Broadband Rectenna Arrays for Randomly Polarized Incident Waves

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***Abstract*— This paper presents a new approach to efficient rectenna arrays for arbitrarily polarized incident waves with broad spectral content. The approach is validated experimentally on a dense grid array that rectifies two orthogonal linear polarizations, and on a self-similar spiral array with alternating right-hand and left-hand circular polarizations. The two arrays operate from 4.5 to 8 GHz and 8.5 to 15 GHz and have maximum open circuit voltages of 3.5 and 4.0 V,respectively. Their efficiencies increase above 35 % and 45 % ,respectively, for higher incident powers.**

I. Introduction

Microwave rectennas – active antennas containing rectification devices – have been investigated for power transmission and detection over the past half century [1]. Applications have included long distance power beaming [2,3,4], signal detection [5] and wireless control systems [6]. In all of these cases, the polarization, CW frequency, and power of the incoming RF field were not time varying and were well defined and known *a priori*. In this paper, we explore a new application of RF rectennas: recycling of unused RF energy in areas where RF radiated power densities are relatively high. For example, the rooftop of the building at 1801 California Street in Denver, Colorado, houses a large variety of transmitting antennas for applications ranging from police communications (at several hundred MHz), cellular (900 MHz) and PCS (around 2 GHz) telephony, two-way microwave radio communications, and up to millimeter-wave satellite communications. A variety of radiated power levels and polarizations are present in this environment, and interference between the antennas, as well as health safety of operating personnel due to RF power densities exceeding FCC regulations are existing problems [7]. In addition, in such multi-path environments, the wave polarization changes as the waves propagate. For example, for a vertically polarized transmitted wave, the waves after propagation contain both polarizations at roughly the same power level and with uncorrelated phases [8]. To mittigate this problem, we investigate the prospect of efficiently capturing power contained in fields with unknown and arbitrary time varying spectral distribution and polarization. To this end, two rectenna arrays, a grid and a spiral array shown in Fig.1, have been designed and characterized with incident waves over an extended frequency band and with arbitrary elliptical polarization.

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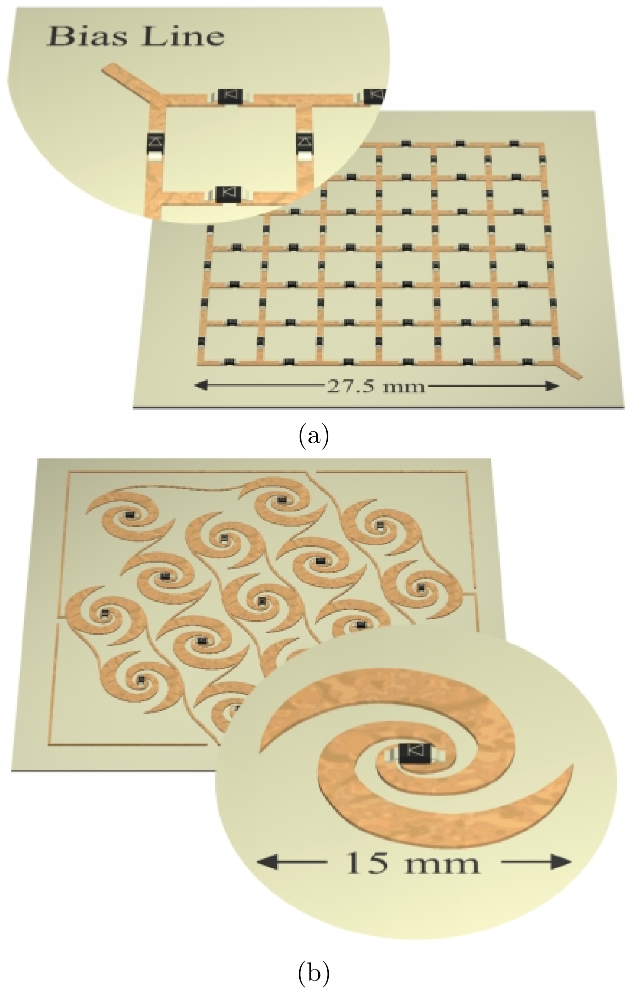

Fig. 1. The grid (a) and spiral (b) arrays. The latter is arrayed as alternating RHCP and LHCP elements, while the former rectifies one half cycle of both polarizations equally.

