# 5.8-GHz Circularly Polarized Dual-Rhombic-Loop Traveling-Wave Rectifying Antenna for Low Power-Density Wireless Power Transmission Applications

Berndie Strassner, *Member, IEEE*, and Kai Chang, *Fellow, IEEE*

***Abstract*—This paper reports a right-hand circularly polarized (RHCP) high-efficiency traveling-wave rectifying antenna (rectenna) designed in a coplanar stripline (CPS) circuit that is etched on a Rogers Duroid 5870 substrate with $\varepsilon_r = 2.2$ and 20-mil thickness. A 4 × 1 traveling-wave array of RHCP high-gain dual-rhombic-loop antennas (DRLAs) and a reflecting plane are used to provide highly efficient RF-to-dc conversion in the presence of lower power densities regardless of the rectenna's broadside orientation. The DRLA array has a circularly polarized antenna gain of 14.6 dB with a 2 : 1 voltage standing-wave ratio bandwidth of 17% and a better than 3-dB axial ratio fractional bandwidth of 7% centered about 5.8 GHz. The rectenna achieves 82% RF-to-dc conversion efficiency at 5.8 GHz and uses a low-profile CPS band-reject filter to suppress the re-radiated second harmonic by over 14 dB. The rectenna operating at low power density should have many applications when the transmitting power is low and/or the transmission distance is long.**

***Index Terms*—Circularly polarized (CP) antennas, coplanar stripline (CPS) filter, microwave power transmission, rectifying antenna, wireless power transmission.**

## I. Introduction

IN THE 1960s, the Raytheon Company, Wayland, MA, developed a rectifying antenna or rectenna that 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 rectenna conversion efficiency, also referred to as the percentage of power converted from RF-to-dc, was improved throughout the 1960s and 1970s. The highest conversion efficiency ever recorded was achieved by Brown in 1977 [1]. Brown used a GaAs–Pt Shottky barrier diode and aluminum bar dipole and transmission lines to achieve 90.6% conversion efficiency at an input microwave power level of 8 W. Later, Brown and Triner developed a printed thin-film version at 2.45 GHz with 85% conversion efficiency [2]. In 1991, a rectenna element was developed with 72% conversion efficiency at 35 GHz [3]. In 1992, the first $C$-band rectenna yielded 80% conversion efficiency [4]. In 1998, McSpadden *et al.* used a printed dipole rectenna to achieve the highest conversion efficiency for 5.8 GHz at 82% [5]. The rectenna used a single MA40150-119 diode for rectification on a coplanar stripline (CPS) layout.

In the last few years, researchers have looked into the designing of circularly polarized (CP) rectennas. Circular polarization enables the receive or transmit antennas to be rotated without significantly changing the output voltage. Suh *et al.* achieved 60% RF-to-dc conversion efficiency for a single CP rectenna element at 5.8 GHz [6] using a truncated patch and microstrip circuit. Hagerty and Popović used spiral rectennas for broad-band rectification [7]. However, these spirals have relatively low gain, resulting in lower efficiencies compared with that of dipole antennas. The best CP rectenna efficiency has been achieved by Strassner and Chang at 81% [8]–[10]. This design used a dual-rhombic-loop antenna (DRLA) and the M/A COM flip-chip detector diode MA4E1317 to obtain this high efficiency.

The rectenna design discussed in this paper combines highly efficient RF-to-dc diode conversion with a high-gain CP traveling-wave DRLA array to produce dc power regardless of the array's orientation. Most previous rectenna designs use a diode for each antenna. By combining multiple antennas to each diode, the diode can receive the necessary power to drive itself into its highly efficient operating region even in the case when the incident wave's power density is low. This technique also reduces the number of diodes that are the expensive components in a rectenna array. If people are working in and around a rectenna array, the power density needs to be at acceptable levels. In many applications, this low power density occurs when the transmission distance is long and/or the transmitting power is low. This technique of using a traveling-wave DRLA array could also be used for very large rectenna arrays where the power density is highest in the very center and decreases toward the rectenna's outer edges. This is due to the fact that a plane wave is unobtainable in this case. In such a case, more DRLAs would be connected to a diode near the outer edges that those toward the rectenna array's center. The rectenna being discussed is fabricated on a single thin layer using CPS transmission lines for fabrication simplicity and size reduction. An array consisting of 72 of the low power density rectennas

Manuscript received July 17, 2002; revised December 11, 2002. This work was supported by the National Aeronautical Space Administration and by Texas A&M University. This work was supported in part by the Jet Propulsion Laboratory, by the National Science Foundation, and by The Center for Space Power, Texas A&M University.

B. Strassner was with the Department of Electrical Engineering, Texas A&M University, College Station, TX 77843-3128 USA. He is now with Sandia National Laboratories, Albuquerque, NM 87185-0529 USA.

