A Compact Rectenna System With High Conversion Efficiency for Wireless Energy Harvesting

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ABSTRACT A novel coplanar waveguide-fed rectenna with high efficiency is proposed and implemented in this paper for 2.45-GHz Bluetooth/wireless local area network applications. The antenna has compact dimensions of 18 mm × 30 mm, which is simulated and manufactured using a low-cost FR4 substrate with a thickness of 1.6 mm. A tuning stub technique with rectangular slots is used for better impedance matching and enhancing the impedance bandwidth of the antenna with a peak gain of 5.6 dB. The proposed novel antenna for RF energy harvesting applications exhibits dipolelike radiation pattern in H-plane and omnidirectional pattern in E-plane with improved radiation efficiency. Single-stage Cockcroft–Walton rectifier with L-shaped impedance-matching network is designed in advance design system and fabricated on FR4 substrate. The dc output of the rectenna is measured as 3.24 V with a load resistance of 5 kΩ. A simulated peak conversion efficiency of 75.5% is attained, whereas the measured one is observed to be 68% with an input signal power of 5 dBm at 2.45 GHz.

INDEX TERMS Rectennas, printed antennas, Wi-Fi, WLAN, ultrawideband, wireless energy harvesting.

I. INTRODUCTION

Self-powered electronic devices have gained significant attention in a wide range of applications including wireless sensor networks, smart buildings and the Internet of Things (IoT). The need for such energy harvesting devices is ever increasing because of the battery charging/replacing and maintenance related issues in conventional battery-operated systems. A lot of energy is wasted in the power conversion process of charging mobile phones, PDA’s and other sensing/actuating components. This problem can be solved by harvesting ambient energy that is abundantly available in the form of solar (100 mW/cm²), thermal (60 µW/cm²), vibration (200 µW/cm²) and radio frequencies (1 µW/cm²) [1]. The idea of RF energy harvesting was floated in early 90’s but the concept of converting microwave energy to electrical energy started much earlier by Nicola Tesla in 1901 [3]. Apart from RF energy, most of the other sources are environment dependent that makes this technology more effective in critical applications such as environmental monitoring, healthcare, and defense etc. [2], [3]. The RF energy harvesting system being the receiving part of Wireless Power Transfer (WPT) has perceived immense development in the last decade [4]–[6]. To obtain the maximum energy in a wide range of frequencies, wideband and the compact antenna is desired to power up small handheld devices i.e., cell phones, tablets, electronic watches and other smart devices. It is desired that the RF systems for energy harvesting should be able to cover most of the telecommunication bands like 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 etc. [7], [8]. A compact antenna with broad bandwidth, reasonable gain and an omnidirectional radiation pattern is desired for such RF harvesting system. Apart from the antenna, the rectifier circuit with high conversion efficiency.
characteristics is needed that can effectively function on most of the frequency bands of 2G/3G/4G networks, Wi-Fi and TV/radio broadcasting. The output power needs to energize the electronic devices while storing sufficient energy for backup. The DC output voltage at low input signal power is core parameter to gauge the performance of the RF harvesting system. Load impedance, inherent power losses in rectenna and non-linearity of the rectifier with corresponding frequencies are major challenges for state of the art rectenna design. The main components of RF power harvesting are shown in Fig. 1.

Some wideband antennas for RF energy harvesting have been proposed using microstrip and coplanar waveguide fed techniques [4]–[10] but suffer from one or more of the above mentioned constraints. In [4] and [5], the conversion efficiencies greater than 80% are achieved using higher input power with a single narrow frequency band, which is not feasible for ambient RF energy as it has low power levels and distributed over a wide range of frequencies. A dual-band meander line rectenna implemented in [11] has 20% conversion efficiency with the overall size of 32 mm × 32 mm. Similarly, an E-shaped patch antenna, a microstrip ring slot antenna, folded meandered-line antenna and circular microstrip patch antenna with circular slots [12]–[15] have limited impedance bandwidth with low gain values. Single-band [16], dual-band [11], multi-band [17] and broadband [18] antennas with conversion efficiencies of 48%, 20%, 40% and 43% respectively are implemented for ambient RF energy harvesting. In these designs, the main focus is put on the conversion efficiencies of the rectifiers while ignoring the bulky sizes of the rectifiers and the antennas, which make them unsuitable for handheld applications.

In this paper, a miniaturized slotted planar antenna with an energy harvesting system is proposed having a compact size of 18 mm × 30 mm with broadband characteristics and a better gain for a wide range of frequencies. A rectangular tuning stub is added to the main patch to improve the overall performance of the antenna in terms of antenna again and radiation efficiency. Finally, a tuning stub is embedded to tune the resonant frequency by varying the electrical wavelength of the antenna. The wideband characteristics of the final proposed antenna design are achieved through the parametric analysis of ground structures, slots and rectangular stub dimensions for 2.45 GHz WLAN band.

