A Flexible 2.45 GHz Rectenna Using Electrically Small Loop Antenna

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***Abstract*—We present the concept and design of a compact flexible electromagnetic energy-harvesting system using electrically small loop antenna. In order to make the integration of the system with other devices simpler, it is designed as an integrated system in such a way that the collector element and the rectifier circuit are mounted on the same side of the substrate. The rectenna is designed and fabricated on flexible substrate, and its performance is verified through measurement for both flat and curved configurations. The DC output power and the efficiency are investigated with respect to power density and frequency. It is observed through measurements that the proposed system can achieve 72% conversion efficiency for low input power level, -11 dBm (corresponding power density 0.2 W/m^2), while at the same time occupying a smaller footprint area compared to the existing work.**

***Index Terms*—flexible rectenna, energy harvesting, wireless power transmission.**

I. Introduction

Collecting and rectifying the ambient electromagnetic energy, commonly referred to as rectifying antenna system (rectenna), has empowered various applications in numerous areas since their essential objective is to reuse the surrounding microwave power.

Flexible electronic devices have received a considerable intention during the past decade where they can be used in many potential applications such as wearable medical device and military applications. Flexible/Conformal antennas, such as cylindrical or spherical antenna arrays, have been already proposed in the literature. Conformal rectenna system, on the other hand, has few examples in energy harvesting literature [1], [2], [3], and [4]. Furthermore, the reported systems have various limitations. Despite the surrounding microwave power resources are normally of low power level, most of those rectennas display insufficient efficiencies at low input power or desire approximately high input microwave power. Classic antennas, which were used in [1], [2], [3], and [4], are in the front end of the rectifier circuits; their physical sizes, which are determined by the operation frequency, result in increasing the complexity of the system. Therefore, increasing the capability of rectenna for low input power while at the same time occupying a smaller footprint area is in high demand.

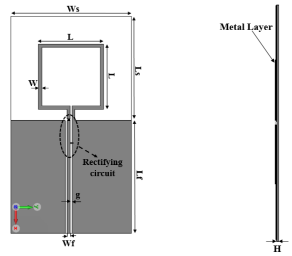
In this letter, a compact rectenna is fabricated on flexible substrate for harvesting low-power RF energy. It consists of electrically small loop antenna operating at 2.45 GHz, a schlocky diode connected in series to one of the two feed terminals of the antenna and to the coplanar transmission line, a capacitor to minimize the ripple level. The reported system in this letter is sufficiently capable of reusing low microwave energy for both flat and curved configurations.

II. Design and Result

The two main parts of rectenna system are largely designed individually and unified through the matching network. In this work, the proposed rectenna is built as an integral system, and thus the rectifier circuit is matched to the collector to maximize the energy transfer. Schottky diodes from Skyworks SMS7630 is used because of the low barrier height ($\approx$ 0.69 eV), which results in good sensitivity, and the low parasitic capacitance that makes the diode a superior detector at high frequencies [5]. Single diode in 0201 surface mount package is chosen. For capacitance selection, ATC 600L 0402 size is chosen because it has high self-resonant frequency (SRF), which is desired to stay away from parasitic effects of the capacitor package [6].

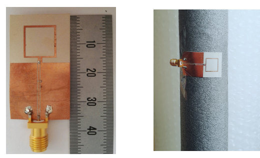
To determine the input impedance of the rectifier circuit, which depends on the frequency of interest, the load impedance and the input power [7], the software Advanced Design System (ADS) has been utilized [8]. The rectifier has an input impedance of $Z_{in} = 106 - j423$ at 2.45 GHz when it is terminated with a load of 560 Ω, and the input power is -11 dBm. The proposed rectenna employs coplanar waveguide (CPW) circuit, which not only reduces the complexity of the system, but also gives excellent control over its input impedance by optimization of its dimensions to stay away from the insertion of a matching network between the collector and the rectifier circuit and to reduce the overall size of the system. To maximize the received energy from an incident wave, the CPW dimensions were optimized to have input impedance equal to the impedance of the rectifier. A full wave simulator (CST) was used to optimize the electrically small loop antenna to operate at 2.45 GHz [9]. The length of each side of the collector is $L = 10.8\ mm$ and the width of the line is $W = 0.55\ mm$ (4L $\approx 0.4\lambda_o$) as shown in Fig. 1. The system is fabricated on flexible substrate (RO3003) with 0.13 mm thickness 35 copper cladding as displayed in Fig. 2.