K. Chang is with the Department of Electrical Engineering, Texas A&M University, College Station, TX 77843-3128 USA.

Digital Object Identifier 10.1109/TMTT.2003.810137

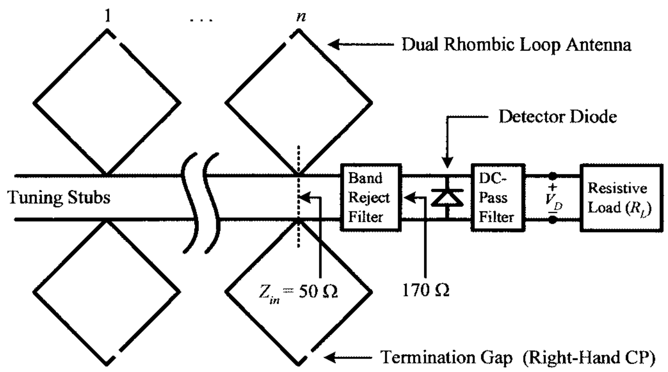



Fig. 1. Block diagram for an $n \times 1$ DRLA traveling-wave rectenna. The $n \times 1$ rectenna consists of $n$ folded dipole antennas, one detector diode, dc-pass filter, and resistive load.

discussed in this paper was demonstrated and proven effective at the 2002 World Space Congress, Houston, TX.

Traditionally, rectennas have used dipoles or patch antennas with low gains. Here, a DRLA array is used with a CP gain of 14.6 dB. The use of a high-gain antenna array has the advantage of reducing the number of rectenna elements (diodes, capacitors, etc.) necessary to cover the same receiving area. The effective area of an antenna is proportional to its gain. The higher antenna gain corresponds to a larger effective area and also results in larger dc rectified voltages.

## II. Single Rectenna Element

Fig. 1 shows a block diagram of the main components of a CPS traveling-wave rectenna necessary for efficient operation. The rectenna consists of $n$-folded dipole antennas, band-reject filter (BRF), Schottky detector diode, dc-pass filter, and a resistive load. The high-gain antenna array couples power into the CPS circuit. A BRF located behind the array allows the incoming power at 5.8 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. IE3D allows for all of the sections to be analyzed together and can deembed sections when necessary.

### *A. CPS Design*

The CPS width and gap are 0.824 and 0.4 mm, respectively. These dimensions provide the proper size for diode and capacitor bonding and the desired CPS characteristic impedance (170 Ω). The impedance of CPS is higher than that of microstrip and matches better to the real input impedance of the diode. At 5.8 and 11.6 GHz, the CPS guided wavelength is 4.3 and 2.65 cm, respectively.

### *B. CP DRLA Traveling-Wave Array*

The rectenna uses a DRLA array configuration [11], as seen in Fig. 1. Each DRLA is terminated with two gaps. The positioning of the gaps, as shown in Fig. 1, yields right-hand circular polarization. If the gaps are mirrored to the opposing sides of each antenna, the DRLA array will become left-hand circular polarization. The advantages for using the DRLA array are high CP gain and fabrication simplicity. A reflecting plane is located 8.7 mm (0.17 $\lambda_o$) behind the rectenna substrate in order to increase the gain of the DRLA array by directing its beam broadside in one direction. Circular polarization is very sensitive to both the gap position and reflecting plane distance. The separation between adjacent DRLAs is the guided wavelength of the CPS at 5.8 GHz or 43 mm. If the spacing is changed from 43 mm, the array's main beam will steer from broadside. This technique could be useful in off-broadside applications. The CPS tuning stubs tune out the imaginary impedance in order to yield a real impedance at the array's input terminals. The stubs also allow for multiple 4 × 1 DRLA arrays to be connected to form a rectenna array. The input impedance ($Z_{\rm in}$) at the array's input terminals for the resonant frequency at 5.8 GHz is shown to be 50 Ω. To find the antenna's simulated input impedances, radiation patterns, and circular polarization, the antenna must be simulated in IE3D with the BRF in place since the filter will couple to the antenna and affect the radiation. The filter is then deembedded in IE3D to find the input impedances.

### *C. CPS BRF*

The CPS BRF is used to pass 5.8 GHz from the DRLA array to the diode and block the second harmonic at 11.6 GHz from flowing from the diode to the array. The filter's geometry uses a band-reject design described by Goverdhanam *et al.* [12]. This filter is low profile and fits neatly into the confines of the CPS line's widths. The CPS BRF uses $\lambda/4$ stubs to block 11.6 GHz. This filter has high harmonic rejection in comparison with other planar CPS filter geometries of comparable size including most commonly used low-pass filter designs. The size of the filter is an issue since the array elements must be close enough together to capture all of the incident microwave energy. The filter blocks 11.6 GHz flowing from the diode to the antenna by over 14 dB. The diode-side port of the CPS BRF is terminated to the characteristic impedance of the CPS. The antenna-side port of the filter is matched to the antenna input impedance ($Z_{\rm in}$). At 5.8 GHz, the CPS BRF's antenna-side port impedance is 50 Ω and the diode-side port impedance is 170 Ω. Therefore, at 5.8 GHz, the filter matches the DRLA to the resistance of the detector diode.

