5.8 GHz Circular Polarized Rectifying Antenna for Microwave Power Transmission

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***Abstract* — This paper reports a new 5.8 GHz circular polarized (CP) high gain, high-efficiency rectifying antenna (rectenna). The CP rectenna can be rotated and still maintain a constant output voltage. A high-gain dual rhombic loop antenna and a reflecting plane are used to achieve a circular polarized antenna gain of 10.5 dB, a 2:1 VSWR bandwidth of 10 %, and average beamwidths of 43° and 59° in the E- and H-planes, respectively. The rectenna circuit has a coplanar stripline (CPS) band reject filter (BRF) which suppresses the re-radiated harmonics by 20 dB. A highly efficient Schottky diode is used for RF to dc conversion with an efficiency of approximately 80%.**

***Index Terms* — microwave power transmission, wireless power transmission, circularly polarized antennas, rectifying antenna.**

I. Introduction

In the 1960's, Raytheon developed a rectifying antenna or rectenna which converted RF to dc power at 2.45 GHz. The rectenna consisted of a half-wave dipole antenna with a balanced bridge or single diode placed above a reflecting plane as well as a resistive load. The rectenna conversion efficiency also referred to as the percentage of power converted from RF to dc increased throughout the 1960's and 1970's. The highest conversion efficiency ever recorded was achieved by Brown at Raytheon in 1977 [1]. Brown used a GaAs-Pt Shottkey barrier diode and aluminum bar dipole and transmission lines to achieve a 90.6 % conversion efficiency at an input microwave power level of 8 W. Later, Brown developed a printed thin-film version at 2.45 GHz with an 85 % conversion efficiency [2].

In 1998, McSpadden *et. al.* used a printed dipole rectenna to achieve the highest conversion efficiency for 5.8 GHz at 82 % [3]. The rectenna used a MA40150-119 diode for rectification and a coplanar stripline layout (CPS).

In the last few years, researchers have looked into the designing of circular polarized rectennas. Circular polarization allows the recieve and transmit antennas to be rotated without changing the output voltage. Suh *et. al.* achieved 60 % for a single element rectenna at 5.8 GHz [4]. Another group at JPL was able to operate a rectenna array around 52 % efficiency at 8.51 GHz [5].

The rectenna design discussed in this paper combines high efficiency RF to dc diode conversion with a wideband, high-gain, circularly polarized antenna to produce large amounts of dc power regardless of the rectenna's orientation. This rectenna is fabricated on a single layer using coplanar stripline transmission lines for fabrication simplicity and size reduction. The harmful harmonics generated by the diode are suppressed using a filter behind the antenna.

II. Simulated and Measured Data for Rectenna Components

The rectenna sections outlined in Figure 1, i.e. antenna, filter, etc., are designed using the full wave electromagnetic simulator IE3D. IE3D allows for all of the sections to be analyzed together and can de-embed sections when necessary.

A. Coplanar Stripline (CPS) Characteristic Impedance

The coplanar stripline (CPS) width and gap are 0.824 mm and 0.4 mm, respectively. These dimensions provide the proper size for diode and capacitor bonding and the desired CPS characteristic impedance (172 Ω). The impedance of CPS is higher than that of microstrip and matches better to the real impedance of the diode.

B. Circular Polarized (CP) Dual Rhombic Loop Antenna (DRLA)

The rectenna uses a dual rhombic loop antenna (DRLA) configuration [6] as seen in Figure 1. The DRLA is terminated with two gaps. The position of the gaps yields left-hand circular polarization. If the gaps are mirrored to the opposing sides of the antenna, the DRLA will become right-hand circular polarized. Circular polarization is very sensitive to the gap position. The advantages for using the

DRLA are high CP gain, wideband performance, and fabrication simplicity. The CPS tuning stubs yield a real impedance (250 Ω) at the antenna's input terminals and allow for the individual rectenna to be connected to other rectennas in an array. The reflecting plane located 11 mm (0.21 λ_o) behind the antenna increases the gain by directing the beam broadside in one direction.

