mm, (c) double stage rectifier with the power combiner.

IV. HARMONICRREJECTION ANTENNA ANALYSIS

A. Antenna Return Loss and Harmonic Rejection Property

There have been many aperture-coupled antennas designs that can provide high gain with the use of an air gap technique. However, these antennas do not provide harmonic rejection capability which make it unsuitable for rectifying antenna applications. Due to the limitations of harmonic suppression property with current aperture coupling rectangular slot antennas, a new aperture coupling antenna with high-order harmonic rejection capability is designed applying Pythagorean Theorem as shown in fig. 2(b). The two sides "B" and "C" are orthogonal and equal in length, while the hypotenuse "A" is opposite to the right angle. The relationship among the three sides, in the right-angled triangular, is presented in (6).

$$A^2 = B^2 + C^2 \tag{6}$$

The antenna with the right-angled aperture coupling slot was fabricated and measured to verify the antenna performance. A comparison of the antenna return loss is shown in figure 5. Despite the fact that FR-4 substrate is lossy, the antenna is able to achieve harmonic rejection at high frequencies up to 10 GHz.

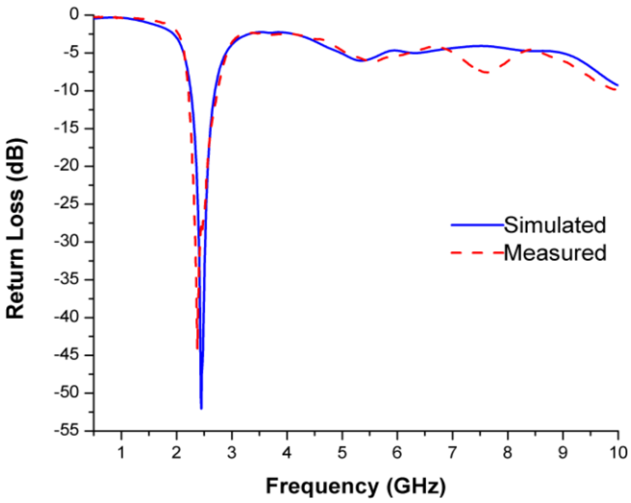


Figure. 5: Comparison between simulated and measured return loss of the aperture-coupled antenna

B. Antenna Gain

The proposed aperture-coupled antenna is designed with a suitable air gap. The air gap is added to enhance the gain to 7.68 dB as shown in figure 6. The total efficiency of the antenna is -0.918. The measured antenna gain is 7.13 dB. the slight difference between simulated and measured antenna gain is due to FR-4 dielectric constant tolerance variation.

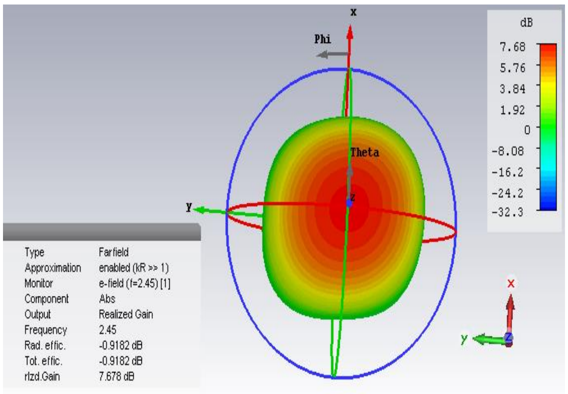


Figure 6: Simulated gain of the proposed antenna

V. RECTIFYING CIRCUIT ANALYSIS

The output DC voltage of the two stages is simulated with different input power ranged from -20 dBm to 20 dBm. The double stage provides maximum output DC voltage of 12.4 V at an input power of 20 dBm, while the single stage of the rectifier reaches its maximum of 5.7 V at the same input power. The double stage can achieve almost twice the output voltage obtained from the single stage based on (7):

$$V_{out} = V_1 + V_2 \tag{7}$$

The measurement of the output DC voltage of the two stages of the rectifier is shown in figure 7. There is a drop in the measured output voltage compared to the output voltage obtained though simulation. This is due to the fabrication process and variation in the dielectric constant of the FR-4 substrate.

