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An Efficient Rectifier for an RDA Wireless Power Transmission System Operating at 2.4 GHz

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Abstract

This paper describes the design and measurement of a full-bridge rectifier and a receiving antenna array operating at 2.4 GHz for wireless power transmission system applications, and with motivations to wirelessly charge an electronic device in the radiating near-field. A retrodirective antenna array (RDA) was also used in the system with high power gain to boost the overall received RF power at the input of the rectenna. In particular, the RDA offered automatic tracking of the rectenna module in 3D space by employing phase conjugating mixers. The diode rectifier of our rectenna, which is the focus of the present work, offers full-wave-rectification and exhibits a 76% efficiency for an RF input power of 26 dBm and 74% at 27 dBm, while also providing more than 60% of RF-to-DC conversion efficiency at 2.4 GHz when considering an input RF power level ranging from 15 dBm to 29 dBm.

1 Introduction

Wireless power transfer (WPT) has been widely studied over the last few years and it is considered a possible technology to wirelessly charge electronic devices. A variety of devices employ WPT such as wireless charging by magnetic resonance [1], [2], for biomedical devices [3], and for electrical vehicles [4]. In this work, WPT is directed towards a rectenna positioned in the near-field in order to receive 27 dBm of RF power at the input of the designed rectifier. The position of the rectenna is automatically tracked using a retrodirective antenna array (RDA) as conceptualized in Fig. 1. The main challenges of this system are related to the needed high power radiation from the RDA, efficient conversion of the received RF signal to DC, and implementation in an operational microwave system. Earlier, more conventional works on the topic of WPT can be found in [5] and the references therein, while in this paper we focus on a low-cost and planar rectifier implementation with a simple bridge diode topology.

Rectifiers are classically used in power supply circuits offering full-wave rectification with high efficiency. The bridge rectifier topology has been commonly used since the 1970's [6]. In [7] the efficiency of this bridge diode rectifier operating at 100 MHz and 2.4 GHz for high power levels

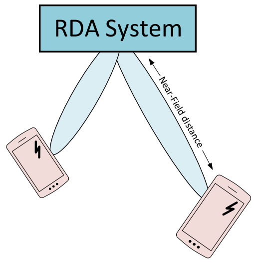

Figure 1. The proposed WPT approach using RDA technology where the device can be self-tracked and charged by steering the radiated fields.

was reported. Other structures using diodes were also used for WPT. More precisely, there is one architecture which uses two diodes, [8] having a 3^{rd} harmonic rejection stub which was also explored in [9]. These structures are able to provide high efficiency at a low input power of 24.7 dBm and 22 dBm, respectively. However, the ripples generated by an imperfect rectification are minimized with these architectures. There are also many rectifiers which have been made to operate for dual-frequencies albeit at lower power levels. In [10], the reported rectenna efficiently converted the RF received signal at 920 MHz and 2.4 GHz by using a four-stage voltage doubler topology. Moreover, in [11], a printed diode rectenna was designed in order to convert 19.5 dBm of input power with high efficiency (84.4%) at 2.45 GHz and 5.8 GHz.

Most of the rectifiers found in the literature have been optimized to obtain high RF-to-DC conversion efficiency at one particular frequency and at a certain power level. However, for WPT applications and in possible system implementations, the rectenna should be able to efficiently convert different power levels. This is because the received power can change due to free-space path loss as it is dependent on the position of the charging device from the RDA and the user should be able to freely move without restriction in 3D space. Moreover, the power levels received by the rectifier at different distances from the RDA are not equal and the rectenna will have to convert different RF power levels with suitable levels of efficiency.

