An Experimental and Theoretical Characterization of a Broadband Arbitrarily-Polarized Rectenna Array

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Abstract— **Planar rectenna arrays for rectification of broadband electromagnetic waves of arbitrary polarization are designed and characterized. The performance of the arrays is accurately predicted using a combination of full-wave analysis for the passive part of the rectenna and harmonic balance simulations for the nonlinear rectification process. The arrays used in this paper to demonstrate the principles of operation consist of self-similar right-hand and left-hand polarized spirals which are simulated and measured over a 2.5:1 band (6-15 GHz). Two arrays with different diodes exhibit conversion efficiencies from 5 to 45% under monochromatic linearly polarized illumination with power densities from 1–1.6 mW/cm^2.**

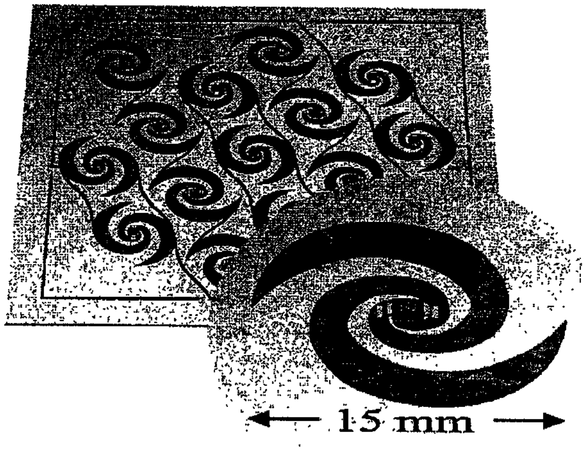

Fig. 1. Layout of a rectenna array using RHCP and LHCP spirals loaded with Schottky diodes.

I. Introduction

Microwave rectennas are active antennas containing rectification devices. 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 on up to millimeter-wave satellite communications. Interference between the antennas as well as health safety of operating personnel due to RF power densities exceeding FCC regulations are existing problems [1]. Additionally, the wave polarization changes as the waves propagate in such multi-path environments [2]. Microwave rectennas have been investigated in the past for power transmission and detection [3]. Applications have included long distance power beaming [4], [5], signal detection [6], and wireless control systems[7]. In all of these cases, the polarization, CW frequency, and power of the incoming RF field were not time varying, well defined, or known *a priori*. In this paper, we investigate the prospect of efficiently capturing power contained in fields with unknown and arbitrary time varying spectral distribution and polarization.

The spiral array shown in Fig. 1 is designed and characterized with incident waves over an extended frequency band and arbitrary polarization. The array consists of both right-hand and left-hand circularly polarized (RHCP and LHCP) antennas. In rectennas presented to date, a CW wave is incident on a resonant antenna, followed by a matching circuit that helps deliver the received power to a rectifying element, typically a Schottky diode. However, resonant antennas followed by matching circuits are narrowband (at

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most 15% fractional bandwidth). In the rectenna array presented here, resonant antennas and matching circuits are absent, and Schottky diodes load a nonresonant radiating array. The diodes are connected in a combined series-parallel DC circuit such that they provide self-biasing.

In previously demonstrated rectennas, the polarization of the incident wave is well defined and linear in most cases. This enables polarization-matching of the rectenna for maximized efficiency. We accomplish efficient rectification of such waves by independently rectifying two orthogonal polarizations (either linear horizontal and vertical [8] or RHCP and LHCP), and adding the rectified DC voltages and/or currents. The rectification process is nonlinear and we show that method-of-moments (MoM) simulations in combination with a harmonic balance (HB) circuit simulation can accurately predict frequency response, open-circuit DC voltage, conversion efficiency, and DC load dependence of the rectennas. A single element of the array is simulated by calculating the frequency-variable impedance of the spiral antenna using a MoM integral-equation solver (Zeland *IE3D*). Then two different diode nonlinear models are connected to a receiving antenna model and analyzed using a harmonic balance circuit simulator (Agilent *ADS*). The single elements are compared experimentally and the validity of the simulations is assessed. The simulations and experimental characterization of the entire array are found to agree within measurement error.

