WIRELESS POWER TRANSMISSION WITH CIRCULARLY POLARIZED RECTENNA

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Abstract—Design of a novel circularly polarized (CP) rectenna (rectifying antenna) at 925MHz for wireless power transmission (WPT) applications involving wireless power transfer to low power consumption wireless device is proposed. In order to build the rectenna, a CP wide-slot antenna and a finite ground coplanar waveguide (CPW) circuit both with good impedance matching, have been developed. In addition, the size of the wide-slot antenna is smaller than the conventional slot antenna up to 60% when the meander line structure is adopted. The rectenna is the voltage-doubler rectifier with the low-pass filter (LPF) for efficiency optimization and higher order harmonics re-radiation elimination. According to the measured results, the maximum RF-to-DC conversion efficiency of the rectenna achieved 75% when the RF power of 15dBm is received with a load resistance of 2kΩ at free space. The experimental results prove that the proposed rectenna is suitable for the WPT applications.

1. INTRODUCTION

Both wireless power transmission (WPT) [1] and solar power transmission (SPT) [2] are the promising techniques for the long-distance power supply of wireless applications, such as radio frequency identification (RFID) tags [3,4], wireless embedded sensors [5-7], medical implant with biotelemetry as a communication link [8,9], etc. The rectenna (rectifying antenna) is one of the most important components for above-mentioned techniques, which has great potential to deliver, collect and convert radio frequency (RF) energy into useful direct current (DC) power for neighbored electronic devices or to recharge batteries through free space without using the physical transmission line [10]. The typical rectenna [11,12] basically consists of an antenna for receiving RF power, a low- or band-pass filter (LPF/BPF) as an input filter for selecting/suppressing energy or signal and impedance matching simultaneously, a diode as the rectifying device for RF-to-DC power conversion, a bypass capacitor as the output filter for RF block/DC pass, and a load resistance is last.

In this paper, a novel rectenna with a CP wide slot antenna and a finite ground coplanar waveguide (CPW) circuit is presented. The CP operation is excited by using the CPW-fed wide-slot antenna with an L-shaped tuning stub which not only has broader axial ratio bandwidth characteristic than the patch antenna [21], but also avoid complex power divider [22] or branch coupler [23] as the feeding. Moreover, the circuit which consists of a voltage-doubler rectifier by using a commercial schottky detector diode pair, a LPF and a load resistance placed on the lower part of the rectenna provides higher output DC voltage as well as greater RF-to-DC conversion efficiency.

2. RECTENNA CONFIGURATION AND COMPONENTS DESIGN

The schematic of the proposed CP rectenna along with its detailed design parameters is illustrated in Figure 2. The experimental prototype of the rectenna is fabricated on single copper-clad FR-4 substrate with a thickness of 0.8mm and a relative dielectric constant $\varepsilon_r = 4.4$, which consists of a CP wide-slot antenna with CPW-fed, a LPF, a rectifying circuit with the voltage doubler rectifier, a bypass capacitor and a load resistance. Both the antenna feed and the

rectifying circuit input port have characteristic impedance of 50Ω for good impedance matching to reduce signal reflection between these components.

The antenna and the circuit design are based on a commercially available full-wave electromagnetic simulator. The following steps are taken as the design of the rectenna.

2.1. CP WIDE-SLOT ANTENNA

The steps taken to design the rectenna begin at the CPW-fed wide-slot antenna for receiving RF power is designed to operate at 925MHz and it has the advantages of the Right-Hand CP (RHCP) character. The chip components involving rectifying device can be easily mounted across the gap of CPW-fed without using the via-holes as seen in Figure 2.

For a wide-slot antenna to achieve the CP radiation and operation at 925MHz, the parameters of the simple strip line and L-shaped tuning stub that loaded at the ground with wide-slot is about 80.42mm which is equal about the $0.247\lambda_0$ of 925MHz from the feed were used for creating unequal lengths for two separate current paths to excite two orthogonal modes with quadrature out of phase as CP operation, and what is more, these current paths correspond to two hybrid operating modes which operate very close in frequency result in good CP performance. λ_0 is the free space wavelength corresponding to the operating frequency.