The rectifier presented in this paper offers suitable RF-to-DC conversion efficiency. Rectification can reach an efficiency level of 76% for an RF input power of 26 dBm at 2.4 GHz while also providing efficiency values over 60%

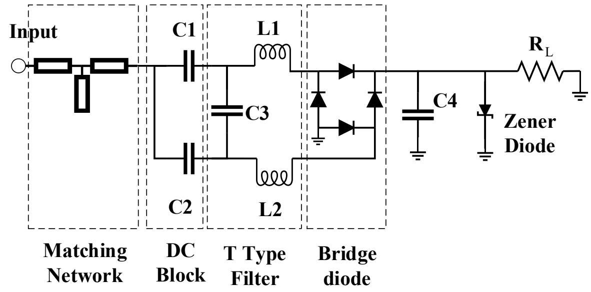

Figure 2. Circuit schematic of the rectifier.

when the input RF power ranges from 15 dBm to 29 dBm. To the best of the authors' knowledge no similiar rectifer performances have been reported and tested within a WPT near-field system employing similiar RDA technology in the litterature.

2 Rectifier Circuit

The structure of the rectifier is illustrated in Fig. 2. As it is shown in the schematic, it is composed of five parts. Firstly, at the input port where the RF signal is collected, the matching network can be found. Its main aim is to avoid reflections to ensure that all the power at the fundamental frequency is transfered to the rectifier and higher order harmonics are rejected. This matching network is an open ended single-stub tuner. The main advantage of this kind of matching network is that lumped elements are not required, reducing the costs and manufacturing time. After the matching section, there are DC block capacitors to suppress any unwanted DC leakage. Then a T-type low-pass filter is applied to recover the efficiency degradation caused by the junction capacitance and eliminate harmonics. After the filter, the RF signal passes through the bridge diode for rectification. The last block is composed of a smoothing capacitor (C4) to improve the rectification efficiency by reactive harmonic termination as well as a Zener diode which acts as a voltage regulator to reduce the ripple on the output load resistance (R_L).

The rectifier has been manufactured using a Taconic substrate material (TLY-5) with a relative dielectric constant of $\varepsilon_r = 2.2$ and a thickness of $h = 1.5748$ mm. The size of the rectifier PCB was 4.5 cm by 2 cm (see Fig. 3). The components used were SMD Ceramic Multilayer MLCC capacitors, inductors, and a chip SMD load resistor. The bridge is composed of Schottky diodes (Avago HSMS-282P) having a series resistance Rs of 7.8 V and a breakdown voltage $Vb = 26.7$ V. The Zener diode is the 1SMB5935BT3 model from ON Semiconductor.

3 Rectifier Simulations and Measurements

The rectifier was designed and simulated using the software AWR. The simulation results are shown in Fig. 4. The rectifier was tested by using a calibrated power generator to introduce the desired input signal. This input signal was also

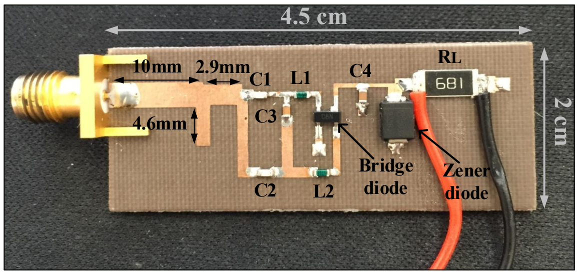

Figure 3. Photograph of the proposed rectifier.

observed and verified using a Keysight PXA Power Signal Analyzer while the DC output signal was measured at the load resistance. With knowledge of the potential difference across the load and the resistance value, the DC output power was computed with the following equation: $Pout = (V^2)/R_L$. The rectifier efficiency is defined and computed as the ratio of DC output power to the input power of the AC signal: $Eff = Pout/Pin$. In Fig. 4, the measured efficiency versus the input power at different frequencies is reported. The simulated voltage and current at the load are also shown in Fig. 5.

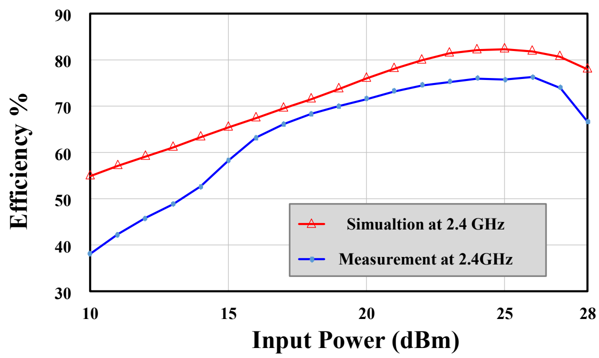

Figure 4. Measured and simulated RF-to-DC conversion efficiency versus the input power.