### *D. Antenna + CPS BRF + Balun Pattern Measurements*

The circuit shown in Fig. 2 is used to obtain the return loss, pattern measurements, and axial ratio for the rectenna. A CPS to microstrip balun with over 100% 2 : 1 voltage standing-wave ratio (VSWR) bandwidth (4.2–14.2 GHz) is used to acquire these measurements. This circuit's return loss is presented in Fig. 3. The simulated IE3D curve closely matches the measured curve. At 5.8 GHz, the circuit is well matched to 50 Ω. This circuit has a 2 : 1 VSWR bandwidth of 17% at approximately 5.8 GHz. The filter also blocks the energy at approximately 11.6 GHz.

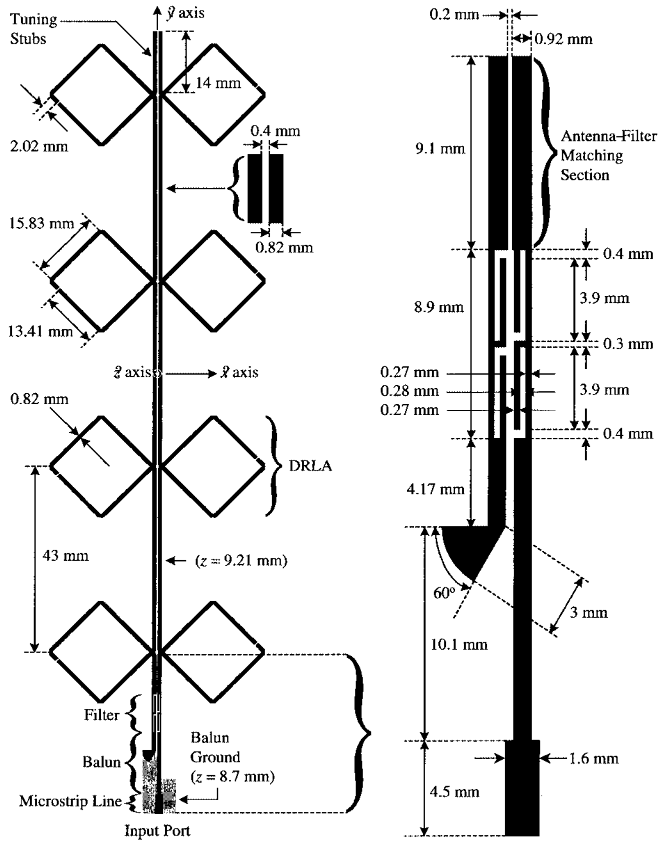



Fig. 2. 4 × 1 DRLA traveling-wave array with BRF and CPS to microstrip balun. The reflecting plane is located at $z = 0$ or 8.7 mm behind the rectenna's 20-mil substrate.

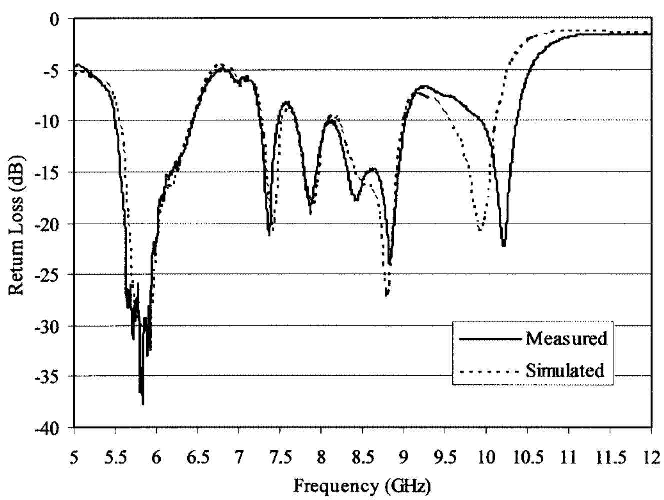



Fig. 3. Return loss for DRLA + filter + balun.

A linear standard gain horn is used to measure the linear gain patterns of the rectenna. By using the equation [13]

$$|\mathrm{LHCP}| = \left[\frac{|E_\phi|^2}{2} + \frac{|E_\theta|^2}{2} + E_\phi E_\theta \sin\left(\angle E_\phi - \angle E_\theta\right)\right] \quad (1a)$$

$$|\mathrm{RHCP}| = \left[\frac{|E_\phi|^2}{2} + \frac{|E_\theta|^2}{2} + E_\phi E_\theta \sin\left(\angle E_\theta - \angle E_\phi\right)\right] \quad (1b)$$