By introducing the meander line structure into the CP wide-slot antenna, the size of the antenna reduces by the increasing of the current path of radiator. For this reason, the proposed CP wide-slot antenna shows a 60% size reduction over the conventional ones. At the same time, the circumference of the wide-slot is about 324.95mm which is equal about the $1.001\lambda_0$ of 925MHz. Furthermore, based on the package size of the chip components, the gap separation of the CPW is chosen to be 1.1mm. Moreover, the measured and simulated return loss of the CP wide-slot antenna is shown in Figure 3. The measured -10dB return loss bandwidth at fundamental frequency of 925MHz extends from 884.4-965.6MHz (B.W.=81.2MHz or 8.77%).

The CP radiation performance of the wide-slot antenna is tested by standard LP horn antenna in an anechoic chamber. The measured 3dB axial ratio (AR) and the radiation patterns at 920MHz are plotted in Figure 4 and Figure 5, respectively, as well as the measured results shows the 3dB AR bandwidth is about 180MHz extends from 800-980MHz. At last, the measured gain of the proposed antenna is about -1 to 0dBi.

2.2. LOW PASS FILTER

In this study, the simple LPF between the wide-slot antenna and the rectifying circuit has designed, which composed of 2 pF chip capacitor-C_M and 18 nH chip inductor-L_M connected in a series-parallel manner as well as shown in the Figure 1.

It allows the RF energy at operating frequency of 925MHz to passes and to rejects unwanted higher order harmonics generated by the nonlinear device and prevents the higher order harmonics from re-radiating through the antenna. Thus, the harmonics generated by the nonlinear rectifying diode are rejected back to it and remixed to generate more DC power and the RF-to-DC efficiency is improved. On the other hand, it should be noted that the LPF is used not only for harmonics and interference suppressing, but also for impedance matching to make the antenna feed and rectifying circuit input port of 50Ω at 925MHz.

2.3. RF-TO-DC RECTIFYING CIRCUIT

The rectifying circuit for rectenna design is composed of a diode as the rectifying device, a bypass capacitor and a load resistance. The adopted rectifying circuit is a 1-stage voltage doubler rectifier which offers several advantages. The output DC voltage of two diodes are added in series, which not only increases the overall value of voltage sensitivity for the network (compared to a single diode detector), but also provides a higher output DC voltage and a greater RF-to-DC

conversion efficiency. The double output voltage is created by storing charge at the series capacitor Cs during the negative phase of RF signal through the parallel diode while charge in Cs is accumulated with the input potential during the positive signal phase by turning on the series diode. In addition, the diode is the key in determining the RF-to-DC conversion efficiency of the rectenna. A commercial schottky detector diode pair (HSMS-282C by Agilent Technologies) is selected here for RF-to-DC power conversion, and there are two diodes connected in a series-parallel manner as voltage doubler rectifier into a single package. It is not only to be the best in reduce the size, but also lower the impedance to make the design of the impedance matching network easier. The equivalent circuit of a single diode consists of a series resistance R_S = 6 Ω and a zero-bias junction capacitance C_{J0} = 0.7 pF. Moreover, its maximum forward voltage V_F and minimum breakdown voltage V_{BR} is 0.34 V and 15 V, respectively. Furthermore, the 300 pF chip capacitor-C_F is parallel connected with the load resistance-R_L, which is used for effectively short the all RF energy and pass the useful DC power to the load resistance. Hence, the ripple voltage is very small and it can be neglected. Besides, the distance between the chip capacitor and diode constitutes an inductance which is used to cancel the capacitive reactance of the diode (i.e., this resonance is needed to maximize the diode's conversion efficiency). Finally, the load resistance-R_L was used to maximize the output DC voltage and the RF-to-DC conversion efficiency of the rectenna.