A photograph of the experimental setup is illustrated in Fig. 3. A Satimo Quad Ridge Reference horn antenna (800 MHz



(a) (b)

Fig. 1: Configuration of the proposed rectenna. (a) Top view. (b) Side view. The parameters are: $W_s = 20mm$, $L_s = 18mm$, $L_f = 18mm$, $L = 10.8mm$, $W = 0.55mm$, $W_f = 0.5mm$, $g = 0.3mm$, $H = 0.13mm$.



(a) (b)

Fig. 2: Fabricated prototypes. (a) Flat rectenna structure. (b) Curved rectenna structure.

- 12 GHz) [10], which has a gain of 9 dBi at the operating frequency, was used as the source of electromagnetic power in the experiment. The signal generator was set to transmit from 2.4 GHz to 2.8 GHz, and it fed the antenna. The electric field of the incident wave was forced to be in parallel to the gap of the loop antenna. The separation between the horn antenna and rectenna system is about $1.1\ m$. considering the largest loop antenna dimension of $10.8\ mm$ and the operating frequency of 2.45 GHz, the separation was calculated as $0.002\ m$ and the experiment separation satisfied the far field conditions. A digital multimater was utilized in order to record the rectified DC voltage across the load, and the DC power P_{DC} was computed by means of dividing the square of the rectified DC voltage to the resistive load. Experimental works were completed with differing load resistance, power density, and frequency.

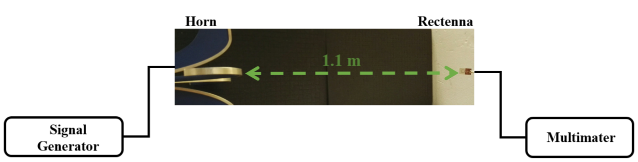


Fig. 3: Photograph of the experimental setup.

The radiation to DC power conversion efficiency η_{Rad-dc} was used to evaluate the performance of the system. It is defined as [11]

$$\eta_{Rad-dc} = \frac{P_{DC}}{P_{Rad}} \tag{1}$$

Where P_{Rad} ,which is the total incident radiated power at the area of the collector, is found by [11]

$$P_{Rad} = S_{Rad} \times A_P \tag{2}$$

Where A_P is physical area of the collector. To measure the power density at the rectenna surface S_{Rad}, a commercial horn antenna, which its efficiency is given, was first utilized to capture the electromagnetic waves at various power levels at a distance of $1.1\ m$. By using a spectrum analyzer, received microwave power was measured and the corresponding transmitting power was recorded. The density power was obtained by dividing received power to the affective area of the horn. The horn antenna was then replaced by the rectenna at the same location.

Fig. 4 represents the rectenna efficiency with respect to the load resistance. By measuring the efficiency with the incident power density of $0.2\ W/m^2$, the maximum efficiencies happened at $560\ \Omega$ load, which is the optimized load for the proposed system.

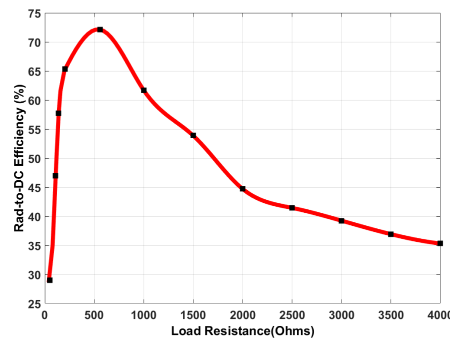
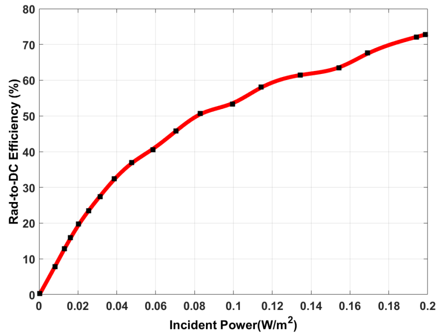
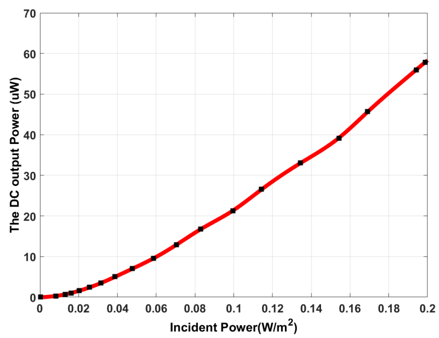


Fig. 4: Radiation to DC efficiency of the rectenna system as a function of the load resistance.