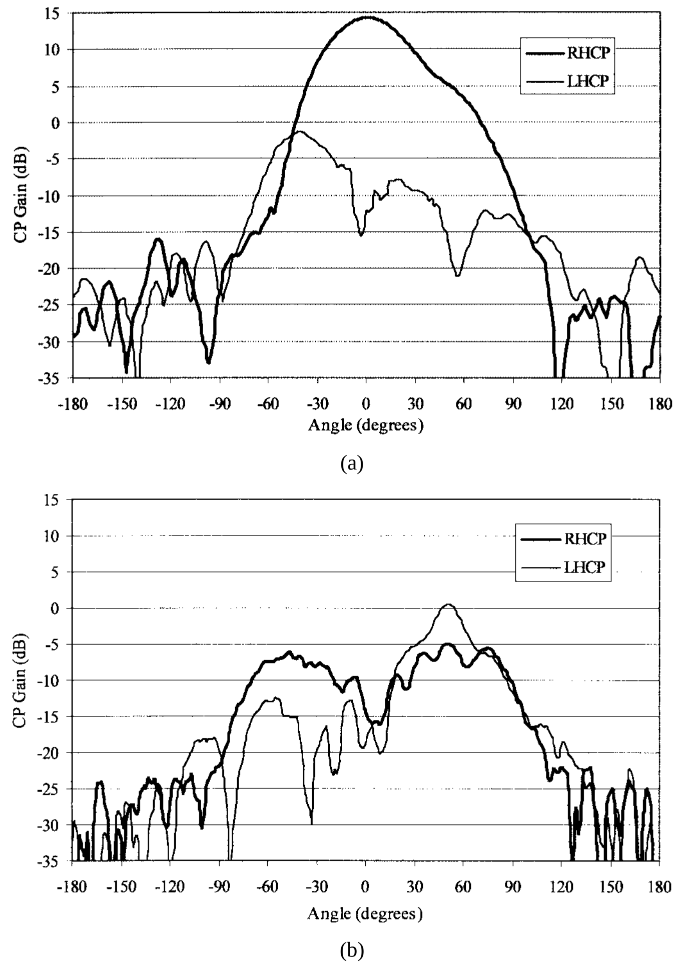



Fig. 4. Measured patterns in the $x$–$z$-plane for the DRLA + filter + balun circuit. (a) 5.8 GHz. (b) 11.6 GHz.

the orthogonal left-polarized (LP) patterns $E_\phi$ and $E_\theta$ are converted to CP patterns. The right-hand circularly polarized (RHCP) (co-pol) and left-hand circularly polarized (LHCP) (cx-pol) patterns for both the $x$–$z$- and $y$–$z$-planes at 5.8 and 11.6 GHz are shown in Figs. 4 and 5. The cx-pol LHCP energy is 16 dB below the desired RHCP energy and the unwanted second harmonic energy at 11.6 GHz is 14 dB below the peak fundamental gain of the 5.8-GHz pattern in both planes. Due to the array's spatial geometry, a fan-shaped beam results with a beamwidth that is 15° in the $y$–$z$ array plane and 44° in the $x$–$z$-plane. These DRLA beamwidths describe a radiation pattern having an elliptical cross section. The CP gain at broadside is 14.3 dB. If the combined 0.3-dB loss contributed by the coax-to-microstrip connector and microstrip-to-CPS balun is deembedded, the DRLA array has a CP gain of 14.6 dB.

Fig. 6 shows the axial ratio for the DRLA + filter + balun circuit versus both frequency and angle of incidence for the incoming wave. Fig. 6(a) reveals an axial ratio of approximately 0.3 dB at 5.8 GHz. The 3-dB bandwidth is almost 7% at approximately 5.8 GHz. Fig. 6(b) shows the axial ratio versus angle of incidence. For an angle of incidence between ±10°, the axial ratio is better than 3 dB. This performance is sufficient for beaming power over long distances, especially in the case of beaming power from a space solar power (SSP) satellite in geo-synchronous orbit to a rectenna array on the earth since the

