A Circularly Polarized Rectifying Antenna Array for Wireless Microwave Power Transmission with over 78 % Efficiency

Berndie Strassner and Kai Chang

Department of Electrical Engineering
Texas A&M University
College Station, TX 77843-3128

Abstract **- This paper reports a new circularly polarized (CP) high gain, high-efficiency rectifying antenna (rectenna) array designed in a coplanar stripline circuit. The array can maintain a constant DC output voltage regardless of its broadside orientation. Each antenna has a CP antenna gain of 11 dB and a better than 1 dB axial ratio fractional bandwidth of 4.7 %. Coplanar stripline (CPS) band-reject filters (BRF) are used to suppress the re-radiated harmonics by more than 19 dB. At 5.61 GHz, using an array loading of 150 Ω, a 3 x 3 rectenna array achieves an RF-to-DC conversion efficiency of 78 % and an axial ratio of 0.25 dB.**

I. Introduction

In the 1960's, Brown developed a rectenna which converted RF-to-DC power at 2.45 GHz. The rectenna consisted of a half-wave dipole antenna with a single diode placed above a reflecting plane. The highest conversion efficiency ever recorded was 90.6 % and was achieved by Brown in 1977 [1]. In 1998, McSpadden *et. al.* used a printed dipole rectenna to achieve the highest conversion efficiency for 5.8 GHz at 82 % [2].

In the last few years, researchers have looked into the designing of CP rectennas. Suh *et. al.* achieved 60 % RF-to-DC conversion efficiency for a single CP rectenna element at 5.8 GHz [3] using a truncated patch and microstrip circuit. Hagerty and Popovic used low-gain spiral rectennas for broadband CP rectification [4]. The rectenna array discussed in this paper uses a wideband, high-gain, CP antenna to produce DC power regardless of the array's orientation. The new array is fabricated on a single thin layer using CPS transmission lines for fabrication simplicity and size reduction. The harmful second harmonic frequency generated by the array's diodes is prohibited from re-radiation with the use of a filter located behind the antenna.

Traditionally, rectennas have used dipoles or patch antennas with low gains. Here a dual rhombic loop antenna (DRLA) [5] is used with a gain of 11 dB. The use of a high gain antenna has the advantage of reducing the number of rectenna elements (diodes, capacitors, etc.) necessary to cover the same receiving area since the effective area of an antenna is proportional to its gain.

II. Rectenna Array Design

Figure 1 shows a block diagram of the main components of a rectenna necessary for efficient operation [6]. The rectenna consists of a DRLA, BRF, Schottky detector diode, DC-pass filter and a resistive load. The DRLA couples power into the CPS circuit. A band reject filter (BRF) located behind the antenna allows the incoming power at 5.61 GHz to pass to the detector diode where a large portion of the RF power is converted to DC power. The RF signal is bounced between the BRF and the DC-pass filter where it remixes at the diode and forms more DC. The resistive load (R_L) is isolated from any RF signals because of the DC pass filter. R_L must be chosen such that the DC-converted portion of the RF power is maximized. Proper placement of the diode and filters is also crucial to maximizing the DC power. The antenna and BRF are designed using the full wave electromagnetic simulator IE3D. The single element antenna has a CP antenna gain of 11 dB and an axial ratio better than 1 dB over a 4.7 % bandwidth. The rectenna gives a conversion efficiency of 80 % [6].

Many rectenna elements can be cascaded together to form a rectenna array like the one shown in Figure 2. Array spacing is governed both by the DC-pass filter placement and the effective areas of each individual rectenna. The capacitors (DC-pass filters) not only optimize DC conversion but also isolate the array elements. Each capacitor should be placed 8.5 mm away from the middle of the nearest antenna and 9.5 mm away from the nearest diode as indicated in Figure 2. These dimensions have been determined from calculated and measured impedance matching data. Proper capacitor placement will enable each rectenna to capture energy at 5.61 GHz with negligible reactance. The second design criteria concerning array spacing is found by computing the effective area of each rectenna from its corresponding measured CP directivity. Given that the DRLA's measured broadside CP gain of 11 dB at 5.61 GHz, the rectenna effective area can be approximated as circular in shape and equal to 25 cm^2 by