The following issues are relevant to the work presented in this paper:

1. In rectennas presented to date, a CW wave at a single frequency is incident on a resonant antenna, followed by a matching circuit that helps deliver the received power to a rectifying element, typically a Schot-

tky diode. However, resonant antennas followed by matching circuits are narrowband (at most 15% fractional bandwidth), and arrays of these circuits take up considerable real estate which reduces overall aperture efficiency, and therefore conversion efficiency. In the rectenna arrays presented here, resonant antennas and matching circuits are absent, and a large number of diodes load a nonresonant radiating array.

2. The rectification process is more efficient when the rectifier diode is biased to an operating point of high *IV* curve nonlinearity. When a large number of diodes are connected in a combined series-parallel DC circuit, they provide self biasing, thereby increasing the conversion efficiency.
3. In previously demonstrated rectennas, the polarization of the incident wave is well defined and linear in most cases (except in [5] where it is right hand circular). This enables polarization-matching of the rectenna for maximized efficiency. Our proposed applications, however, involve generalized elliptical waves with arbitrary and time-varying polarization. We accomplish efficient rectification of such waves by independently rectifying two orthogonal polarizations (either linear vertical and horizontal, or RHCP and LHCP), and adding the rectified DC voltages and/or currents.

II. Generalized Rectenna Design

A. Physical Principles of Rectenna Operation

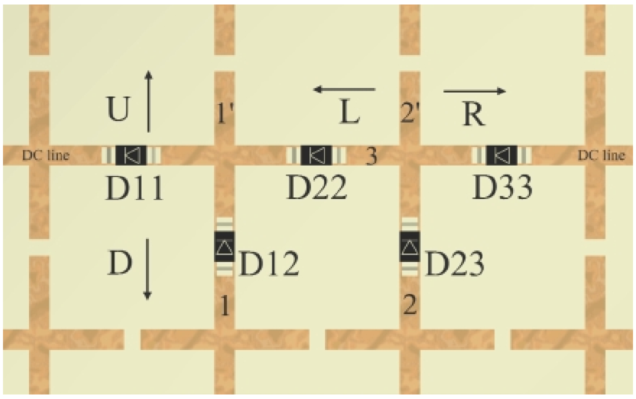

Fig. 2. Schematic of a portion of the grid rectenna array used in the explanation of the physical principles of operation.

An elliptically-polarized wave can be represented as two orthogonal linearly polarized waves of appropriate amplitudes and phases. Therefore, there is an average 3-dB loss associated with a single-feed rectenna. Separate rectifiers for each of the two orthogonal polarizations must be used to avoid effects of distructive phasor addition. A diode-loaded antenna has nonlinear performance and does not conform to standard linear antenna theory; therefore, a qualitative analysis becomes useful. Fig.2 illustrates the physical principles of operation in the context of a unit cell of the grid rectenna array. The reference directions for the electric field vector with respect to the page are labeled as U (up), D (down), R (right) and L (left). The rectified DC current is directed through the horizontal and vertical lines and collected at the diagonal ends of the array (Fig.1a). Assume first a vertically polarized incident wave and all the diodes in the horizontal lines (D11, D22 and D33) to be unbiased or forward biased. During the half period in which the electric field vector is in the U direction, diode D12 conducts, and there is a current in leads 11'. In the next half-period, the electric field is in the D direction, so that charges stored in strip 1 are discharged through diode D11 into the DC line, and strip 1' draws current from the horizontal line 3. The same happens to radiators 2 and 2', so that the two DC generators corresponding to antennas composed of strips 1-1' and 2-2' are connected in series. Consider now the horizontal conductor 3, when the diodes in the vertical strips are unbiased or forward biased. If the horizontally polarized component of the electric field is in the R direction, diodes D11, D22 and D33 prevent the induced current from flowing. In the next half-period, when the electric field vector is L-directed, a current will flow through these diodes into the horozontal "DC collection" line, simultaneously charging to some extent strips 1 and 1'. The entire structure receives both horizontally and vertically polarized waves and adds the electromotive forces after rectification. Note that the capacitance of the antenna array has the effect of smoothing the rectified induced emf.