The length of the slots at the center frequency of 2.4 GHz are calculated from following equations [25].

\[
L = \frac{C}{2f_r \sqrt{\varepsilon_{reff}}} \quad (1)
\]

\[
f_r = \frac{C}{4 \times h \sqrt{\varepsilon_{reff}}} \quad (2)
\]

Where ‘C’ is the speed of light, ‘f_r’ is the center frequency and ‘\varepsilon_{reff}’ is effective relative permittivity of the substrate which is calculated to be 2.7. Some of the prominent techniques used to improve the gain of the antenna are by the use of parasitic

| Table 1. Comparison of antennas used in RF energy harvesting systems. |
|------------------------|----------------|------------------|------------------|-------------------|
| Ref. | Frequency (GHz) | Antenna shape | Dimension (mm²) | Antenna Gain (dBi) |
| [4] | 0.915, 2.45 | Slot-loaded folded dipole | 3600 | 1.87, 4.18 |
| [5] | 0.915, 2.45 | Yagi-Uda | 2795.8 | –3, 6 |
| [19] | 2.45, 2.5 | Quasi-Yagi | 1650 | 5.5, 5.7 |
| [20] | 0.900 | Rectangular patch | 3795 | –0.7 |
| [21] | 2.45 | Rectangular patch | 1193.58 | 4.7 |
| [22] | 2.45 | Differentially-fed rectangle patch | 1071.6 | 6.2 |
| [23] | 0.900 | Folded antenna | 25600 | 6.3 |
| [24] | 0.900 | Inset fed antenna | 10647 | 3.57 |
| Proposed Work | 2.45 | CPW fed rectangular antenna with slots | 540 | 5.6 |

II. ANTENNA DESIGN

The proposed antenna is fabricated on a low-cost FR4 substrate having a relative permittivity (\varepsilon_r) of 4.4, loss tangent of 0.02, and a thickness (h) of 1.6 mm. The overall size of the substrate is 18 × 30 mm², which is 0.14 \lambda_o × 0.24 \lambda_o at 2.45 GHz. A Coplanar Waveguide (CPW) feeding technique with 50 Ω transmission line is used to excite the antenna. The basic antenna structure with its different components and the evolution process is shown in Fig. 1. Four rectangular slots are created in the main radiating element for enhancing impedance bandwidth to cover different frequency bands. The design process of the proposed antenna starts with the CPW design guiding principles and then further optimized with commercially available software package Ansoft HFSS v. 16. An asymmetric rectangular conducting strip is attached to the feed line and slots are created step-by-step to improve the overall performance of the antenna in terms of antenna again and radiation efficiency. Finally, a tuning stub is embedded to tune the resonant frequency by varying the electrical wavelength of the antenna. The wideband characteristics of the final proposed antenna design are achieved through the parametric analysis of ground structures, slots and rectangular stub dimensions for 2.45 GHz WLAN band.

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Where ‘C’ is the speed of light, ‘f_r’ is the center frequency and ‘\varepsilon_{reff}’ is effective relative permittivity of the substrate which is calculated to be 2.7. Some of the prominent techniques used to improve the gain of the antenna are by the use of parasitic
elements, folding grounds, vertical embedded ground plane, metamaterials, differential patches and introducing slits in the antenna designs [2], [9], [15], [23].

Apart from etching slits, all other techniques make the antennas more bulky [25]–[28]. The detailed geometry of the proposed antenna with different dimensions in terms of variables is illustrated in Fig. 3 (a), whereas the fabricated prototype of the proposed antenna is shown in Fig. 3 (b).

All the dimensions of rectangular slots and tuning stub are tuned using Ansoft HFSS. The gap between the ground and the feed line is optimized to be 0.62 mm and other designed parameters are specified in Table 2.

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Some designs found in the literature [9], [23] use vertical ground planes that contribute to the increased volume of the device, whereas a small sized coplanar ground is used in our design to attain coplanar structure. This design arrangement is easy to fabricate thus suitable for mass production. The simulated reflection coefficients of four design steps are shown in Fig 4. The four rectangular slots have been introduced gradually in the basic rectangular antenna to reduce the size of the antenna while maintaining broad bandwidth. In other words, VSWR is kept less than 2 at a wide range of frequencies by inducting adjacent slots to enhance the bandwidth of the antenna. The creation of these slots not only reduce the size of the antenna but also helps in improving the antenna gain by enhancing the radiation intensity in the direction of interest due to additional current paths.