Fig. 5 represents the rectenna efficiency and the DC output power versus the power density. The maximum efficiency happened when the incident power intensity S_{Rad} was 0.2 W/m^2, which was used to obtain the impedance reference in the previous experiment. The peak output power of 58 μW was achieved and the conversion efficiency is about 72% when the incident microwave power was -11 dBm. In [1], [2], [3], and [4], similar conversion efficiency definitions were used reporting 56%, 57%, 64.6%, and 43% efficiencies for incident power as low as 21 , -1.3, -2, and -2 dBm, respectively. It can be observed that the rectenna presented in this work has achieved higher efficiency at lower incident power. Capturing of continues waves (CW) was tested at the operating frequency and other frequencies. Fig. 6 shows the rectenna efficiency with respect to frequency while maintaining the load resistance and the power density at their best values. The peak efficiency was recorded at the operating frequency. Since the collector was designed to receive electromagnetic waves at 2.45 GHz with reasonable impedance matching with the rectifier circuit, the frequency dependency of the efficiency of the system was observed to be in good concurrence with design targets. However, the proposed system is able to capture the electromagnetic radiation at other frequencies.



(a)



(b)

Fig. 5: Measured (a) radiation to DC efficiency and (b) DC output power with respect to the incident power density.

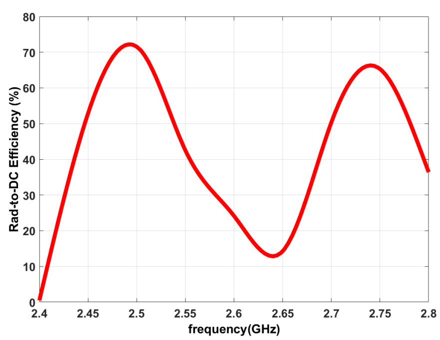


Fig. 6: Measured radiation to DC efficiency of the rectenna system as a function of the frequency.

Fig. 2(b) illustrates the rectenna when it is curved and mounted on 2 cm diameter foam roller. To ensure that the proposed rectenna maintains its operating frequency when it is bent or conformed on a curved structure, it was tested for the conversion efficiency of the curved structure and compared to the efficiency of the flat configuration. The comparison is displayed in Fig. 7, which indicates that the operating frequency for both flat and curved configurations is the same. However, there is a small drop in the conversion efficiency at the operating frequency, which is expected since the distance between the rectenna and the transmitter, when the system is bent, is not similar to one without bending.

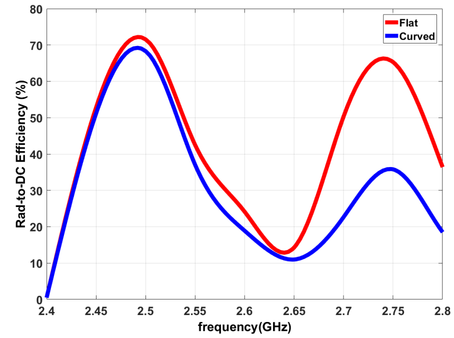


Fig. 7: Measured radiation to DC efficiency of the rectenna system as a function of the frequency for different configurations: flat and curved

III. Conclusion

In this letter, a flexible 2.45 GHz rectenna, which is able to work at low input power, is propsed. A compact rectenna is verified through measurements. The overall efficiency, which includes capturing the radiated RF power , transferring it to the rectifier circuit, and converting it into DC, is measured. It is demonstrated that the efficiency of the proposed rectenna can achieve 72% with power density of $0.2\ W/m^2$. A comparison between the performance of the flat and curved rectenna system is included to examine the impact of the radius of curvature on the conversion energy. It is observed that it maintains its performance.

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