New 5.8-GHz Circularly Polarized Retrodirective Rectenna Arrays for Wireless Power Transmission

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***Abstract*—This paper proposes two new circularly polarized retrodirective rectenna arrays, including a 2 $\times$ 2 array and a 4 $\times$ 4 array. A proximity-coupled microstrip ring antenna is used as the retrodirective rectenna array element, which can automatically block harmonic signals up to the third order from reradiating by the rectifying circuit. These arrays are printed on a Rogers Duroid 5880 substrate of $\varepsilon_r = 2.2$ with a two-layer structure, with a total thickness of 1.5748 mm (or 62 mil). The new retrodirective rectenna array can track the incoming power source signals automatically and is less sensitive to the power incident angle variations, i.e., main-beam alignment deviation. It can provide a nearly constant dc output voltage within $\pm 10^\circ$ and 90% dc output voltage within $\pm 45^\circ$. The conversion efficiencies of the two arrays are 73.3% and 55%, respectively, when the power density is 10 $\mathrm{mW/cm^2}$. The retrodirective rectenna array can be used in the low-power density applications for microwave wireless power transmissions.**

***Index Terms*—Circularly polarized, microwave power transmission, rectenna, retrodirective array.**

I. Introduction

In THE future, space solar power transmission (SPT) and microwave wireless power transmission (WPT) could play an important role in gathering clean energy from the space [1], [2]. The rectenna, rectifying antenna, is one of the primary components in the application of SPT and WPT. The rectenna can be used for ground-to-ground, ground-to-space, space-to-ground, and space-to-space power transmissions, and its development has been reviewed in [3]. Recently, many rectennas have been reported, including a rectenna using a dual rhombic hula loop antenna [4], a dual-frequency rectenna [5], a dual-diode rectenna [6], and rectennas with various patch antennas [7]–[10]. The circular polarization (CP) has become one of the important considerations in these rectenna designs. The advantage of using CP is that the antenna performance will not be significantly affected due to the rotation of the circuit because the CP does not require the polarization alignment of the electric field at the transmitting and receiving antennas.

Even with CP, the efficient power transmission still requires a precise main-beam alignment between the transmit antenna and the receive rectenna arrays. The transmit antenna usually has a quite narrow beamwidth at the broadside. Despite the fact that the circularly polarized antenna can preserve the output voltage constant when the transmitter or the receiver rotates, it cannot prevent the output voltage variations due to the improper main-beam alignment. In [11], it was proposed that using a nonuniform antenna array replaces the traditional uniform antenna array in the microwave power transmission applications. The nonuniform array can be designed to have a flatten pattern with a wide beamwidth. The rectenna with a broadened main beam can keep the output voltage invariant even if the rectenna has an improper beam alignment. Although this method indeed makes the main beam broadened, numerous antenna elements with various sizes are needed and the nonuniform array gain may be lower than that of the uniform array. The process is complicated and difficult to implement.

The second method to solve this problem is to use a retrodirective antenna array [12]–[14]. A retrodirective array does not require accurate information of the source location, but is able to resend the incident wave toward to where it comes from. Its automatic beam-steering feature has been widely used in many wireless communication systems [15]–[18], including multipath fading reduction [19] and spatial power combining [20]. The retrodirective antenna has two basic array architectures: the phase-conjugated array and the Van Atta array. The phase-conjugated array needs a mixer circuit that requires a large frequency difference between RF and local oscillator (LO) signals and the RF leakage has to be suppressed for good performance. It has many circuit components and is difficult to integrate with the rectenna. The Van Atta array is simpler. It consists of array elements connected by transmission lines. The Van Atta array can be a passive or an active type, unlike the phase-conjugated array that always requires active devices [21]. The advantages of the Van Atta array make it easy to combine with the rectennas.

The other consideration of designing the rectenna is its harmonic-rejection ability. The harmonic signals are created by the rectifying circuit and will be reradiated by the receiving antenna, which interfere with other signals and result in the rectenna efficiency reduction. Usually the magnitude of the third-order harmonic is much smaller than the second-order harmonic, however, it was found in [22] that the power level of the third-order harmonic may still have a relatively large level as compared with the power level of the second-order harmonic. Therefore, a high-order harmonic-rejection rectenna is preferred to suppress the second-order, third-order, and even higher order harmonic signals simultaneously. A microstrip proximity-coupled antenna that inherently blocks harmonics in the rectenna is used in this approach. Alternatively, a frequency-selective surface can be used to diminish the reradiated harmonics [23].

Manuscript received February 5, 2006; revised March 31, 2006. This work was supported in part by the National Science Foundation.