B. Design of Grid and Spiral Rectenna Arrays

The grid rectenna array (Fig.1a) was designed based on the unit cell described above. The diodes in the grid are all aligned in the horizontal and vertical leads, and therefore the grid rectenna acts as a half-wave rectifier. The broad bandwidth results from the electrically-small period of the grid (roughly a tenth of a wavelength at the center of the band), as well as the non-resonant nature of the metal pattern. For the measurements presented in this paper, a 6 by 6 grid was fabricated on a Duroid substrate ($\varepsilon_r = 2.2$, 0.508-mm thick) with a period of 4.5 mm and a strip width of 0.5 mm. Eighty-four MA4E2054A M/ACom low-cost Schottky diodes were used to populate the mesh. The rectenna delivers DC power to a load between 4.5 and 8.0 GHz. The two diagonal corners are the DC collection leads, and the diode orientation results in a net current from bottom right to top left corner of the grid. The rectified current and voltage is therefore a combination of series and parallel connections of diodes. The grid rectenna array is roughly $0.5\lambda_0^2$ wide at the center of the band, and uses about 160 diodes per squared wavelength.

The spiral array shown in Fig.1b includes broadband loaded elements with both orthogonal circular polarizations (RHCP and LHCP). The antennas are self-similar spirals with a single diode in the feed. The DC collection points are again at the diagonal corners, with the diodes connected in a hybrid series-parallel circuit. In this array, the antennas are approximately half of a free-space wavelength at the largest diameter at the center of the operating band (from 8.5 to 15.0 GHz). In contrast to the very dense grid rectenna arrays, the spiral rectenna array is $5\lambda_0^2$ in area at the center of the band, with 3 diodes per square wavelength.

C. Figures of Merit for Rectenna Performance

The most relevant figure of merit for rectenna arrays is the efficiency of the RF to DC conversion, given the physical area of the array and the incident power density. Other significant figures of merit for the rectenna arrays are: (1) frequency response; (2) DC power (efficiency) as a function of input RF power; (3) DC power (efficiency) as a function of input wave polarization; (4) DC power (efficiency) as a function of input wave spectral content; and (5) optimal DC load impedance for maximal power transfer.

III. Experimental Results

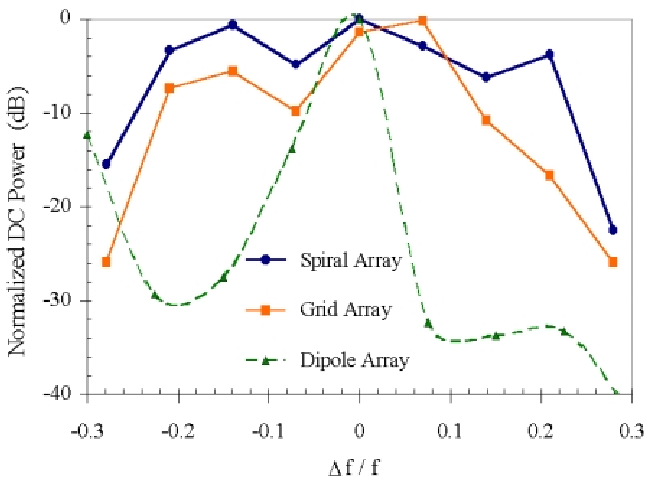

Fig. 3. Measured frequency response of normalized DC power delivered to an optimal load for the grid rectenna array (square symbols), spiral array (circular symbols) and linear 8-element resonant dipole array (triangular symbols). The response is measured with an incident circularly polarized wave at boresight.