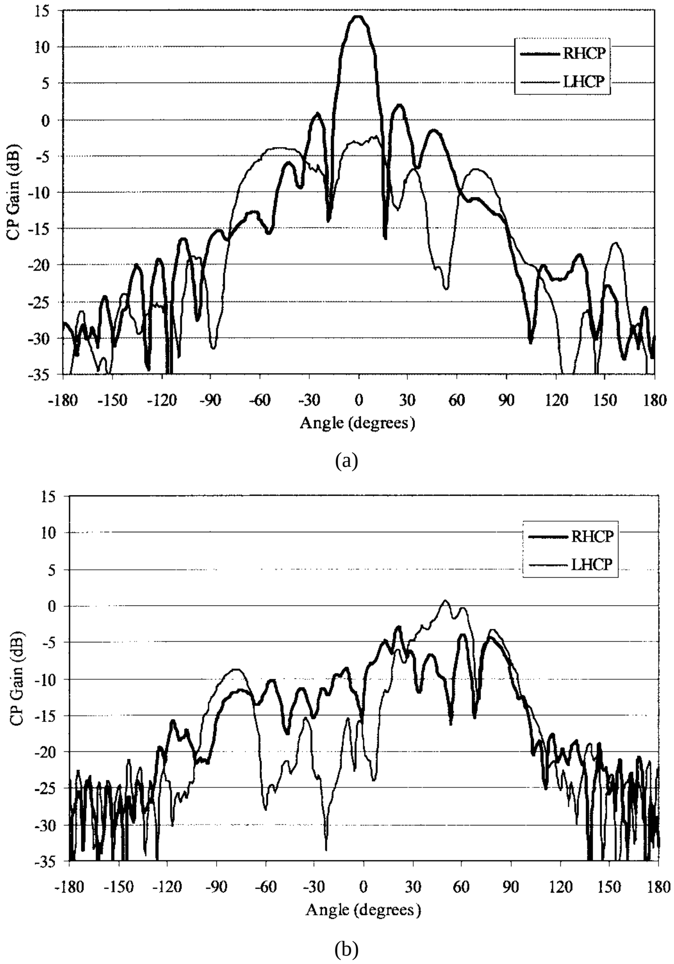



Fig. 5. Measured patterns in the $y$–$z$-plane for the DRLA + filter + balun circuit. (a) 5.8 GHz. (b) 11.6 GHz.

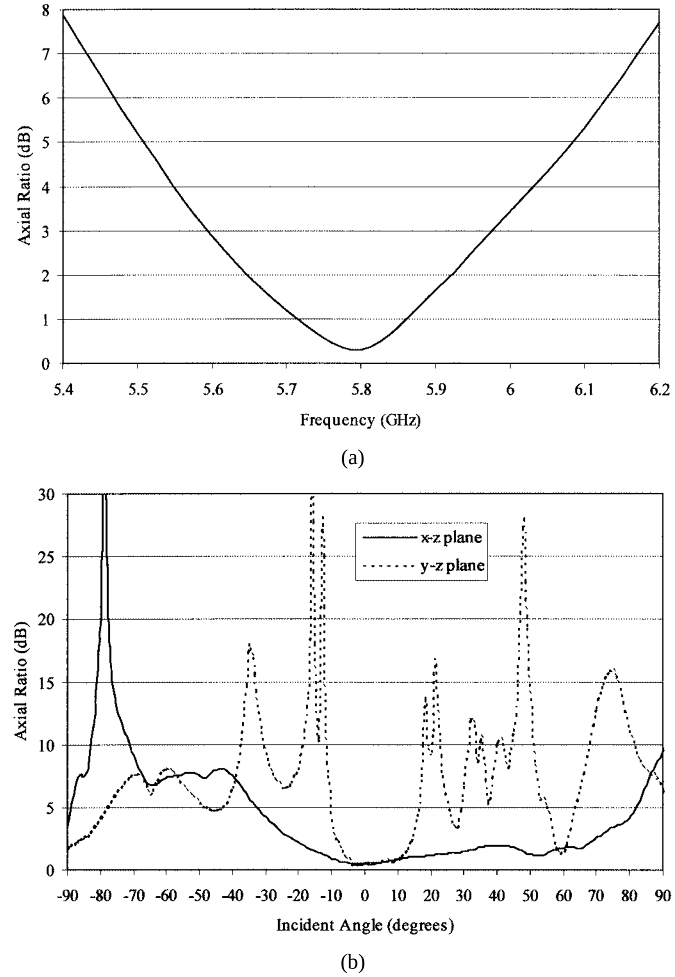



Fig. 6. Measured DRLA + filter + balun circuit axial ratio: (a) versus frequency and (b) versus incident angle.

orientation of the SSP and rectenna array will not vary more than a few degrees from broadside. The spikes in Fig. 6(b) represent the angles off broadside for which the DRLA + filter + balun circuit is linear polarized.

The CP gain versus frequency is illustrated in Fig. 7. The gain is highest at approximately 5.8 GHz with a fairly constant gain between 5.63–5.97 GHz. The CP gain has a 3-dB bandwidth of 11%. The LHCP is well suppressed below the desired RHCP.

### *E. Rectenna Design*

The diode used in the rectenna circuit is the M/A COM flip-chip detector diode MA4E1317 characterized in [10]. It has series resistance $R_S = 4\ \Omega$, zero-bias junction capacitance $C_{j0} = 0.02$ pF, built-in turn-on voltage $V_{bi} = 0.7$ V, and breakdown voltage $V_B = 7$ V. The load resistance ($R_L$) was originally chosen to be 150 Ω. A diode model described by Yoo and Chang [14] is used to predict the rectenna diode's behavior. According to this model, the 150-Ω load resistance results in the diode impedance being $Z_D = 170 - j9\,\Omega$ at 5.8 GHz and $V_B/2 = 3.5$ V. A 50 VDC C08BLBB1X5UX dc-blocking chip capacitor manufactured by Dielectric Laboratories, Cazenovia, NY, serves as the dc-pass filter to not only tune out this diode reactance, but also to optimize the remixing of the power at the harmonic frequencies. The capacitor is used to reflect all of the microwave energy arising from the diode from reaching the load resistor, thus returning the RF energy back to the diode. When shunted across the CPS lines, the capacitor blocks the 5.8-GHz signal by 17 dB and 11.6 GHz by greater than 23 dB. This translates to less than 1% of the total second harmonic energy reaching the load resistor $R_L$. The optimal distance between the dc-pass capacitor and the diode has been