Figure 6 shows the good agreement between measured and simulated input return loss of the rectifying circuit with the LPF. It shows that the LPF has wide rejection band covering 2nd and 3rd harmonic frequencies range of fundamental band. By comparing the Figure 3 and Figure 6, good impedance matching between the wide-slot antenna and the rectifying circuit with a LPF can be observed at operation frequency of 925MHz.

3. MEASUREMENTS AND RESULTS

The measurement of RF-to-DC conversion efficiency of the proposed rectenna is depicted in Figure 7. The standard LP horn antenna with gain of 6.5dBi at 925MHz and the vector signal generator which provides the input RF energy and allows the energy and frequency to be varied are used as a transmitter in the rectenna measurements. For the receiver, the RF power received by the antenna of the rectenna is monitored with a spectrum analyzer connected with the antenna through used the SMA connector as well as the Out DC voltage from the rectenna by used a voltmeter connected across a load resistance.

The RF-to-DC conversion efficiency is defined as follows:

$$\eta_C = \frac{P_{DC}}{P_{incident} - P_{loss}} = \frac{V_{DC}^2}{R_L} \cdot \frac{1}{P_{receiver}} = \frac{V_{DC}^2}{R_L} \cdot \frac{1}{P_d \cdot A_e} \tag{1}$$

Where $P_{incident}$ is the incident RF power in the whole system, $P_{receiver}$ is the RF power received by antenna of the rectenna, P_{loss} is the power loss, included the transmission loss and conversion loss, P_{DC} and V_{DC} are output DC power and voltage across the load resistance of the rectenna, respectively, P_d is the incident power density, and A_e is the effective area of the antenna.

The measured output DC voltage and RF-to-DC conversion efficiency of the proposed CP rectenna at 925MHz versus received power with the various load resistances are shown in Figure 8 and Figure 9, respectively. The higher output DC voltage and greater RF-to-DC conversion efficiency can be acquired when either the received power or load resistance of the rectenna increased. According to the measured results, when the RF power of 15dBm is received with a load resistance of 2kΩ at free space, the maximum RF-to-DC conversion efficiency and the output DC voltage of the rectenna achieved 75% and 6.9 V, respectively.

4. CONCLUSION

A novel CP rectenna with wide-slot structure at 925MHz exhibits the CP characteristic for power receiving with more fade resistant than dual- or linearly polarized. High output DC voltage with great RF-to-DC conversion efficiency of the designed rectenna has been developed. With the consideration of output DC voltage and RF-to-DC conversion efficiency, the load resistance of 2kΩ is selected for rectenna designed which has the maximum RF-to-DC conversion efficiency of 75% as well as the output DC voltage of 6.9 V when the RF power of 15dBm is received at free space. The rectifying circuit has good impedance matching with the proposed CP wide-slot antenna corresponding to its optimum frequency response at 925MHz. The experimental results prove that the rectenna using CP wide-slot antenna and rectifying circuit composed of voltage-doubler rectifier with LPF is fairly suitable for component of the WPT applications.

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microwave power transmission," *IEEE Trans. Microwave Theory Tech.*, vol. 50, no. 8, pp. 1870-1876, Aug. 2002.