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Digital Object Identifier 10.1109/TMTT.2006.877422

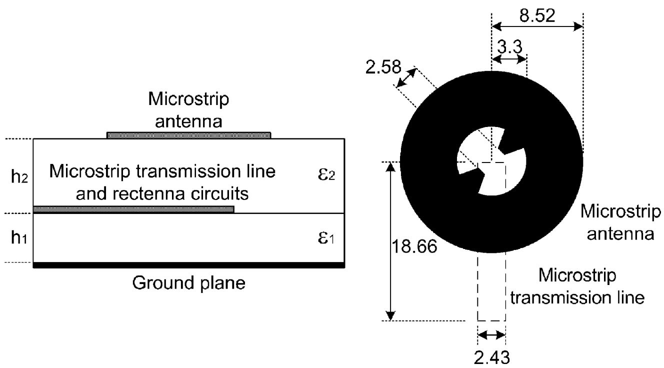

Fig. 1. Geometry of the proximity-coupled microstrip ring antenna and the two-layer dielectric structure. All dimensions are in millimeters.

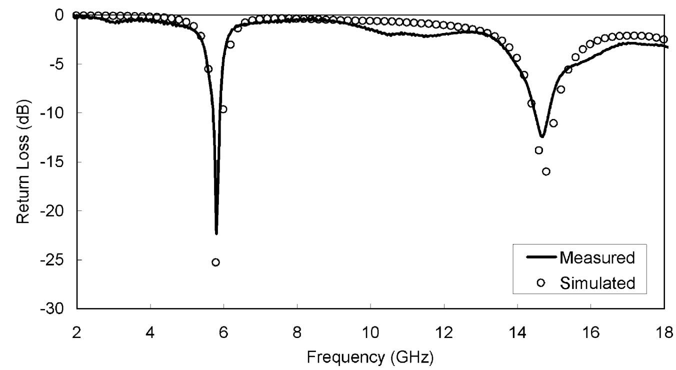

Fig. 2. Measured return loss of the single-ring antenna element.

In this paper, two novel retrodirective rectenna arrays are demonstrated. They are a 2×2 array and a 4×4 array. A circular polarized proximity-coupled microstrip antenna is selected as the array element because this antenna can be designed to block harmonic signals and can be used to easily build the Van Atta array. The antenna array elements are located on one dielectric layer and the circuits of the retrodirective array and the rectenna are located on the other dielectric layer. This two-layer structure provides easy design and fabrication for a large retrodirective rectenna array. The new retrodirective array can track the power source automatically and, hence, keep the output voltage nearly constant. The 4×4 retrodirective rectenna arrays can be viewed as a four-series-connected 2×2 array so its output voltage should be four times when an optimum load is used. The design methods of the 2×2 and 4×4 retrodirective rectenna arrays are described in Sections II and III, respectively. The measurement results of the retrodirective rectenna arrays are presented in Section IV. Finally, conclusions are given in Section V.

II. 2×2 RETRODIRECTIVE RECTENNA DESIGN

A. *Circularly Polarized Microstrip Antenna*

The circular polarized proximity-coupled microstrip ring antenna is chosen as the antenna element of the retrodirective array [24]. Its geometry is shown in Fig. 1. The advantages of the proximity-coupled microstrip antenna are its circularly polarized characteristic and its two-layer structure. When designing the Van Atta array, the transmission line connecting two elements may have a length of multiple wavelengths and its schematic may be complicated. Separating the antenna elements and the transmission-line networks on different dielectric layers will reduce the unnecessary coupling between the antenna elements and the transmission lines and provide more space for the retrodirective rectenna array circuits.

A full-wave three-dimensional (3-D) electromagnetic simulator IE3D by Zeland, Fremont, CA, is used to design the antenna elements and the retrodirective rectenna array. The proximity-coupled antenna is designed at the center frequency of 5.8 GHz and is printed on a Rogers Duroid 5880 substrate. The two layers are of the same material with a thickness $h_1 = h_2 = 0.7874$ mm $= 31$ mil, a dielectric constant $\varepsilon_1 = \varepsilon_2 = 2.2$, and the conductor (copper) thickness of 0.0356 mm (equivalent to 1-oz metallization). At 5.8 GHz, the effective dielectric constant ($\varepsilon_{r,\mathrm{eff}}$) of the transmission line between the two layers is 1.92 and λ_g (guided wavelength) is 37.34 mm. The transmission line has a characteristic impedance (Z_0) of 50 Ω, which is chosen to match the impedances of the antenna and the diode to reduce the signal reflections between these components [3], [4].