II. Rectenna Element

A single spiral element was simulated and the resulting frequency-dependent impedance is shown in Fig. 2. The two curves represent the impedance as seen from two different feed connection points, corresponding to a larger 2 mm (dotted line) and smaller 0.5 mm (solid line) diode package. The two diodes are a packaged M/A-COM beam-lead MA4E2054A and Metelics MSS20-146-B10D, respectively. The solid line approaches the theoretical 189 Ω impedance expected from a self-complementary antenna. The Duroid substrate with $\epsilon_r = 2.2$ is 0.5 mm thick, which is $\lambda/60$ at the center frequency. Simulations for the larger feed are very sensitive to particular feed placement and are not believed to be accurate representations of the actual diode placement and soldering location. Therefore, we demonstrate comparisons of simulations with measured results only for the Metelics diodes, which are small beam-lead packages and can be repeatedly connected to the 0.5 mm feed point.

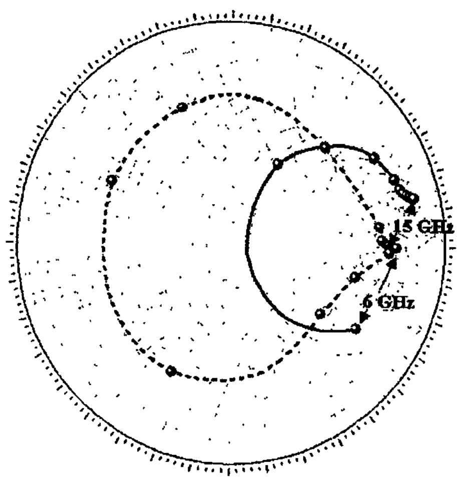

Fig. 2. Simulated impedance of the spiral antenna element for a 0.5 mm feed (solid line) and 2 mm feed (dashed line).

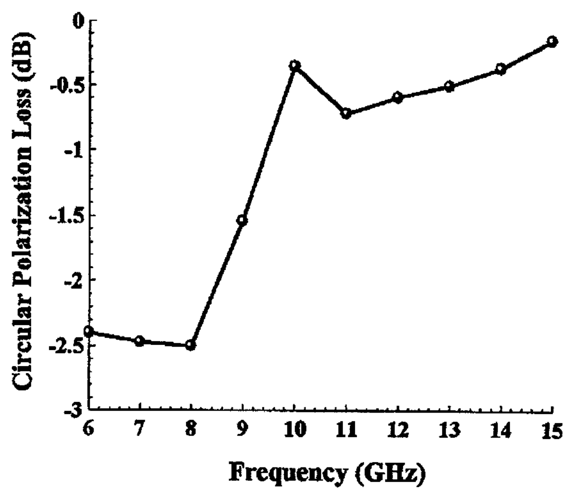

Fig. 3. Simulated loss in relative received power for a circularly polarized incident wave for the spiral antenna.

The polarization characteristics were simulated for the single spiral element, as shown in Fig. 3. The antenna element is nearly linearly polarized at the lower frequencies and becomes circularly polarized above 10 GHz. Theoretical analyses of a single and seven-element array were carried out using a nonlinear harmonic balance simulation. The basic circuit used for the rectenna element is shown in Fig. 4. The antenna element of the rectenna is modeled using a power source with variable CW frequency and source impedance. The source impedance corresponds to the simulated input impedance of the antenna. A DC block simulates the free space isolation between the

RF source and rectifying circuit. Finally, an inductor is used to model the two-wire line that connects the rectenna to the DC load. The harmonic balance simulations were carried out to seven harmonics of the input frequency, plus the dc component. The critical parameters in the simulation are the source impedance, which models the antenna, and the diode model. Spice parameters given by the manufacturer are used in the diode model for the Metelics MSS20-146-B10D diode. The results of the simulation compared with measurements are shown in Fig. 5 for a single element with linearly polarized incident wave and taking into account the simulated curve from Fig. 3 Close agreement is seen over a 2.5:1 frequency band from 6 to 15 GHz.