The design is started with an antenna having a rectangular radiating patch that operates in the frequency range of 1.1 GHz to 4.9 GHz having a fractional bandwidth of 70% at an acceptable VSWR. The reflection coefficient of the sec-
ond antenna with two slots is further improved by creating uniformly concentrating current distributions at 2.45 GHz. The Third design with 4 slots exhibit ultrawide bandwidth characteristics from 0.9 GHz to 8.5 GHz and fourth design having 4 slots with an added slit cover 0.9 GHz to 9.1 GHz for $S_{11} < -10$ dB with a fractional bandwidth of above 150%.

Apart from fractional bandwidth, overall antenna performance depends on other interlinked parameters like gain, radiation efficiency, power losses and materials used in the design. Some of these prominent attributes are discussed in the following section.

III. CURRENT DISTRIBUTION AND IMPEDANCE MATCHING

To understand the principle of antenna resonance, current distribution at 2.45 GHz is shown in Fig. 5 (a). It is evident that maximum current appears at the top slot and at tuning stub along with uniform high current density at the feed line. This justifies the creation of multiple slots which store the EM energy to establish high inductance around the top of the antenna. The stub element is responsible for the reflection of stored EM energy to the top of the radiator. Moreover, the distribution of current at the antenna for 2.45 GHz band provide better insight on the antenna design as the current varies along the antenna x-axis dimension with minimum current at the left side due to the reduced ‘end effect’. As a matter of fact, the antenna radiates energy because of the radiation resistance. The loss resistance of the antenna on the top side is small as compared to radiation resistance that is usually considered negligible in the measurements. The maximum current at the top strip is obtained for 2.45 GHz frequency band which has a phase shift of 90-degrees.

Furthermore, impedance is well matched by varying the length of the stub which is measured to be 50 $\Omega$ with imaginary part equal to 0 at 2.45 GHz as shown in Fig 5 (b).

IV. RESULTS AND PARAMETRIC STUDY

The simulated and measured results of reflection coefficient $S_{11}$ [dB] versus frequency [GHz] of the final proposed antenna are shown in Fig. 6. Simulated and measured results are in accordance with the design goals and exhibit ultra-wideband characteristics covering IEEE 802.11 (2.4 GHz-2.48 GHz) for Bluetooth/Wi-Fi and a future expected sub-6 GHz 5G band (3.4-3.6 GHz). The variation between measured and simulated results is due to soldering effects, quality of SMA connector, discontinuities of substrate dielectric constant and manufacturing tolerance etc.

Parametric studies have been carried out for all the major lengths and widths of the conducting strips for overall optimum antenna performance. Fig. 7 shows the simulated results of reflection coefficients ($S_{11}$) versus frequency [GHz] for the variation of tuning stub length from 2 mm to 5 mm. It is obvious that this antenna design can be individually tuned to any desired frequency band by varying the length of tuning stub.

The radiation pattern of the final antenna design is shown in Fig. 8 for both E-plane and H-plane. Distribution effect is observed at higher frequencies due to higher order mode excitations. It is evident from the 2D graphs that the antenna performs almost isotropically in H-plane (YZ plane, $\Phi = 90^\circ$).
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V. RECTIFIER DESIGN

As the RF energy is mostly available in a low power density, which ranges from $-50$ dBm to $-20$ dBm, therefore, the distance from the RF source and the efficiency of the rectifying circuit plays an important role in obtaining desired output power from RF system. The RF signal voltage level normally fluctuates from 0.1 V to 1 V that cannot function many electronic devices and sensors. Therefore, a single stage Cockcroft-Walton voltage multiplier circuit [29] is used in our design with HSMS-2850 diode that has ideally low forward bias voltage of 0.15 V with fast switching at high frequencies which is most suitable for enormously low RF input power applications. The diode in SOT-323 layout configuration is used on PCB circuit with a parasitic series resistance of 25 $\Omega$, the low junction capacitance of 0.18 pF, breakdown voltage of 3.8 V, minimum forward voltage of 150 mV at 0.1 mA, maximum reverse leakage current of 150 $\mu$A and high detection of 50 mV/$\mu$W [32].

Advance Design System (ADS) 2011 software package is used for simulation and FR4 substrate with a thickness of 1.6 mm is selected for device fabrication. The inductor and capacitor values for impedance matching network are optimized by the ADS design tuning utility and multiplier capacitor parameters are calculated from equation 3 and 4.

$$C = \frac{Q}{V} \quad (3)$$

$$C = \frac{I}{dt} \cdot \frac{dV}{dV} \quad (4)$$

Here, “C” is capacitance to be calculated, “I” is branch current and “dt/dV” is ratio of voltage change with frequency variations. The topology used for rectifying circuit is shown in Fig. 10 along with its impedance matching network block.