The dumbbell slot in the antenna center has to be designed carefully for good antenna performance, especially for low axial ratio (AR). The dumbbell slot yields a left-handed CP. A right-handed CP can be obtained by rotating the dumbbell by 90°. Fig. 2 shows a good agreement between the measured return loss and simulated return loss. The bandwidth of 2 : 1 voltage standing-wave ratio (VSWR) at the fundamental frequency of 5.8 GHz is approximately 3.3%. It has a measured gain of 5.89 dBi and an AR of 1.7 dB. The AR can be reduced by tuning the dumbbell slot. While the antenna in perfect CP (i.e., $\mathrm{AR} = 0$ dB) has its highest CP gain, the corresponding rectenna conversion efficiency is increased until the rectifying diode saturates.

While the proximity-coupled microstrip antenna is used as the antenna element of the retrodirective array, the beamwidth of the array main beam will not influence the rectenna performance much. This is because the retrodirectivity of the array will require the main beam constantly focused on the direction of the incoming waves.

B. *2×2 Retrodirective Array*

The 2×2 retrodirective rectenna array is shown in Fig. 3(a) and (b). This array consists of two pairs of antenna elements. Each pair of antenna elements is equally spaced from the array center and, hence, has a transmission line of equal length (l_1 and l_2). The transmission line between the two antennas is used to invert the phase of the incident wave and then steer the main beam of the array toward to where the incident waves come. Each transmission line is connected together through the gap when the diode is turned on by the incident microwave power, as shown in Fig. 3(c). At that time, the retrodirectivity activates and the diodes also convert RF power to dc power. Therefore, the diode in the gap acts as a switch for the retrodirective circuit and as a rectifier for the rectenna circuit. The remaining circuits belong to the rectenna rectifying circuit and will be discussed in Section II-C.

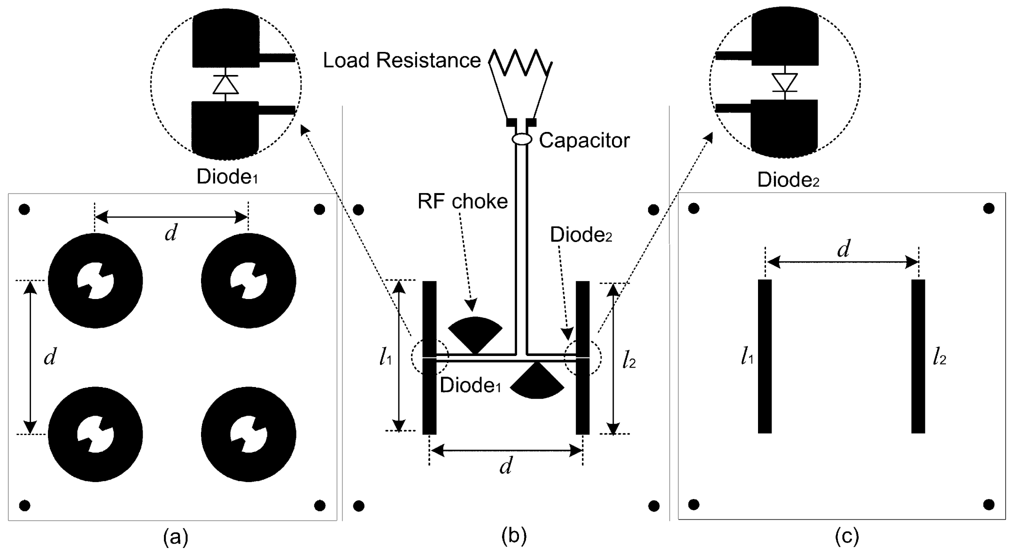

Fig. 3. Geometry of the 2×2 retrodirective rectenna array. (a) Antenna array elements. (b) Rectenna circuit. (c) Retrodirective array equivalent microstrip line network when the diodes are ON for retrodirective action.

The transmission lines connecting each pair of antenna elements should have the same length or have a length difference equal to a multiple of the microstrip line guided wavelength (λ_g), i.e., $\Delta l = n\lambda_g$, where $n = 0, 1, 2, 3, \ldots$. To avoid the grating lobes, the spacing between antenna elements has to be considered. The element spacing should satisfy

$$d < \frac{\lambda_0}{(1 + |\sin\theta_{\text{in}}|)} \tag{1}$$

where d is the element spacing, λ_0 is the free-space wavelength, and θ_{in} is the incident angle of the incoming signals. It assumes the incident angle scans from -90° to $+90^\circ$ so d should be smaller than $0.5\lambda_0$. Here, d is chosen as $0.5\lambda_0 = 25.9$ mm at 5.8 GHz. The lengths of the two transmission lines are equal to d, i.e., $l_1 = l_2 = 0.5\lambda_0 = 0.69\lambda_g$, with $\lambda_g = \lambda_0/\varepsilon_{r,\text{eff}}^{1/2}$.