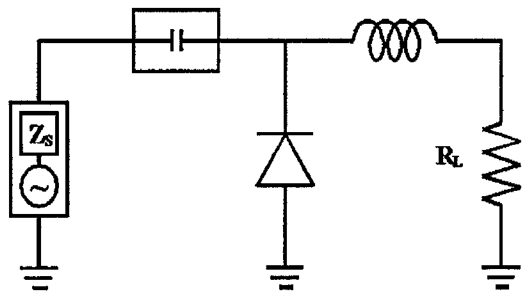

Fig. 4. Circuit model used in harmonic balance simulations. The diode is modeled with *Spice* parameters obtained from the manufacturer. The source impedance is found from the MoM code.

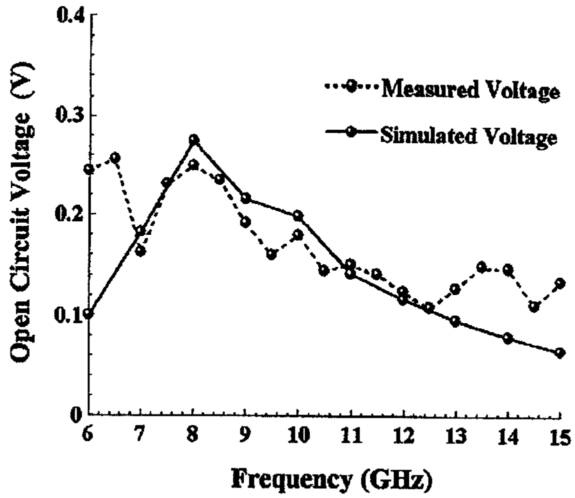

Fig. 5. Measurements and simulations of the open circuit voltage for the single rectenna element using the Metelics diode.

In order to assess the effect of diode parameters on rectenna behavior, an experimental comparison was made between the two diode types, each connected at the feed of identical spiral antennas. The main differences between the diodes are the size of the package and the turn-on voltage. The resulting comparison of open-circuit DC voltage for identical linearly-polarized input waves is shown in Fig. 6, which indicates that the diode with a lower turn-on voltage and smaller package results in broader rectenna bandwidth and larger rectified output voltage.

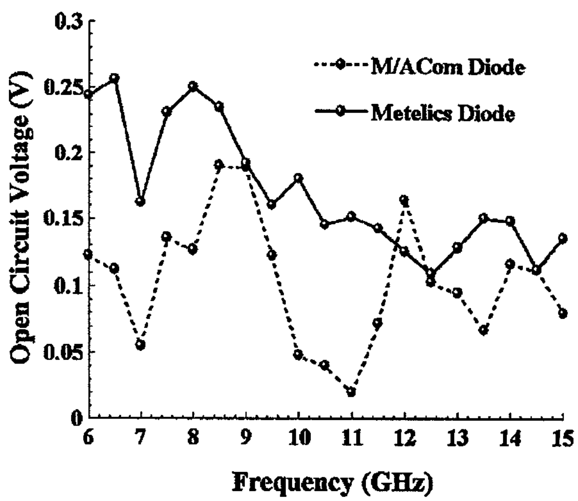

Fig. 6. Measured open circuit voltage over a 2.5:1 band for the two different diodes connected at the feeds of identical spirals.