C. Coplanar Stripline Band Reject Filter (CPS BRF)

The coplanar stripline band reject filter (CPS BRF) is used to pass 5.8 GHz from the antenna to the diode and block the 2^{nd} harmonic 11.6 GHz from flowing from the diode to the antenna. The CPS BRF uses λ/4 stubs to block 11.6 GHz. This filter has high harmonic rejection in comparison with other planar CPS geometries of comparable size. IE3D predicts an insertion loss of 0.3 dB at 5.8 GHz from the antenna to the diode. The filter blocks 11.6 GHz flowing from the diode to the antenna by more than 20 dB.

D. Microstrip to Coplanar Stripline (CPS) Baluns

In order to measure the pattern and s-parameters of the antenna and the filter, a balun must be designed which matches the 172 Ω CPS BRF diode-side impedance to 50 Ω microstrip line. The balun's return loss at 5.8 GHz and 11.6 GHz is 20 dB. The insertion loss for both frequencies is 0.21 dB.

E. Antenna + Filter + Balun Measured Results

The circuit used to obtain the rectenna's return loss, patterns and gain measurements is shown in Figure 2(a). The circuit includes the DRLA, CPS BRF and CPS to microstrip balun. Using the HP 8510B network analyzer measurement system, the return loss was obtained as shown in Figure 2(b). At 5.8 GHz, S_{11} = -17.7 dB, and at 11.6 GHz, S_{11} = -1.1 dB. Therefore, 5.8 GHz will pass through with low loss, and the second harmonic 11.6 GHz will have high loss. The 2:1 VSWR bandwidth centered about 5.8 GHz is 10 %.

To determine the axial ratio, H- and E-plane broadside linear gain measurements versus frequency are taken using a Narda 642 standard gain horn. The rectenna is measured for three rotated orientations at 0°, 45° and 90° for both H- and E-planes. These measurements are shown in Figure 2(c). The axial ratio (*AR*) is determined to be 0.15 dB by subtracting the smallest broadside gain from the largest. From the axial ratio, the gain correction factor (*GCF*) for scaling LP gains into CP gains is determined. *GCF* in dB is defined as follows:

$$GCF = 20 \cdot \log\left(\frac{10^{\frac{AR}{20}} + 1}{\sqrt{2} \cdot 10^{\frac{AR}{20}}} \right). \qquad (1)$$

Since AR = 0.15 dB, GCF = 2.94 dB. By taking the broadside ($\theta = 0°$) LP gain average and adding GCF, the adjusted CP gain is 9.8 dB. If the CPS BRF, balun, and connector losses are de-embedded, the DRLA can be shown to have a CP gain of 10.5 dB.

Antenna patterns at 11.6 GHz for the three rotated rectenna orientations at 0°, 45° and 90° for both H- and E-planes revealed the main beam to be at $\theta = 36°$ for the 2^{nd} harmonic. The filter suppresses the maximum gain down to around –5 dB.

The air gap thickness (d) separating the rectenna from the reflecting plane greatly affects the axial ratio as revealed by the measurement data shown in Figure 2(d). The best axial ratio of 0.15 dB at 5.8 GHz is obtained when d = 11 mm. When d < 11 mm for the 0° rectenna orientation, the H-plane LP gain will be greater than the E-plane LP gain. Similarly, if d > 11 mm, the E-plane gain will be greater.

F. Capacitor Characterization

The dc pass filter consists of the 50 VDC C08BLBB1X5UX dc-blocking capacitor manufactured by Dielectric Labs. The capacitor is used to block all of the microwave energy arising from the diode from reaching the load resistor, thus returning the RF energy back to the diode. The capacitor blocks 5.8, 11.6 and 17.4 GHz greater than 17 dB.

G. Rectenna Efficiency Measurement

The diode used in the rectenna circuit is the M/A COM detector diode MA4E1317. It has series resistance R_S = 4 Ω, zero-bias juction capacitance C_{j0} = 0.02 pF, built-in turn-on voltage V_{bi} = 0.7 V, and breakdown voltage V_B = 7 V. It is in a flip-chip package with negligible parasitics. The diode converts the incoming 5.8 GHz microwave energy coming from the CPS BRF into a dc output.