It is clear from Fig. 10 that RF AC signals received from the antenna is converted to DC by full-wave rectification.
The diode $D_1$ is operational at the negative cycle and stores energy in capacitor $C_1$ while on positive cycle, diode $D_2$ is functional whereas $D_1$ is off in the positive cycle. Voltage at first capacitor ($V_{c1}$) and output voltage ($V_{OUT}$) is calculated by using the following equations [30].

$$V_{c1} = V_{in} - V_{TH1}$$

$$V_{out} = 2V_{in} - V_{TH1} - V_{TH2}$$

Where $V_{TH1}$ and $V_{TH2}$ are the threshold voltages of diodes $D_1$ and $D_2$ respectively. Source pull technique is used to match the rectifier circuit input impedance with 50 Ohm antenna source by sweeping the impedance to obtain best case scenario performance. As in rectenna RF-DC conversion efficiency is a major check to evaluate the performance, this is calculated from equations (7-8) [31].

$$\eta = \frac{OutputPower}{InputPower} \times 100$$  \hspace{1cm} (7)$$

$$\eta = \frac{P_{DC}}{P_{IN}} = \frac{V_{DC}^2}{R_L} \cdot \frac{1}{P_{L}}$$  \hspace{1cm} (8)$$

The designing process is accomplished by creating a topology of Fig. 9 in the ADS and the input impedance of the voltage multiplier is calculated to be 7.9-j102.6 Ohm. The impedance of the rectifier is dependent on a number of factors like resonant frequency, load conditions and input power levels. Therefore, to implement a rectifier circuit for a wide range of frequencies, reconfigurable maximum power point tracking (MPPT) enabled circuit is needed. In [36], the maximum efficiency is obtained to be 61% having peak $V_{out}$ of 1.25 V which is quite low as compared to our design conversion efficiency of 68% and $V_{out}$ of 3.24 V. Most modern rectennas use multiple impedance matching networks/rectifier circuits in one design to obtain multiband characteristics. Although, to visualize the wideband behavior of the rectifier at a single frequency band is still quite challenging as the impedance varies drastically due to dependent variables [33], [34]. The rectifier designed in [35] has a small bandwidth of 2.38-2.46 GHz at a low power signal of 4 dBm whereas our proposed rectifier has bandwidth from 2.37 GHz to 2.52 GHz which is more than the reported rectifier circuit in [35].

Additionally, it is observed that the incursion of multiple rectifier/IMN circuits to obtain wideband characteristics is undesirable in our case as more lumped/distributed elements are subjected to more losses for WLAN energy harvesting. Therefore, simple yet efficient topology is selected to obtain high conversion efficiency of rectenna. Simple L-type matching network is implemented to match rectifier impedance to the antenna and then lumped elements are converted to transmission lines. Final transmission-lines values and simulation variables are depicted in Fig. 11.

VI. RESULTS AND DISCUSSION

The fabricated prototype of the compact rectifier circuit is shown in Figure 12. Simulated and measured reflection coefficient results of the rectifier for different input power signal levels are shown in Fig 13 (a) and are found generally in good agreement. Tuning and optimization of the components is simultaneously performed for the reflection coefficient results.

The impedance matching characteristic of the rectifying circuit for different input power levels of $-20$ dBm, $-10$ dBm and 5 dBm are shown in Fig 13 (b) using the Smith chart. It can be seen that excellent impedance matching is achieved at 2.45 GHz.

The rectenna is well matched for 2.37 GHz to 2.52 GHz frequencies and beyond this range the inductive and capacitive parts of the impedance become unsuitable for the targeted WLAN applications. Furthermore, harmonic balance
non-linear circuit simulation, planar EM simulation and their co-simulation are performed in ADS 2011 at 2.45 GHz in order to evaluate the performance of the rectifier with best possible practical considerations. During this process, FR4 substrate with a thickness of 1.6 mm is chosen and the effects of component pads and their respective sizes are also considered for achieving optimal performance. The measurement set-up consists of a traditional wireless local area network (WLAN) router placed at a distance of 1 meter from the rectenna system and the output is connected to a Voltmeter. At first, the individual response of the rectifier was measured by feeding the variable input power signal using Agilent E5080A vector network analyzer (VNA). Afterwards, the antenna is attached to the rectifier circuitry while using NETGEAR (AC1200) WLAN router as an RF source. This module has a built in option of varying RF signal power which leads to the effortless rectenna performance measurement. The overall measured parameters of the rectenna are comparable to the simulated results, while the orientation of the rectenna was periodically adjusted to obtain the final optimum results. A variable resistor with a range of 01-50 KΩ is connected at the rectifier output to analyze the load resistance behavior. As expected, when we increase the distance between the WLAN router and rectenna system, the rectified power starts to deteriorate. The complete rectenna prototype is shown in Figure 14 (a) and the measurement arrangement is illustrated in Figure 14 (b).