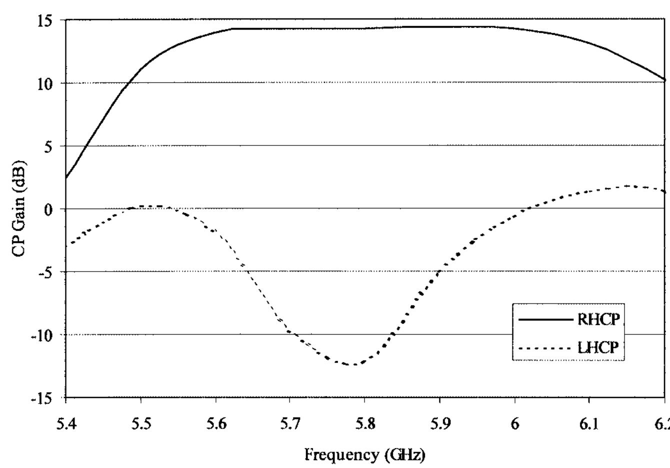



Fig. 7. Measured gain versus frequency for the DRLA + filter + balun circuit.

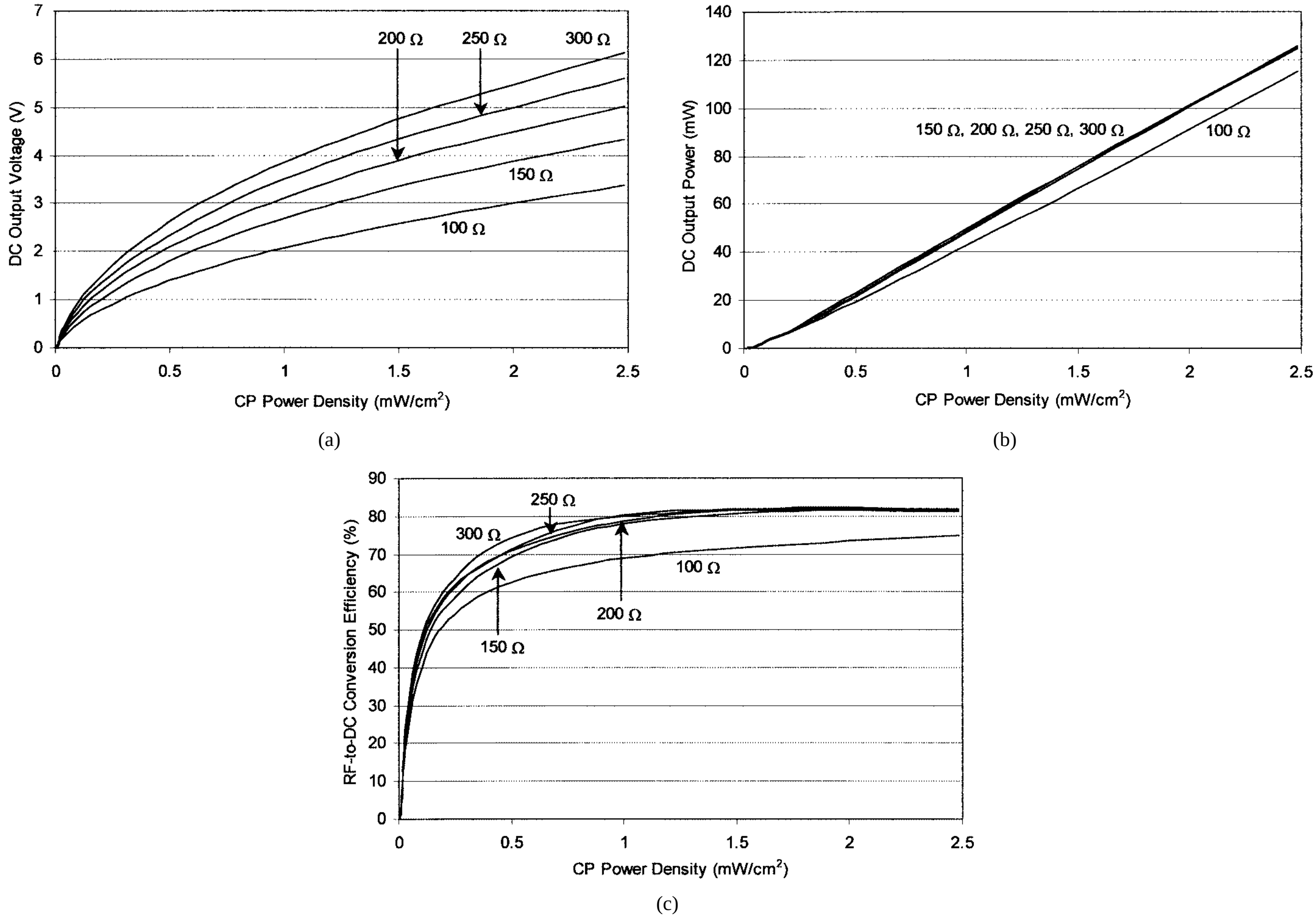



Fig. 8. Rectenna CP measured performance. (a) Rectified voltage. (b) Output power. (c) RF-to-dc conversion efficiency for various resistive loading.