$$A_R^{eff} = \frac{\lambda_o^2}{4\pi} D_o = \pi r^2 \qquad (1)$$

where D_o is the CP directivity, r is 28.2 mm and represents the radius of the circular area. Since the effective area of each element is circular, the array layout is chosen to be the honeycomb lattice shown in Figure 2. Each array column contains 5 rectennas that are separated by d_y of 42.12 mm. Likewise, the element columns are separated by d_x of 39 mm. Both d_x and d_y are made to be less than $2r$. These distances ensure that the adjacent rectenna effective areas (A_R^{eff}) will overlap with one another. In other words, this 2-D spacing captures all of the microwave power incident upon the array's surface by eliminating undesirable void regions. The design is optimized by moving the elements as far away from one another as possible while maintaining effective area coverage over the entire array with the use of the effective area overlap between adjacent rectennas. Minimizing the void results in higher overall array efficiencies, while minimizing the overlapped regions results in fewer necessary elements.

Diodes are placed on the innermost 9 elements of the 5 x 5 array for RF-to-DC rectification. The "unactivated" surrounding rectennas are etched in order to account for mutual coupling effects. This allows the performance of the 3 x 3 prototype array to predict the performance of a larger array. The rectennas on each column each produce DC currents that are summed at the end of that column. Likewise, the DC voltages of each column are summed resulting in the voltage V_A across the load resistor R_A.

The array's DC output power is measured as a voltage V_A across a single load resistor. This array load resistor is defined by

$$R_A = R_L \frac{N_x}{N_y} \qquad (2)$$

where N_x is the number of columns in the array and N_y is the number of rectennas in each column. R_L is the optimal load resistance for each individual rectenna. The diodes are connected in parallel in each column, and the columns are connected in series.

The array's efficiency measurement is simply the ratio of the converted DC power to the received RF power. The measurement was done in free-space using a high power microwave source.

IV. Array Measurements

Figure 3 presents the axial ratio of the array with respect to changing frequency. Rotating linear measurements using a C-band Narda standard gain horn were carried out to find the array's CP operating frequency. The best axial ratio of 0.25 dB occurs at 5.61 GHz.

Figure 4 shows the array's RF-to-DC conversion efficiency versus CP power density for various array loading. A best efficiency occurs of 78 % occurs at an input power density of 7.6 mW/cm^2 for an array loading of 150 Ω. The array's output voltage at this power density is around 11 V meaning that each diode has 3.66 V across its terminals. This is close to half of the diode's breakdown voltage or $V_B/2$ = 3.5 V which is usually considered a device rectification safety threshold for extended periods of operation.

V. Conclusions

A CP rectenna array has been developed to rectify RF energy to DC power with 78 % efficiency at 5.61 GHz. The capacitor blocks the RF energy by more than 17 dB, and the CPS BRF suppresses the 2nd harmonic signal to around 19 dB below the peak fundamental gain. This results in minimal radiation at the 2nd harmonic frequency. This 9 element array can be expanded to larger arrays in order to provide an efficient means of rectifying large amounts of microwave power incident upon the array's surface.

Acknowledgements

The authors would like to thank Mr. Ming Li and Mr. Chunlei Wang at Texas A&M University for fabricating the microstrip circuits. The authors would also like to acknowledge James McSpadden at Boeing and Dick Dickinson at the Jet Propulsion Laboratory for their helpful guidance and support.

REFERENCES

[1] W. C. Brown, "Electronic and mechanical improvement of the receiving terminal of a free-space microwave power transmission system," Raytheon Company, Wayland, MA, Tech. Rep. PT-4964, NASA Rep. CR-135194, Aug. 1977.

[2] J. O. McSpadden, L. Fan and K. Chang, "Design and experiments of a high-conversion-efficiency 5.8-GHz rectenna," *IEEE Transactions on Microwave Theory and Techniques*, vol. 46, no. 12, pp. 2053-2060, December 1998.