H- and E-plane free-space voltage measurements for the 0° rectenna orientation and R_L = 150 Ω are taken in order to determine the rectenna's dc conversion efficiency. The diode conversion efficiency is represented by:

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$$\eta_D = \frac{\left(\dfrac{V_D{}^2}{R_L}\right)}{P_t \cdot G_t \cdot G_r \cdot \left(\dfrac{\lambda_o}{4\pi r}\right)^2} \times 100\% \qquad (2)$$

where P_t and G_t are the transmitted power and transmitter gain, respectively. G_r is the gain of the rectenna, and r is the distance between the transmitter and the rectenna in m. λ_o is the free-space wavelength at 5.8 GHz in m. The free-space efficiency curves are shown in Figure 3 for $R_L = 150$ Ω. Both E- and H-plane curves saturate at around 80 %.

V. Conclusions

The rectenna achieves circular polarization with great efficiency. The DRLA provides high gain increasing the power handling capability of the rectenna. The DRLA wide bandwidth allows for rectenna operation from 5.5 GHz to around 6.1 GHz with decent circular polarization. The flip-chip schottky diode used provides excellent efficiency around 80 % and very small size. The capacitor blocks the RF energy by about 20 dB, and the CPS BRF suppresses the 2nd harmonic signal to around 20 dB below the peak fundamental gain resulting in minimal radiation at 11.6 GHz.

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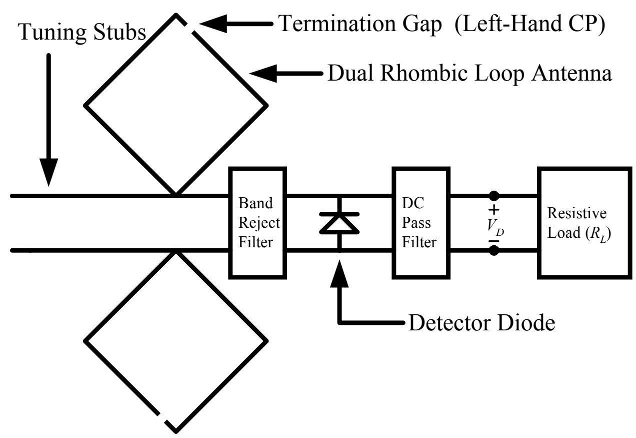

Fig. 1. Rectenna block diagram ($\theta = 90°$).

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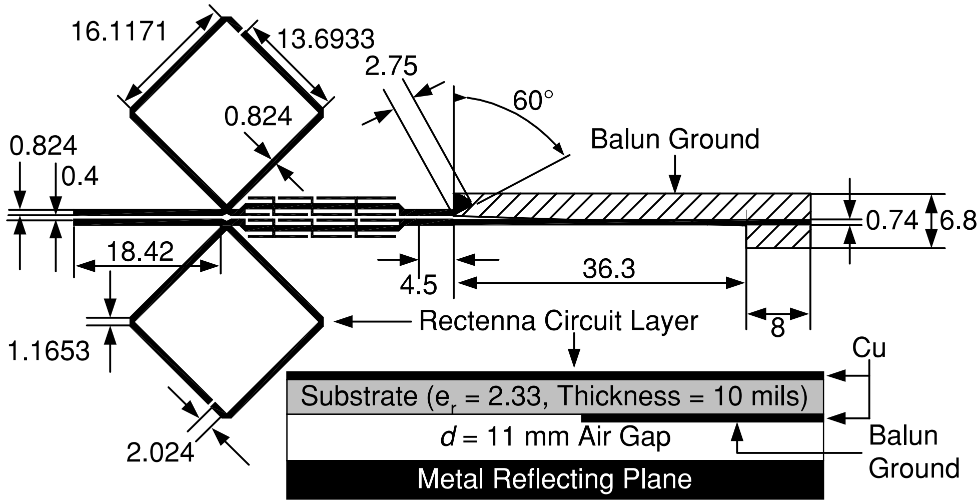

Fig. 2a. Rectenna pattern and gain measurement circuit layout. (All dimensions in mm).