The bistatic patterns of the 2×2 retrodirective array are shown in Fig. 4 for three different θ_{in} angles. To measure the bistatic patterns, the transmitting horn and the retrodirective array are stationary while the receiving horn scans from -90° to $+90^\circ$, as shown in Fig. 4(a). During the scan, both the transmitting power source output and the distance between the array and the source are kept constant. In Fig. 4(b), the incoming waves come from $\theta_{\text{in}} = 0^\circ$, -25°, and -50° and the patterns are separately normalized to 0 dB, which means their peak gains may be different. The corresponding 3-dB beamwidths of the main beam for the array are 18°, 18°, and 13° and the 10-dB beamwidths are 36°, 32°, and 28°. It is observed that the 2×2 retrodirective array can track the incoming signals well.

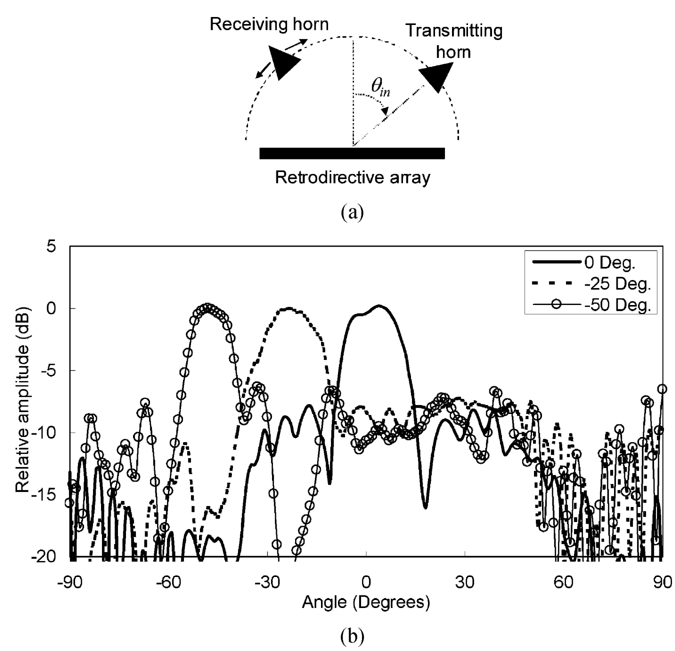

Fig. 4. (a) Measurement setup for the bistatic patterns. (b) Measured bistatic patterns of the 2×2 retrodirective array at different incoming signal directions from 0°, -25°, and -50°.

C. Rectenna Circuits of the 2×2 Retrodirective Array

A rectenna usually consists of a receiving antenna or array, a low-pass or bandpass filter to suppress the second- and/or the third-order harmonic signals, a rectifying diode for RF-to-dc conversion, a dc pass filter, and a resistive load. The diode is the key component in determining the RF-to-dc conversion efficiency. The resistive load also affects the output voltage and the rectenna performance.

The 2×2 retrodirective rectenna circuit is shown in Fig. 3(b). In this study, the low-pass or bandpass filter is not needed since a harmonic-rejection antenna is employed. The harmonics of the circular patch antenna is the solution of the Bessel's function. Therefore, the harmonic frequencies of the circular patches are different from those of the diodes. The antenna element designed here has such an advantage, which can be observed from Fig. 2. The return loss at 5.8 GHz (fundamental frequency) is 22.35 dB and the return losses at 11.6 and 17.4 GHz (harmonic frequencies) are 2.15 and 3.02 dB, respectively. The en-