The measurements were performed with the rectenna arrays in the far field of one or several transmitting antennas. The power incident on the rectenna arrays was calculated from the Friis transmission formula, using the geometrical area of the arrays. Since the grid and the spiral arrays are different in electrical size and operating frequency range, the data were normalized w.r.t. the quantity of interest to compare their performance. Below we present experimental data for the frequency, polarization, and power responses of the grid and spiral arrays.

A. Frequency Response for CP Incident Wave

The normalized frequency response is given in Fig.3. Both the DC power delivered to an optimal load and the frequency of operation are normalized for fair comparison. In addition, the two arrays are compared to a linear 8-element dipole rectenna array with diodes connected in series DC-wise. For these measurements, the incident field was circularly polarized by using two orthogonally polarized linear horn antennas in quadrature. For all three arrays, the same incident power was used. The measurements show that the grid and spiral areas indeed deliver DC power to a load over a broad fractional bandwidth, while the dipole array is resonant, as expected.

B. Performance for Complex Incident Waves

Since we have designed the arrays to operate over a wide range of incident frequencies and polarizations, it is of interest to measure the nonlinear response of the rectennas. As the rectification process is non-linear, superposition does not hold.

To quantify the produced DC power when waves at different frequencies are simultaneously incident on the arrays, three measurements were performed using the spiral array. The results with low incident power at 12.2 GHz and varying power at 8.5 GHz are shown in Fig. 4. One would expect that the power contained in one frequency will upon rectification provide bias and therefore improve rectification for a wave at another frequency. As can be seen in Fig.4, this process is very nonlinear. Namely, when only a vertically-polarized wave at 8.5 GHz is incident with a power P, the received normalized DC power was measured as shown with circular symbols in the figure. When a 12.2-GHz horizontally-polarized wave of power ($P_{\rm dB} - 17\,{\rm dB}$) was turned on, the increase in DC power measured in the load was 5 dB (or, a factor of 6). As the power of the 8.4 GHz signal is increased, the DC power follows this trend, but not linearly.

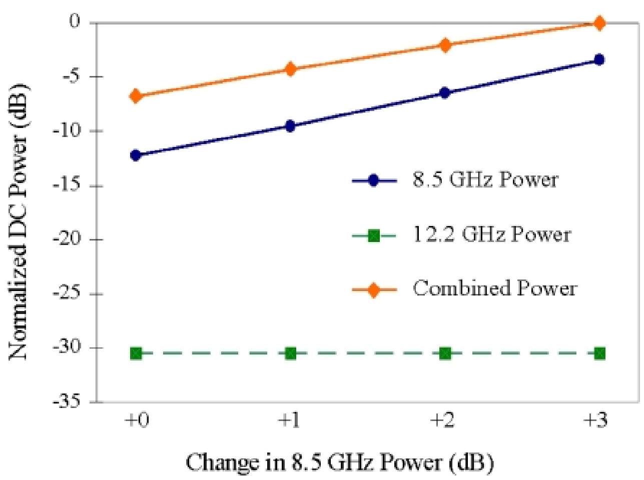

Fig. 4. Measured normalized DC power for a vertically polarized incident wave at 8.5 GHz (circular symbols), at 12.2 GHz (square symbols), and for waves at both frequencies simultaneously (diamond symbols). In the latter case the DC measured power is increased by 3 to 5 dB over the simple sum of the first two cases.