determined to be 10 mm, approximately $\lambda_o/4$ at 5.8 GHz. This distance produces the maximum diode RF-to-dc conversion over 85%. This diode conversion efficiency sets the upper limit on the rectenna's RF-to-dc conversion efficiency. The CPS transmission line, which allows power to flow between the various rectenna components, is designed to have a characteristic impedance $Z_o = 170\ \Omega$. This matches the real part of the diode's impedance in order to minimize the reflection of the 5.8-GHz RF power at the diode terminals, thus increasing the rectenna's efficiency. A complete description of this rectifying circuit is given by Strassner and Chang in [10].

## III. Rectenna Measurements

In order to obtain the rectenna's efficiency, CP energy is transmitted from a 64-element RHCP truncated patch antenna array, with 21 dB of CP gain, to the rectenna located a distance $s$ from the transmitting antenna. The rectenna's efficiency is simply the ratio of the converted dc power to the received RF power [10]. The rectenna CP efficiency $\eta_R$ is defined as [13]

$$\eta_R = \frac{P_{DC}}{P_r} = \frac{(4\pi s)^2 \left[\frac{V_D^2}{R_L}\right]}{P_t G_t G_r \lambda_o^2} \tag{2}$$

where $P_t$ and $G_t$ represent the transmit power and the transmitting antenna's gain, respectively, and $G_r$ is the DRLA traveling-wave array's gain. $V_D$ is the voltage across the rectenna's load resistor $R_L$. The distance between the patch array and the rectenna is $s$, and $\lambda_o$ is the free-space wavelength of the incoming energy.

Fig. 8(a) shows the array's output voltage versus CP power density. As the load resistance increases, so does the output voltage as a function of $V_D^2/R_L$. Fig. 8(b) shows the array's output power versus CP power density. The output power is fairly constant over a range of output resistors. Fig. 8(c) shows the array's RF-to-dc conversion efficiency versus CP power density for various loading. The rectenna provides excellent RF-to-dc conversion over a wide range of power densities and load resistances. A best efficiency of 82% occurs at an input power density of 2 mW/cm$^2$ ($\sim$115-mW RF incident upon the diode) for an array loading of 150 Ω. The rectenna's output voltage at this power density is around 3.8 V. 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. The array's dc output power at 2 mW/cm$^2$ is 95 mW.

## IV. Conclusions

A CP traveling-wave low power-density rectenna has been developed to rectify RF energy to dc power with a record 82% efficiency at 5.8 GHz. The capacitor blocks the RF energy by more than 17 dB, and the CPS BRF suppresses the second harmonic signal to approximately 14 dB below the peak fundamental gain. This results in minimal radiation at the second harmonic frequency. The electromagnetic simulator IE3D models each microwave circuit section of the rectenna with reasonable accuracy providing the insight necessary to facilitate the design.

## ACKNOWLEDGMENT

The authors would like to thank M. Li and C. Wang, both of Texas A&M University, College Station, for fabricating the microstrip circuits and S. Kokel, Texas A&M University, for assisting in the data collection. The authors would also like to acknowledge Dr. J. McSpadden at Boeing, Dr. D. Dickinson and Dr. N. Marzwell, both of the Jet Propulsion Laboratory, Pasadena, CA, and Dr. F. Little, Texas A&M University, 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] W. C. Brown and J. F. Triner, "Experimental thin-film, etched-circuit rectenna," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Dallas, TX, June 1982, pp. 185–187.

[3] P. Koert, J. Cha, and M. Macina, "35 and 94 GHz rectifying antenna systems," in *Power from Space Dig.*, Paris, France, Aug. 1991, pp. 541–547.

[4] S. S. Bharj, R. Camisa, S. Grober, F. Wozniak, and E. Pendleton, "High efficiency $C$-band 1000 element rectenna array for microwave powered applications," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Albuquerque, NM, June 1992, pp. 301–303.

[5] J. O. McSpadden, L. Fan, and K. Chang, "Design and experiments of a high-conversion-efficiency 5.8-GHz rectenna," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 2053–2060, Dec. 1998.

[6] Y. H. Suh, C. Wang, and K. Chang, "Circular polarized truncated-corner square patch microstrip rectenna for wireless power transmission," *Electron. Lett.*, vol. 36, no. 7, pp. 600–602, Mar. 2000.

[7] 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.

[8] 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.