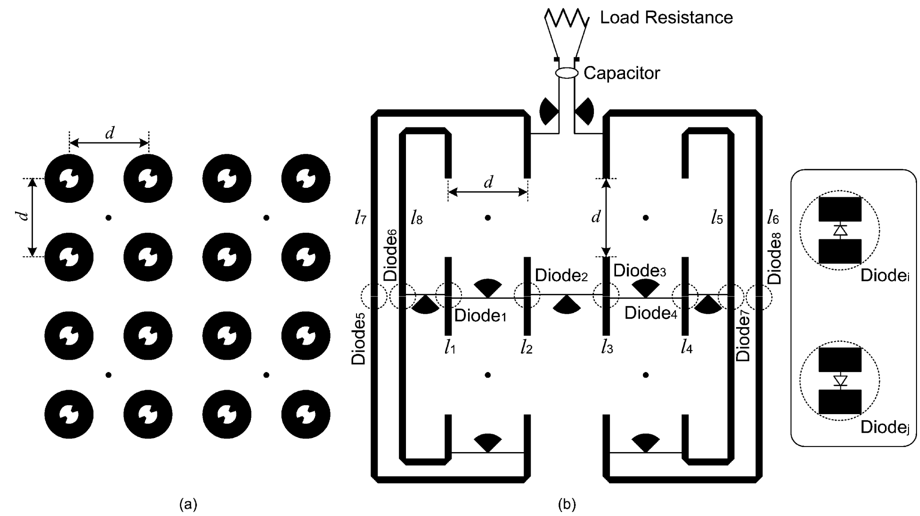

Fig. 5. Geometry of the 4×4 retrodirective rectenna array. (a) Antenna array. (b) Retrodirective rectenna circuit. The insets show the mounted direction of the diode$_i$ and diode$_j$, where $i = 1, 3, 5, 7$, and $j = 2, 4, 6, 8$.

ergy re-radiated by the antenna is then at 5.8 GHz due to these high harmonic return losses, as well as the fact the energy after mixing process is significantly smaller at the harmonic frequencies comparing to the fundamental frequency. This advantage reduces the space for the rectenna circuit and makes it more compact.

The Schottky diode MA4E1317 by M/A COM is used to convert RF power to dc power. Usually higher dc output voltage results in a smaller junction capacitance, which also gives better conversion efficiency. A broadband capacitor from Dielectric Laboratories, Cazenovia, NY (model C08BLBB1X5UX) is chosen as the dc pass filter. The dc pass filter not only tunes out the reactance of the diode, but also blocks the unwanted RF signals from reaching the resistive load. This capacitance is in shunt with the loading resistance.

The 2×2 retrodirective rectenna array can be viewed as two series-connected rectenna elements. Each rectenna element includes a pair of antenna elements and a rectifying diode. Each antenna element couples the energy to the connecting transmission line and sends it to the other antenna element for the retrodirective purpose. For power rectification, the diode is mounted across the transmission line at its midpoint by using silver epoxy. Rectenna elements are series connected by using a thin high-impedance transmission line with RF chokes to reject the unwanted RF signals from each diode and to avoid RF signals leaking. These two series-connected rectenna elements share a resistive load where the dc output voltage is detected. As the diode is ON, signals received by one antenna element can be reradiated by the other antenna element and the beam steering is completed. In other words, the retrodirectivity of the array and the rectifying process will be activated at the same time. It is noted that every rectenna element is behaved as a unilateral device and, hence, their outputs can be added together.

III. 4×4 Retrodirective Rectenna Design

There are two methods to build a 4×4 retrodirective rectenna array. The first one is to arrange four 2×2 retrodirective rectenna arrays described in Section II and connect them by series or parallel arrangement. Both series and parallel connections should collect the same amount of dc power. This method is easy to implement and can be used to build a large rectenna array. A dc power combiner can be connected to collect higher output power. It is noted the circuit of the multiway dc power combiner may couple with the transmission-line network of the retrodirective rectenna array, which affects the array pattern and reduces the antenna gain.

The second method is to build the 4×4 retrodirective rectenna array by designing another distinct transmission-line network, as shown in Fig. 5. The structure and the operation process of the 4×4 array are similar to the 2×2 array. Eight sections of transmission lines (l_1 to l_8) are used for the retrodirective function. They are also used to link the rectenna elements with other thinner sections to the load resistance. Eight diodes are used for the rectifying purpose. The lengths of the transmission lines are given by $l_1 = l_2 = l_3 = l_4 = 0.69\lambda_g$, $l_5 = l_8 = 4.69\lambda_g$, and $l_6 = l_7 = 6.69\lambda_g$. The antenna element spacing is the same as that of the 2×2 array, i.e., $d = 0.5\lambda_0$.

Same as the 2×2 retrodirective rectenna array, the rectifying diode is mounted at the midpoint of each transmission line, as shown in Fig. 5(b). The two diodes beside each other (Diode$_i$ and Diode$_j$) are to be mounted in opposite directions, i.e., the anode of one diode links the cathode of the other diode. Intuitionally, this array can be viewed as a series-connected rectenna array because eight rectenna elements are series connected together via the transmission-line network with RF chokes and share the same loading resistance.