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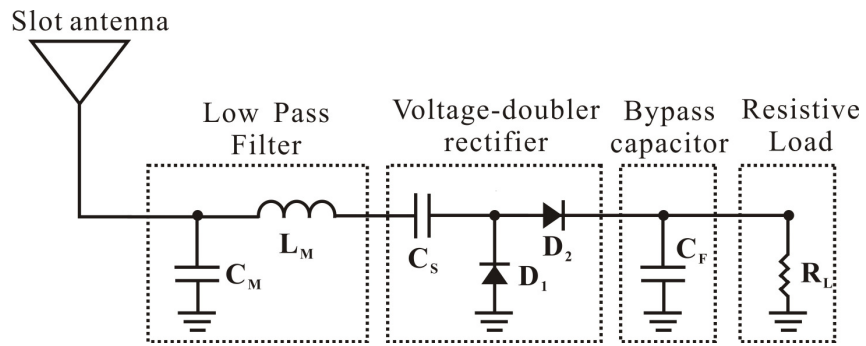
Slot antenna

Figure 1 Five main rectenna element components: antenna, input low-pass filter, Voltage-doubler rectifier, Bypass capacitor, and resistive load.
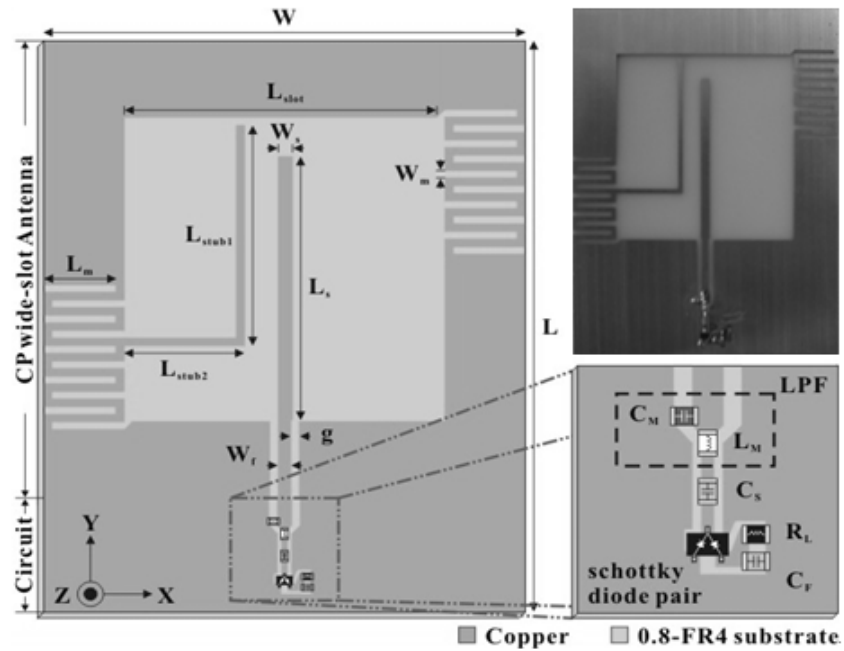
Figure 2 Configuration and photograph of the proposed CP rectenna. Parameters of the CP wide slot antenna: L=75, W=60, L_{slot}=40, L_m=9, W_m=1, W_f=1.5, g=1.1, L_s=34.5, W_s=1.75, L_{stub1}=29, L_{stub2}=15 (unit: mm).
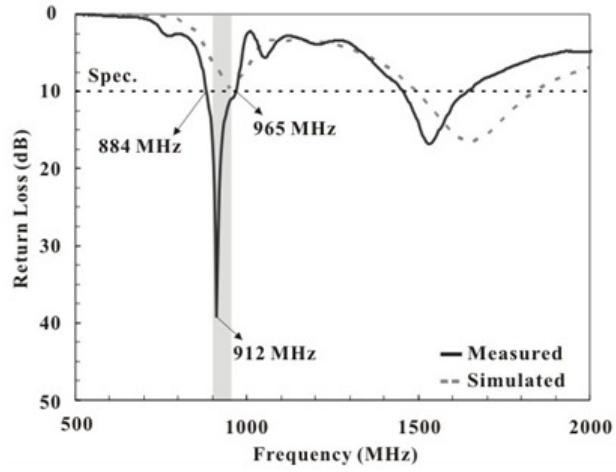
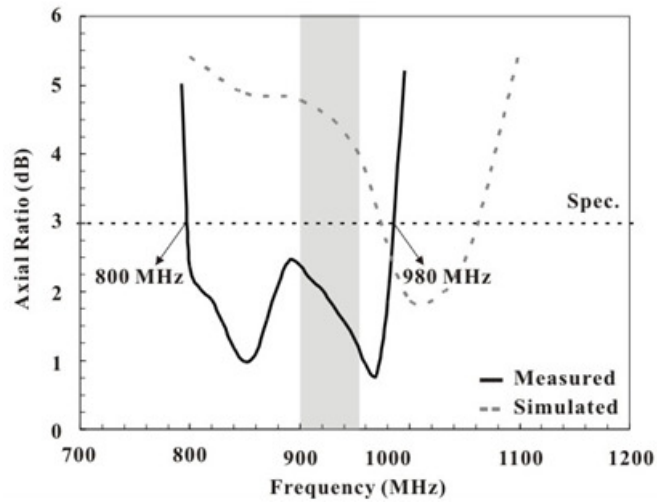Figure 3 Measured and simulated return loss of the CP wide-slot antenna.