[9] ——, "A circularly polarized rectifying antenna array for wireless microwave power transmission with over 78% efficiency," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Seattle, WA, June 2002, pp. 1535–1538.

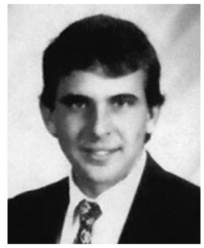
[10] ——, "5.8-GHz circularly polarized rectifying antenna for wireless microwave power transmission," *IEEE Trans. Microwave Theory Tech.*, vol. 50, pp. 1870–1876, Aug. 2002.

[11] H. Morishita, K. Hirasawa, and T. Nagao, "Circularly polarized rhombic hula loop antennas," *Electron. Lett.*, vol. 32, no. 11, pp. 946–947, May 23, 1996.

[12] K. Goverdhanam, R. N. Simons, and L. P. B. Katehi, "Coplanar stripline propagation characteristics and bandpass filter," *IEEE Microwave Guided Wave Lett.*, vol. 7, pp. 214–216, Aug. 1997.

[13] C. Balanis, *Antenna Theory*. New York: Wiley, 1982, p. 51.

[14] T. Yoo and K. Chang, "Theoretical and experimental development of 10 and 35 GHz rectennas," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 1259–1266, June 1992.



**Berndie Strassner** (S'96–M'03) received the B.S. degree in electrical engineering from the Rose-Hulman Institute of Technology, Terre Haute, IN, in 1995, and the M.S. and Ph.D. degrees in electrical engineering from Texas A&M University, College Station, in 1997 and 2002, respectively.

During the summer of 1992, 1993, and 1995, he was with the Johnson Space Center, Lockheed-Martin, where he was involved in the areas of space-shuttle navigational controls, power systems, and communication systems, respectively. In 1994, he was involved with microwave deembedding processes at the Technische Universität Hamburg-Harburg, Harburg, Germany. From 1996 to 1997, he was with Sandia National Laboratories, where he was involved with the study of the effects of harmonic termination on power-amplifier performance. From 1998 to 2002, he was a Research Assistant with the Electromagnetics Laboratory, Texas A&M University, where his research focused on RFID tags, rectifying antenna arrays, reflecting antenna arrays, and retro-directive antenna arrays. He is currently with Sandia National Laboratories, Albuquerque, NM, where he is involved with synthetic aperture radar for weapon guidance systems.

**Kai Chang** (S'75–M'76–SM'85–F'91) received the B.S.E.E. degree from the National Taiwan University, Taipei, Taiwan, R.O.C., in 1970, the M.S. degree from the State University of New York at Stony Brook, in 1972, and the Ph.D. degree from The University of Michigan at Ann Arbor, in 1976.

From 1972 to 1976, he was with the Microwave Solid-State Circuits Group, Cooley Electronics Laboratory, The University of Michigan at Ann Arbor, where he was a Research Assistant. From 1976 to 1978, he was with Shared Applications Inc., Ann Arbor, MI, where he was involved with computer simulation of microwave circuits and microwave tubes. From 1978 to 1981, he was with the Electron Dynamics Division, Hughes Aircraft Company, Torrance, CA, where he was involved in the research and development of millimeter-wave solid-state devices and circuits, power combiners, oscillators, and transmitters. From 1981 to 1985, he was with TRW Electronics and Defense, Redondo Beach, CA, where he was a Section Head involved with the development of state-of-the-art millimeter-wave integrated circuits and subsystems, including mixers, voltage-controlled oscillators (VCOs), transmitters, amplifiers, modulators, upconverters, switches, multipliers, receivers, and transceivers. In August 1985, he joined the Electrical Engineering Department, Texas A&M University, College Station, as an Associate Professor, and became a Professor in 1988. In January 1990, he became an E-Systems Endowed Professor of Electrical Engineering. He has authored and coauthored several books, including *Microwave Solid-State Circuits and Applications* (New York: Wiley, 1994), *Microwave Ring Circuits and Antennas* (New York: Wiley, 1996), *Integrated Active Antennas and Spatial Power Combining* (New York: Wiley, 1996), and *RF and Microwave Wireless Systems* (New York: Wiley, 2000). He has served as the Editor of the four-volume *Handbook of Microwave and Optical Components* (New York: Wiley, 1989 and 1990). He is the Editor of *Microwave and Optical Technology Letters* and the Wiley Book Series on "Microwave and Optical Engineering." He has also authored or coauthored over 350 technical papers and several book chapters in the areas of microwave and millimeter-wave devices, circuits, and antennas. His current interests are microwave and millimeter-wave devices and circuits, microwave integrated circuits, integrated antennas, wide-band and active antennas, phased arrays, microwave power transmission, and microwave optical interactions.

Dr. Chang was the recipient of the 1984 Special Achievement Award presented by TRW, the 1988 Halliburton Professor Award, the 1989 Distinguished Teaching Award, the 1992 Distinguished Research Award, and the 1996 Texas Engineering Experiment Station (TEES) Fellow Award presented by Texas A&M University.