Measured bistatic patterns of the 4×4 array are shown in Fig. 6. The patterns are separately normalized to 0 dB. The incoming waves come from 0°, 20°, and 40°. The corresponding 3-dB beamwidths are 19°, 22°, and 19°. The 10-dB beamwidths are 34°, 36°, and 35°. These results demonstrate that the 4×4 retrodirective array can effectively perform the beam steering to align the rectenna array with the power transmitting antenna.

IV. Retrodirective Rectenna Array Measurements

A. Broadside Measurements

The measurement method and the equipment setup for the rectenna test have been studied in [3]. The rectenna measure-

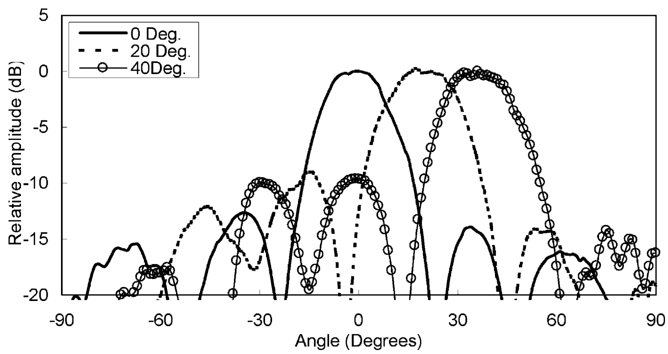

Fig. 6. Measured bistatic patterns of the 4 × 4 retrodirective rectenna array at different incoming signal directions from 0°, 20°, and 40°.

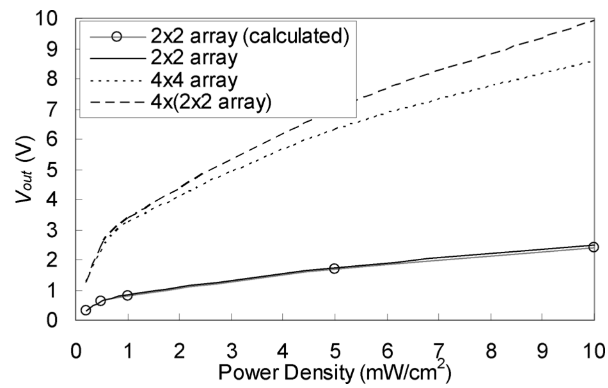

Fig. 7. Measured dc output voltages of the 2 × 2 array and the 4 × 4 array at broadside.

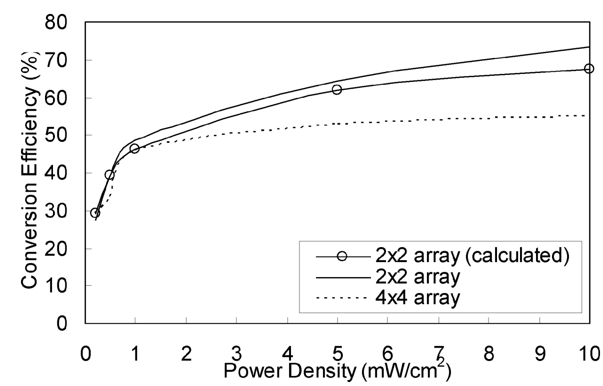

Fig. 8. Measured conversion efficiencies of the 2 × 2 array and 4 × 4 array at broadside.

ments can be carried out in free space or in waveguides. Free-space measurements were conducted here. The RF-to-dc efficiency (η) of the rectenna is defined as

$$\eta = \frac{P_{dc}}{P_r} \times 100\% \tag{2}$$

where P_{dc} is the dc output power and P_r is the power received by the array that is calculated by using the Friss transmission equation. By changing the distance between the transmitting antenna and the retrodirective rectenna array, the efficiencies for different power densities can be determined. The power density (P_d) is given by

$$P_d = \frac{P_t G_t}{4\pi D^2} \tag{3}$$

where P_t is the transmitting power, G_t is the horn antenna gain, and D is the distance between the horn antenna and the center of the rectenna array.

The dc output voltages and the RF-to-dc conversion efficiencies of a 2×2 retrodirective rectenna array are shown in Figs. 7 and 8, respectively, as a function of the power densities at the broadside. The external resistive load of the 2×2 array is chosen as 150 Ω for the maximum dc output voltage. The calculated results are computed by using the equations described in [4]. The measured results match the calculated results well. When the power density (P_d) is 10 mW/cm^2, the 2×2 array has an output of 2.48 V and a conversion efficiency of 73.3%. The output voltage increases while the power density becomes larger, and so does the conversion efficiency. However, the rectifying circuit may be burned out due to the excessive incoming power. A Zener device can be used to protect the rectifying circuit from breakdown.