III. Rectenna Array

The rectenna array from Fig. 1 consists of alternate right-hand and left-hand polarized self-similar spirals that are on the order of $\lambda_0/2$ in diameter at the center frequency of 10 GHz. The ends of the spiral arms are connected to high-impedance DC collection lines in a hybrid series/parallel configuration. The series connections are used to increase the rectified voltage by adding the voltages from several rectenna elements, while the parallel connections are used to increase the current with a goal of obtaining a convenient optimal DC load. In general, a rectenna array connected predominantly with series connections matches its output power to a higher load resistance. Alternatively, parallel connections lead to a comparatively low optimal load. Arraying the spiral elements does not significantly affect the frequency response of the rectenna as a whole. The simulation of the array is performed by combining copies of the circuit of Fig. 4 with the exception of the load resistor, which is common to each

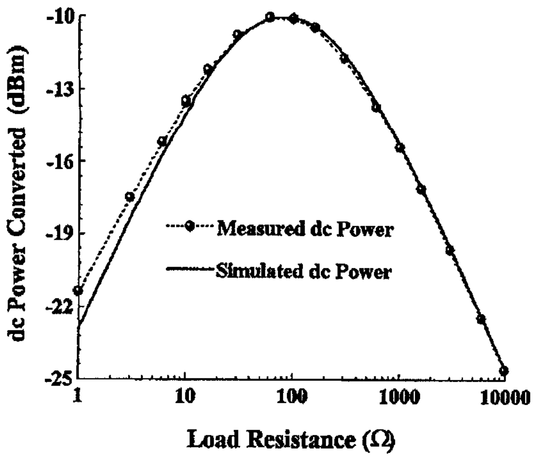

Fig. 7. Measured and simulated DC output power over four decades of load resistance for a seven-element array with linearly polarized incident power.

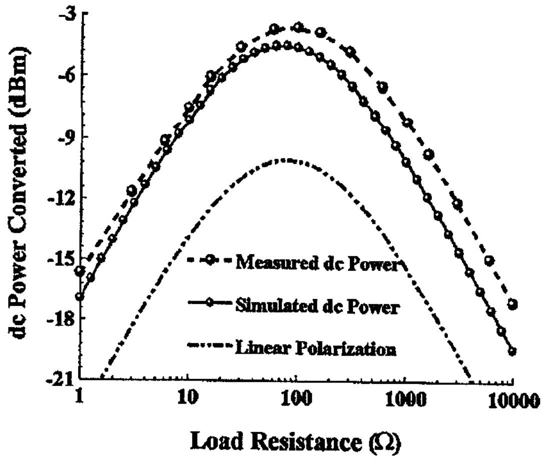

Fig. 8. Measured and simulated output power with circular polarization. The linear case (dashed) is repeated for comparison.

subcircuit. For series combinations, the anode of the first diode is removed from ground and connected to the cathode of the second. Parallel combinations are made by connecting the cathodes of each sub-circuit. In this preliminary work, the 15-element array was populated with seven diodes. The seven element array was fabricated and simulated with three series and four parallel elements.

Measurements were then taken on the seven-element array populated with the Metelics Schottky diodes. Array performance is demonstrated at a single frequency over a range of load resistance values. The optimal load for the rectenna array depends on the antenna impedance, the input power, and the diode nonlinear parameters. The simulations and measurements in Fig. 7 show the power delivered to DC loads from $1\,\Omega$ to $10\,k\Omega$ at 12 GHz with a linearly polarized input wave of $1\ mW/cm^2$. There is close agreement between measured and predicted values with slight discrepancy at the lower resistance levels where series resistances of contacts is believed to affect the measured results. The curves in Fig. 8 show the simulated and measured results under the same operating conditions with the exception that the field is circularly polarized, rather than linearly. In this case the antenna element receives 2.5 dB more power than the linear case, according to MoM simulations as seen from Fig. 3. Since the DC conversion is also a nonlinear function of input power, the gain in output DC power is expected to be greater than the 2.5 dB increase in received power by the antennas. The results of Fig. 8 demonstrate a measured increase of 6 dB and predicted increase of 4 dB, as compared to the linearly polarized case (dashed line). In summary, by comparing simulations with measurements, we show that nonlinear behavior of arbitrarily polarized broadband rectenna arrays can be predicted using a combination of a MoM and harmonic balance circuit simulation. The method will be used in future work to optimize broadband rectenna arrays for efficiency and specific load conditions.

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