Another measurement was performed to investigate the advantageous nonlinear properties of the rectennas, and is

Table 1: Nonlinear Power Combining

Horizontal Pol.	Vertical Pol.	Independent Sum	Dual Pol.
-12.1 dBm	-8.32 dBm	-3.97 dBm	0.0 dBm

summarized in Table 1, demonstrated on the spiral array. First a vertically-polarized wave of power P was incident on the rectenna and the rectified power measured in an optimal load. Then the rectified DC power resulting from a horizontally-polarized wave of equal power P was measured, and subsequently waves of both polarization with total power $2P$ were incident on the two arrays. The relative phase between the two waves was varied in order to achieve different elliptical polarizations for the total incident wave. The DC power produced in this case is on average (averaged over all relative phases) larger than the summ of the DC powers measured when only one linear polarization is present. This again is because the arrays are designed to rectify both polarizations, and power in one provides some biasing of the diodes, resulting in a nonlinear increase, as expected from the diode nonlinear IV curve.

C. Rectenna Array Optimal Load

As the incident RF power is increased, the efficiency increases, as expected. The optimal load for maximum delivered power decreases as a result of the fact that the derivative of the IV curve of the diode increases as the diode is biased by rectified RF power. Since the optimal load is given as the ratio V/I, Fig.5 shows the decrease in measured load impedance as a function of normalized incident power.

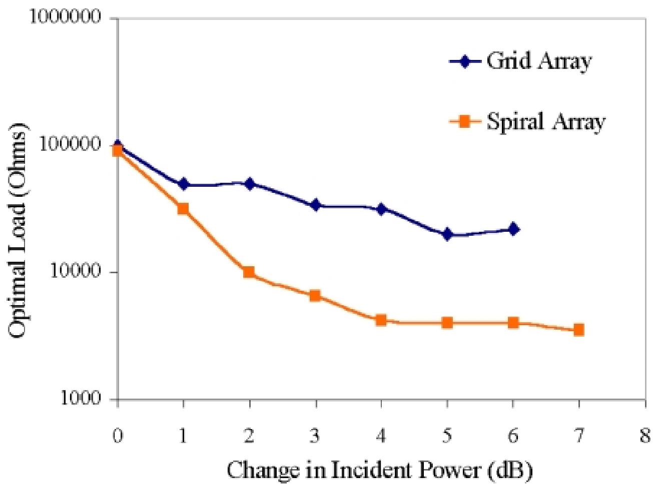

Fig. 5. Measured optimal load for maximum DC power transfer as a function of incident power for both the grid and the spiral rectenna arrays.

The maximal open-circuit voltage of the grid rectenna array was 3.5 V at 5.7 GHz, and the maximal conversion efficiency was calculated from measurements to be 35 % at 5.7 GHz and for 7.78 mW/cm^2. The maximal open-circuit voltage of the spiral rectenna array was 4.0 V at 10.7 GHz, and the maximal conversion efficiency was calculated from measurements to be 45% at 10.7 GHz and for 1.56 mW/cm^2.

IV. Discussion

This paper presents an experimental study of wideband rectenna arrays for arbitrarilly polarized input waves. The study is based on physical principles. A theoretical (numerical) investigation needs to combine sophisticated electromagnetic modelling of the passive antenna structure with nonlinear circuit modelling of the diodes, and is in progress. Some remaining issues related to the rectenna designs that we are also working on are: coverage of a very large frequency range, proper DC connections for very large arrays, conformal low-cost (flexible) rectenna arrays, and reliability and degradation.

The grid rectifiers have excellent reliability and graceful degradation. The limiting factor on the size of the grid rectifier is the current rating on the diodes. Note that in the grid in Fig.1a the four corner diodes are the most critical ones, because one half of the current through the DC terminals passes through each of the diodes. If these 4 diodes are replaced by shorts, the current in the DC leads can be twice as large. The current intensity in the next diodes closest to the terminals is half of that through the four most critical diodes. Any overloaded diodes in the grid are automatically eliminated if the fail as shorts, and the rest of the grid will function. If a diode fails as an open, the current will find a path through the other diodes/shorts across the grid.

V. References

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