Figure 4 Measured and simulated axial ratio of the CP wide-slot antenna.
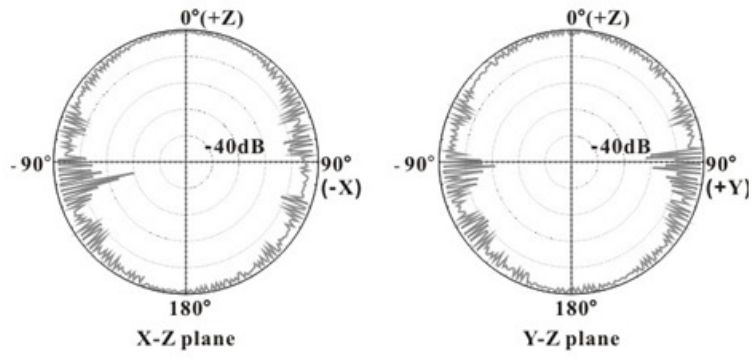
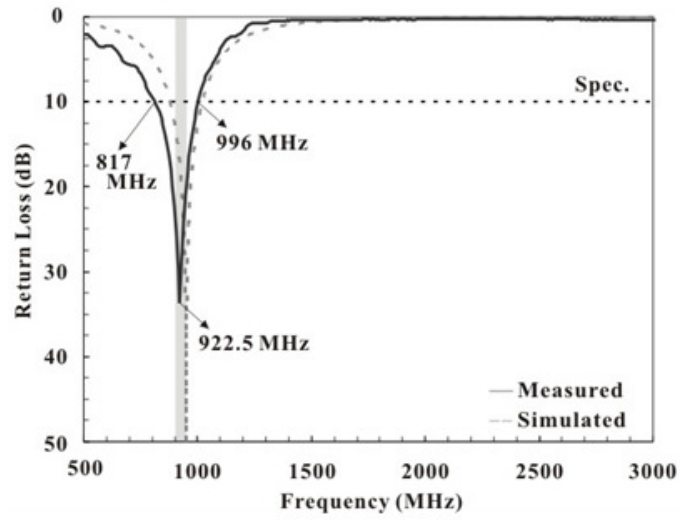Figure 5 Measured radiation pattern of the CP wide-slot antenna at 920MHz.