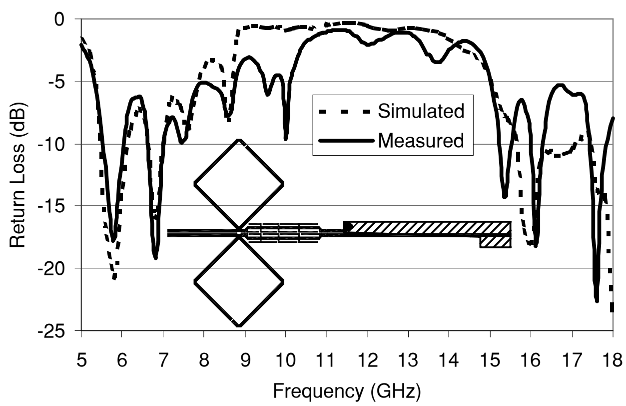

Fig. 2b. Return loss of the pattern and gain measurement circuit.

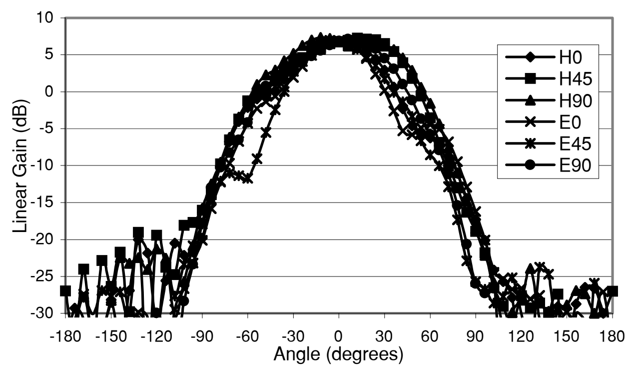

Fig. 2c. H- and E-plane linear polarized gains at 5.8 GHz for 0°, 45° and 90° rhombic loop orientations.

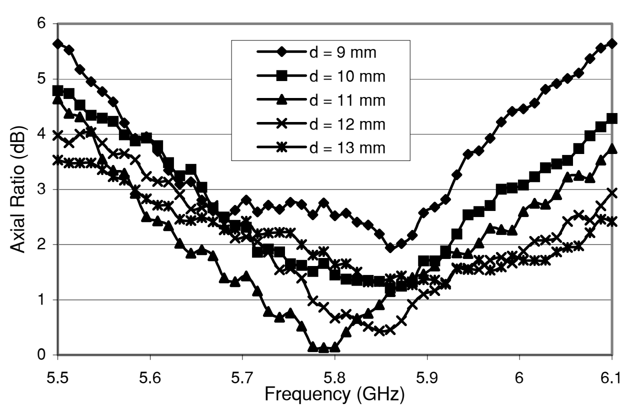

Fig. 2d. Rectenna axial ratio for different reflecting plane spacing.

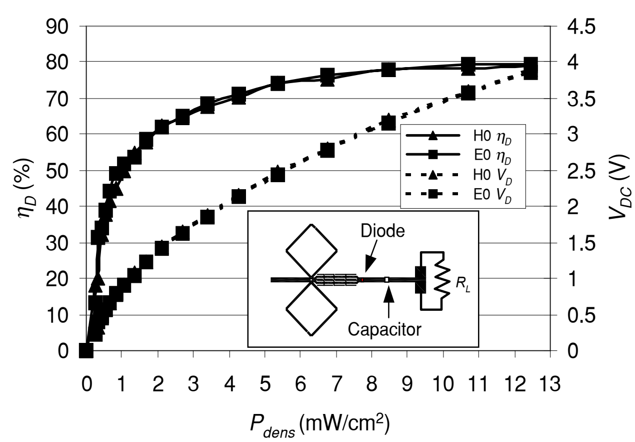

Fig. 3. Free-space voltage and efficiency measurement for R_L = 150 Ω.