[3] Y. H. Suh, C. Wang and K. Chang, "Circular polarized truncated-corner square patch microstrip rectenna for wireless power transmission," *Electronic Letters*, vol. 36, no. 7, pp. 600-602, March 2000.

[4] J. Hagerty and Z. Popović, "An Experimental and Theoretical Characterization of a Broadband Arbitrarily-Polarized Rectenna Array," *in IEEE MTT-S Int. Microwave Symp. Dig.*, Phoenix, AZ, May 2001, pp. 1855-1858.

[5] H. Morishita, K. Hirasawa and T. Nagao, "Circularly polarised rhombic hula loop antennas," *Electronic Letters*, vol. 32, no. 11, pp. 946-947, May 23, 1996.

[6] B. Strassner and K. Chang, "5.8 GHz Circular Polarized Rectifying Antenna for Microwave Power Transmission," *in IEEE MTT-S Int. Microwave Symp. Dig.*, Phoenix, AZ, May 2001, pp. 1859-1862.

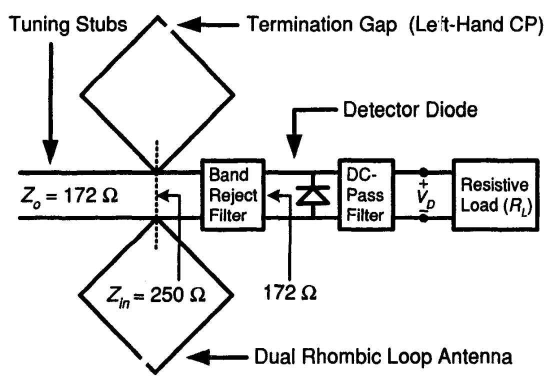

Fig. 1. Rectenna block diagram. The rectenna is located a distance *d* above a reflector ground plane.

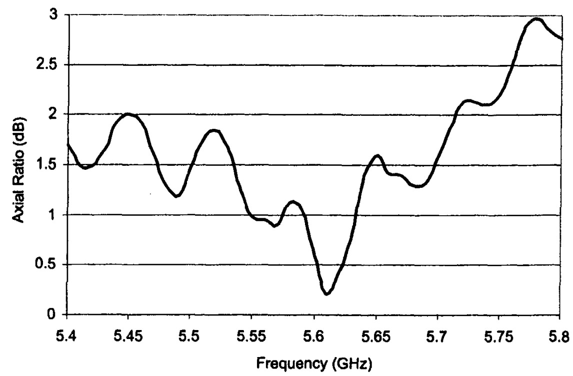

Fig 3. Array axial ratio versus frequency when $d = 8$ mm. The curve is based on free-space measurement data taken at 10 MHz increments.

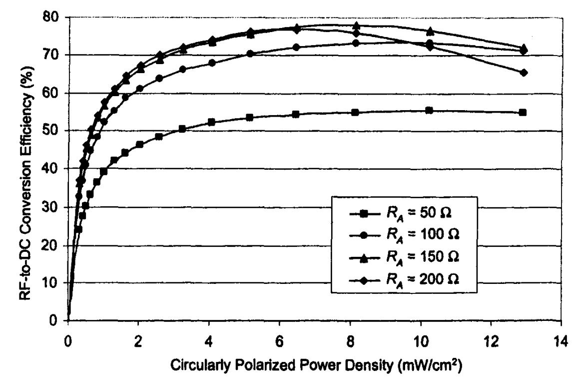

Fig 4. Array RF-to-DC conversion efficiency versus circularly polarized power density at 5.61 GHz for various array loading (R_A).