A linear equivalent model [25] is applied to verify the linearity of the 4×4 retrodirective rectenna array to the 2×2 array. The linear model has been shown to be effective in predicting the output power or voltage when the optimum load resistance is used for the rectenna. According to the model, four series-connected rectenna elements should generate four times the output voltage of the single rectenna element. In our experiments, the 4×4 array can be viewed as an array series connected by four 2×2 arrays so it should have four times dc output voltage under the optimum condition. Here, the load resistance of the 4×4 array is chosen as 600 Ω.

The output voltage of the 4×4 array ($V_{\text{out},4\times4}$) is shown in Fig. 7 in which a $4\times$ 2×2 array output voltage ($4V_{\text{out},2\times2}$) is also plotted as a comparison. It is observed that the 4×4 array has a good performance and agree well with $4V_{\text{out},2\times2}$, especially at low P_d levels. For example, at $P_d = 1$ mW/cm^2, $V_{\text{out},4\times4}/4V_{\text{out},2\times2} = 97\%$. At $P_d = 10$ mW/cm^2, $V_{\text{out},4\times4}/4V_{\text{out},2\times2} = 87\%$, while the conversion efficiency is 55% for the 4×4 array, as shown in Fig. 8. From these measurement results, when the power density increases, the 4×4 array does not work as well as those at lower power density. One possible reason is that the incident power density is not uniform for a large array. Therefore, not all of the rectenna elements have the same output voltage due to their different positions. When the rectenna elements with different outputs are connected in series or parallel, the rectenna array output will be less than the summation that assumes that same individual rectenna element output. Under this condition, the array output decreases and, hence, its conversion efficiency is reduced. The other reason affecting the rectenna array performance is the imperfect CP of the array. Furthermore, the sidelobes of the array patterns also result in the degradation. These characteristics become significant when the incident angle changes, while the power source scans.

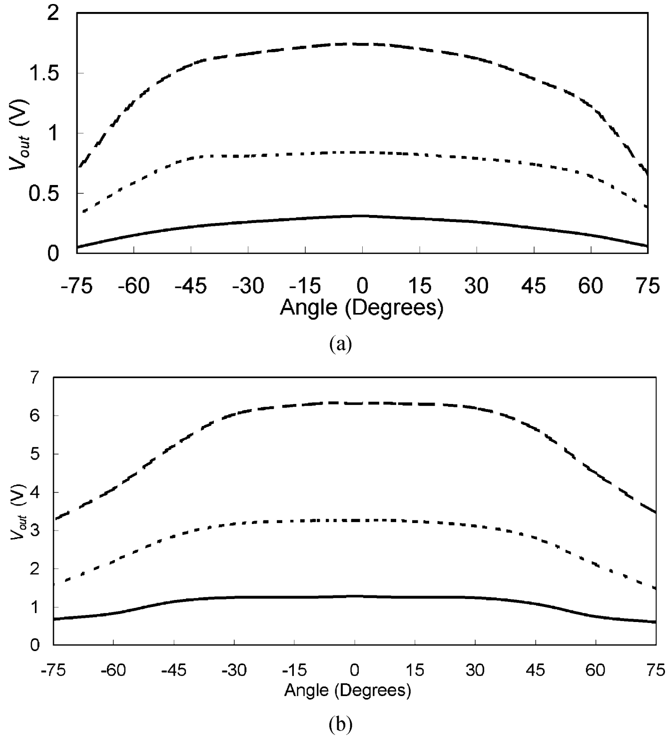

Fig. 9. Measured dc output voltages as a function of incident angles for the: (a) 2×2 array and (b) 4×4 array. Solid line: $P_d = 0.2$ mW/cm^2. Dotted line: $P_d = 1$ mW/cm^2. Dashed line: $P_d = 5$ mW/cm^2.