Simulated conversion efficiency as a function of input power for 5 KΩ, 30 KΩ, and 50 KΩ is depicted in Fig. 15 (a). It is clear from the graph that the efficiency is low at low input power levels and increases with the increase of RF input signal power. Below 50% conversion efficiency is observed for −10 dBm input power, while a peak conversion efficiency of 75.5% is found at 5 dBm.

The simulated and measured conversion efficiency for 2.3 GHz–2.6 GHz at different input power levels for 5 KΩ resistive load is depicted in Fig 15 (b). A measured RF-DC conversion efficiency of 18%, 42%, and 68% are achieved at 2.45 GHz for −20 dBm, −10 dBm and 5 dBm input power levels respectively.

A parametric analysis is performed for different values of the inductor $L_1$ and the capacitor $C_1$ (shown in Fig. 9) to observe their effects on the performance of rectifier in terms of frequency. The corresponding effects on the resonant frequency are shown in Fig. 16 (a). It is clearly visible that the rectenna can be easily tuned to any desired frequency ranging from 1.5 GHz to 4.5 GHz by just varying the inductor $L_1$ whereas the capacitor $C_1$ further tunes the resonant frequency in the desired band to obtain optimum results. It can be clearly observed that the resonant frequency reduces with the increase of inductance values and vice versa. Above 13.32 nH and below 2.32 nH, a complete impedance mismatch is observed, which represents the maximum possible tuning range of our design. As shown in the Fig. 16 (a), the value of the inductor $L_1 = 4.82$ nH tunes the circuit to 2.45 GHz for the maximum power transfer.
The different load resistance of 1 KΩ, 2 KΩ, 3 KΩ, 5 KΩ, 30 KΩ and 50 KΩ are simulated for maximum $V_{out}$. It is noted that at 5 KΩ, a voltage of 3.89 V is calculated with better efficiency at 2.45 GHz band. During the designing process, it is observed that 4.02 V is obtained at 100 KΩ load, but at this load value, the conversion efficiency drops down to around 23% with the same input power signals. Final rectenna measurements have been carried out by selecting physical components ranging from 5 KΩ to 50 KΩ. It is found that 5-15 KΩ load resistances produce similar output voltage levels with minor variations. The simulated and measured $V_{out}$ at 5 KΩ is plotted in Fig 16 (b). The simulated value of $V_{out} = 3.89$ V at 5 dBm input power implies that the rectifying circuitry is in good operational order with the design requirements.

Table 3 compares the proposed rectenna system with other related work published during 2018. The major contributions of this work include a compact and novel wideband antenna implementation with improved gain and the design of a simple yet efficient rectifying circuitry with a high efficiency rectenna for WLAN applications. From Table 3, it can be seen that our proposed design demonstrates improved efficiency with compact size while covering better bandwidth range for rectification.

**VII. CONCLUSION**

A compact rectenna circuit comprising of an efficient antenna with a peak gain of 5.6 dB and Schottky diode HSMS-2850 based rectifying circuitry is designed and tested at 2.45 GHz frequency band. A simple L-shape impedance matching
network is designed to match the rectifier input impedance of 7.9-j102.6 Ω to the 50 Ω antenna. Further, a tuning stub technique is implemented in the antenna design with four symmetrical slots to receive RF energy from the dedicated microwave source to improve the impedance bandwidth. The proposed antenna has a wide measured bandwidth from 0.9 GHz to more than 9 GHz. This antenna is equally feasible for WiMAX, 4G and WLAN based IoT applications. The proposed rectifier achieved 75.5% simulated and 68% measured conversion efficiencies respectively at WLAN 2.45 GHz band. The output voltage at 5 KΩ load resistance is measured to be 3.24 Volts, which is adequate to function for most of the handheld electronic devices. Embedding this rectenna circuit in electronic gadgets will reduce the charging requirement for the next generation IoT devices and it is also capable to provide battery-less operation for devices with power requirements of 150 mW or less. The proposed antenna is 540 mm² (0.14 λo × 0.24 λo), which makes it a suitable candidate for different ultra compact energy harvesting applications.

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