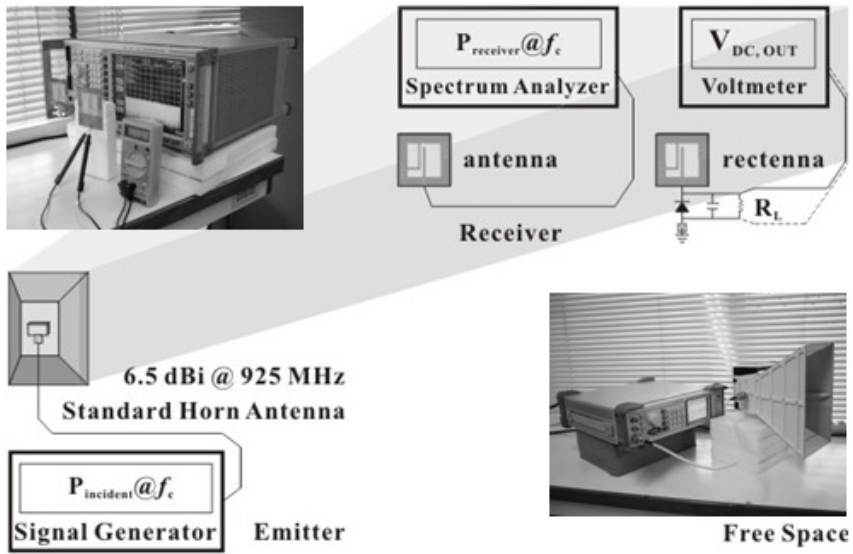Figure 6 Measured and simulated return loss of the proposed rectifying circuit with LPF.

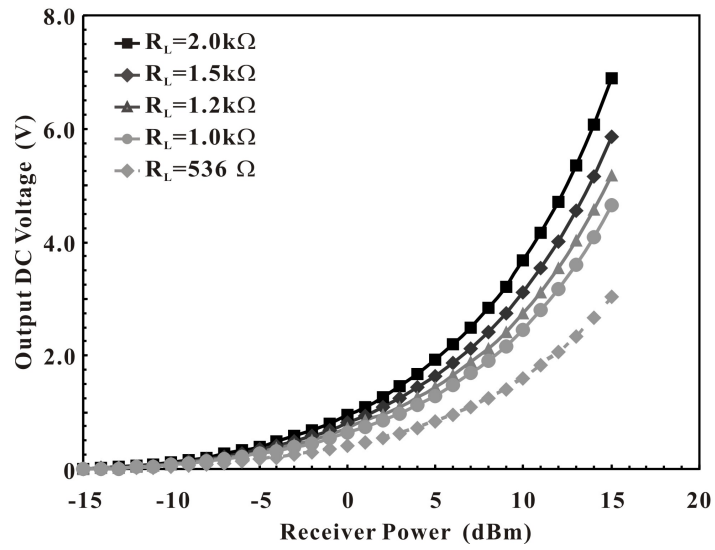Figure 7 Rectenna Measurement setup in free-space.

Figure 8 Measured output DC voltage of the rectenna versus receiver power with the various load resistance at 925MHz.
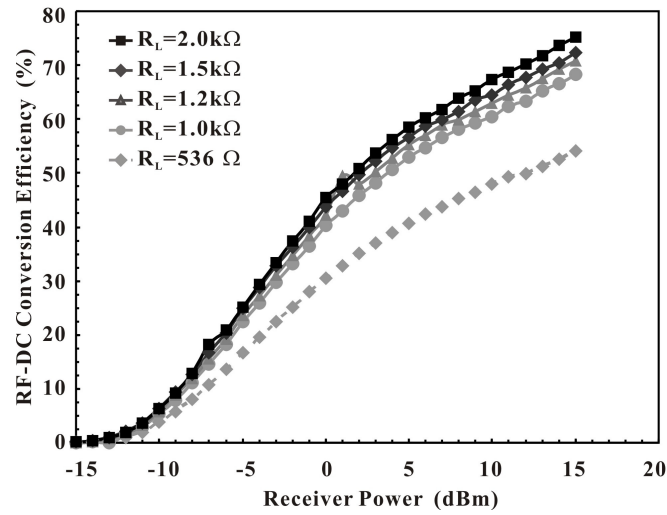
Figure 9 Measured RF-to-DC conversion efficiency of the rectenna versus receiver power with the various load resistance at 925MHz.