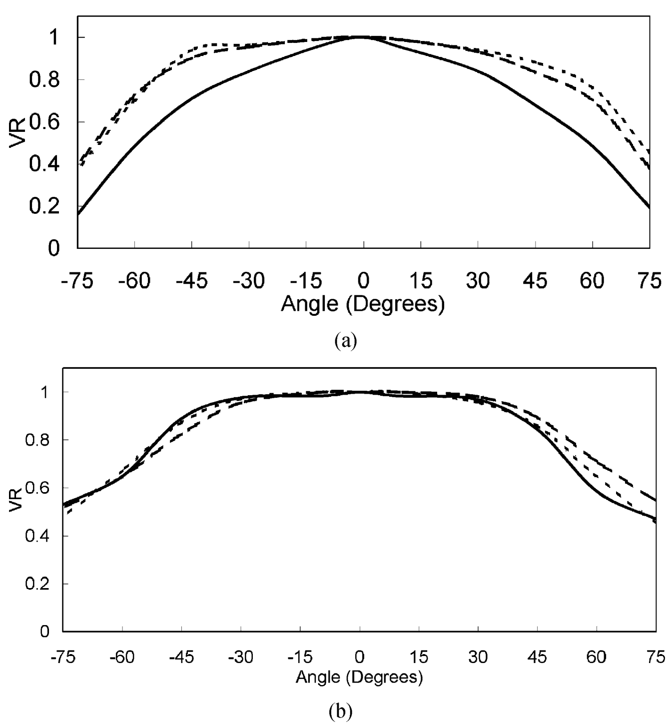

Fig. 10. Output VRs as a function of incident angles for the: (a) 2×2 array and (b) 4×4 array. Solid line: $P_d = 0.2$ mW/cm^2. Dotted line: $P_d = 1$ mW/cm^2. Dashed line: $P_d = 5$ mW/cm^2.

B. Scanning Measurements

The retrodirectivity of the rectenna arrays was tested by using the same procedure of measuring the bistatic patterns shown in Fig. 4(a). During the measurement, the distance between the transmitting horn antenna that provides the microwave power and the retrodirective rectenna array is constant. Fig. 9 shows measured dc output voltages of the retrodirective rectenna arrays as a function of the RF signal incident angles ($\theta_{\rm in}$) for three different power densities. In the past rectenna experiments, the maximum output voltage is confined to be detected at the broadside direction and it drops sharply when the main beam is not aligned with the rectennas. By using the retrodirective arrays, it is obvious that this drawback has been improved significantly. Whether the main-beam beamwidth is narrow or wide, the rectenna array becomes less sensitive to the power incident angle variations, i.e., main-beam alignment deviation.

The voltage ratios (VRs) versus the incident angles are shown in Fig. 10. The VR is defined as the ratio of the output voltage at $\theta_{\rm in}$ to that at $\theta_{\rm in} = 0^\circ$. For both 2×2 and 4×4 arrays, the VR within $\pm 10^\circ$ is larger than 0.98, except the results of 2×2 array with $P_d = 0.2$ mW/cm^2. This may be due to the low power density resulting in lower output voltage that cannot drive all the rectifying diodes well. In most cases, the VR is very close to 0.9 as $\theta_{\rm in} < 45^\circ$. When $\theta_{\rm in} > 45^\circ$, the VR starts to reduce because the gain of the retrodirective rectenna array decreases. The VR becomes smaller than 0.5 when $\theta_{\rm in} > 75^\circ$. Compared with the traditional rectennas, the retrodirective rectenna arrays indeed can automatically align its main beam toward to the power source and achieves good rectenna performance.

V. Conclusions

In this paper, a 2×2 and a 4×4 C-band circular polarized retrodirective rectenna arrays have been developed. No bandpass filter is needed in the retrodirective rectenna array because the antenna element of the array is inherently able to reject the reradiated harmonic signals. The antenna element is a proximity-coupled microstrip ring antenna that has a circular polarized gain of 5.89 dBi and an AR of 1.7 dB. At the broadside, the conversion efficiencies of the 2×2 and 4×4 retrodirective rectenna arrays are 73.3% and 55%, respectively, when the incident power density is 10 mW/cm^2. The dc output voltages are 2.48 and 8.59 V, respectively. The output voltage and the conversion efficiency can be higher if a larger incident power density is used.

The main beam of the retrodirective rectenna array can steer toward to the power source automatically. The output voltage is almost constant within $\pm 10^\circ$ of the incident angle. For $\theta_{\rm in} < 45^\circ$, the VR is still as high as 0.9. These results show that the dc output voltage will not change due to the improper beam alignment. This technique is very suitable for the WPTs with a high gain, but narrow beamwidth transmitting antenna. The antenna is usually consists of many elements and, hence, the tracking is very critical.

Acknowledgment

The authors would like to thank M.-Y. Li, Texas A&M University, College Station, for his technical assistance and S.-H. Hsu, Texas A&M University, for his helpful suggestion on measurements.

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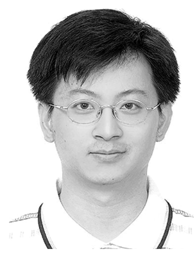

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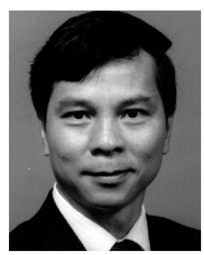

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