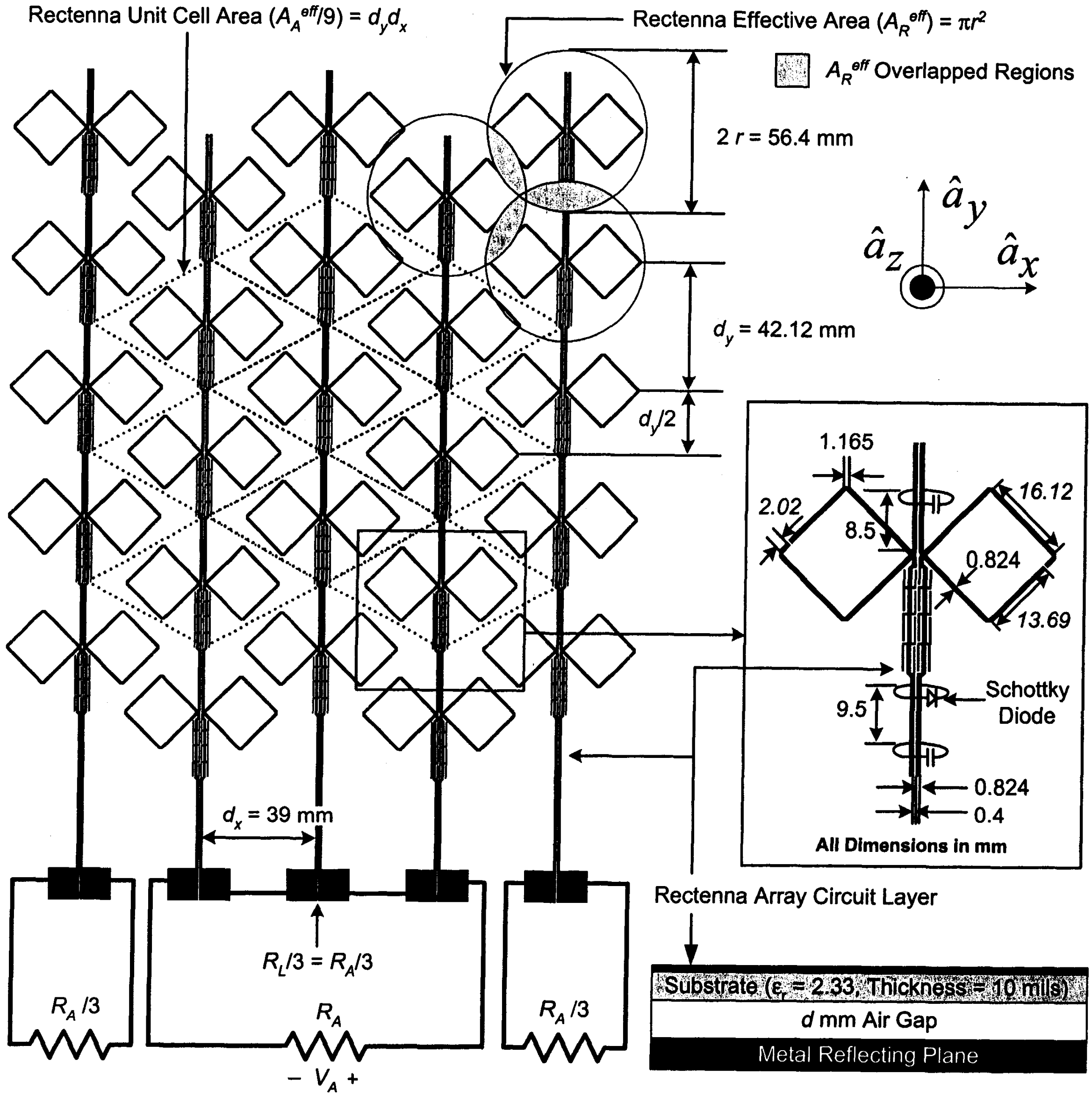

Fig. 2. Array layout showing both rectenna and array effective areas along with all relevant spacings. The innermost 9 elements with the dotted unit cell areas represent the 3 x 3 array that rectifies the incident microwave energy. The remaining elements are present in order to account for the mutual coupling between adjacent rectenna elements. This allows the performance of the 3 x 3 array to predict the performance of larger arrays.