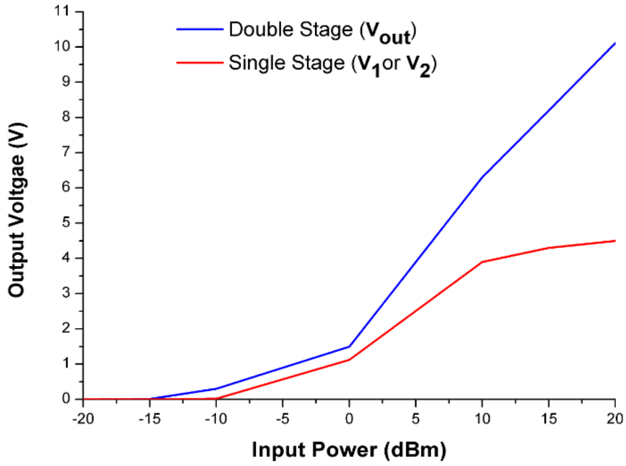


Figure 7: Measured output voltage of the two stages rectifier

VI. ANALYSIS OF THE COMBINED ANTENNA AND RECTIFIER

Figure 8 shows the combined antenna and double stage rectifier. A male-to-male SMA connector is used to connect the aperture coupling antenna and the double stage rectifier.

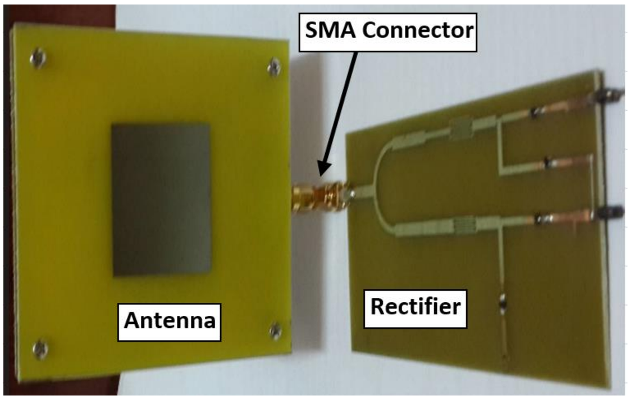


Figure 8: The combined antenna and rectifying circuit prototype.

The experimental setup of the proposed rectenna is conducted in the laboratory. A horn antenna is used as transmitter. The horn antenna has a gain of 10 dBi at frequency of 2.45 GHz. The distance between the transmitting horn antenna and the proposed rectenna was set to 50 cm for measurement process. The output DC voltage and the conversion efficiency are recorded based on the input power and the distance set. It is found that the rectenna can achieve an output DC voltage of 2.97 V at power as shown in figure 9. Base on the achieved output DC voltage, the conversion efficiency is calculated in term of the load resistance, distance, and input power. A 78.7 % conversion efficiency is obtained at 20 dBm power and 4 KΩ load resistance.

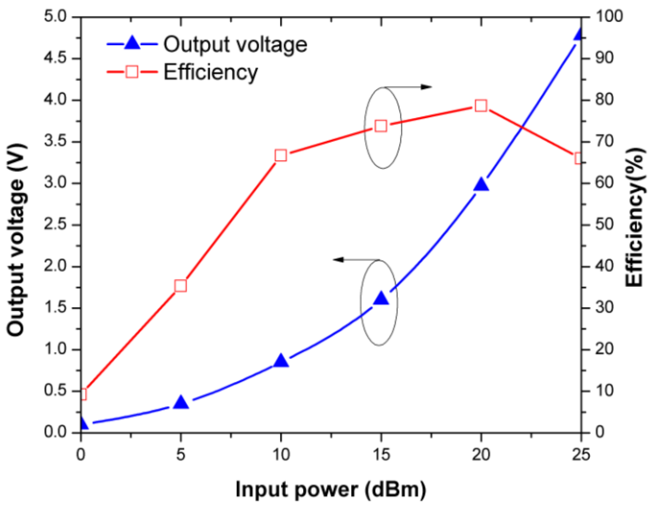


Figure 9: Measurement of the conversion efficiency and output DC voltage of the proposed rectifying antenna.

VII. CONCLUSION

In this paper, an efficient low-cost rectifying antenna design at 2.45 GHz has been presented. The antenna can provide high gain and harmonic rejection property. A double stage rectifier is integrated with the high gain harmonic rejection antenna to improve the overall rectenna conversion efficiency. The proposed rectenna can achieve conversion efficiency of 78.7 % at an input power of 20 dBm. The elimination of harmonic rejection filter and the use of FR-4 substrate. These benefits make it suitable for RF energy harvesting applications.

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