This rectifier was designed to convert a 2.4 GHz signal at 27 dBm with an efficiency of at least 70%. This can be confirmed in Fig. 4, where measurements are seen to match the simulations. Also, at 2.4 GHz an efficiency of 76% is achieved for an input RF power of 26 dBm and an efficiency of 74% for 27 dBm.

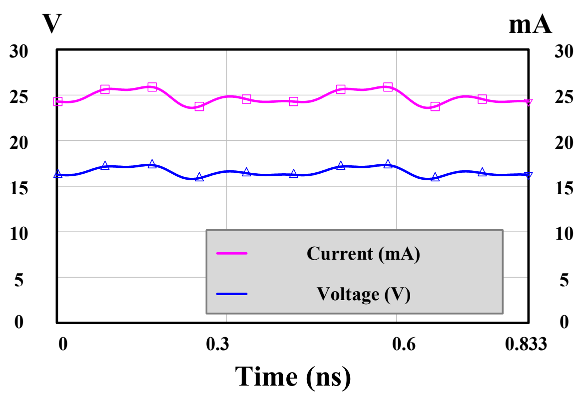

Figure 5. Simulated output voltage and current for an RF input power of 27 dBm at 2.4 GHz.

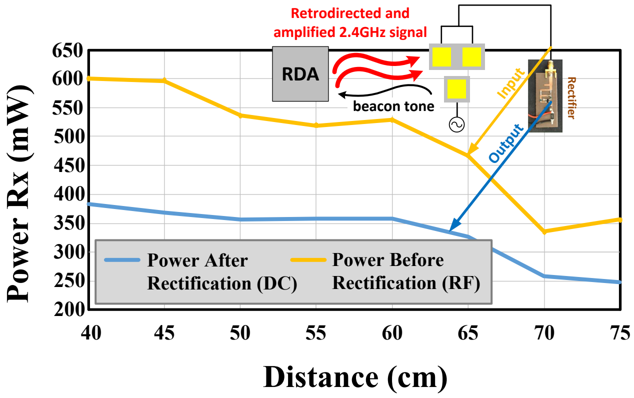

Figure 6. Measured received power at RF and DC at broadside for different distances from the RDA. A beacon signal on the rectenna module was used for RDA self-tracking.

The simulated voltage and current at DC are also presented as mentioned in Fig. 5 for an input RF power of 27 dBm. The simulation shows that at DC, the voltage fluctuates between 15.8V and 17.3V and the current between 23.6 mA and 25.9 mA. These minor variations of current and voltage offer stable DC voltage rectification and are suitable for our WPT application. In addition, the RDA system was measured in a calibrated anechoic chamber at Heriot-Watt University for the WPT system demonstration. The rectifier was connected with a 2-by-1 patch antenna array, specifically designed for the experiment, forming the rectenna. During the measurements in the reactive near-field, the rectenna was rotated around the RDA at different angles and distances. In Fig. 6, the power received at RF (input to the rectifier) and DC (output of the rectifier), is shown at broadside from 40 cm to 75 cm.

As per design, the RDA was able to retrodirect RF power to the rectenna to enable efficient system operation, rectifying the RF power into DC and providing around 250 mW (24 dBm) of DC power at a distance of 75 cm with more than 350 mW ($>$ 27 dBm) between 40 cm and 60 cm. To the authors' knowledge no similar experiment demonstrating a WPT system in the radiative near-field has been reported which employs a high-power RDA. Further details on the RDA structure, the measurement setup, and the rectifier will be reported at the conference.

4 Conclusion

A rectifier using a full-bridge diode topology has been presented in this summary paper. It has been included in a WPT system which employed an RDA in order to rectify RF power to DC and demonstrate the capability of wireless charging. Simulations and measurements show good agreement in terms of conversion efficiency and minimal DC voltage and current ripple, making the active system suitable for many applications that require WPT, such as the wireless charging of electronic devices.

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