OPTIMIZATION OF THE EFFICIENCY AND OTHER PROPERTIES OF THE RECTENNA ELEMENT

William C. Brown
Raytheon Company
New Products Center
Waltham, Massachusetts 02154

Abstract

The rectenna which captures and rectifies the microwave power at the receiving end of a free space microwave power transmission system is comprised of many elements consisting of halfwave dipoles with microwave filter and rectification circuits attached. This element has been independently optimized for efficiency and analyzed for losses. The paper describes the device, the special test equipment used, the results of the mathematical modelling and computer simulation, special low loss Schottky barrier diodes that have been constructed to improve the efficiency, and life tests that have been made on these devices. An efficiency, defined as the ratio of DC power output to incident microwave power, of over 90% has been achieved.

Introduction

In a free-space microwave power transmission system, an efficient and directionally non-critical device for capturing and rectifying the microwave power at the receiving point is the "rectenna".[1] A common form of the rectenna consists of a large array of rectenna elements, each comprised of a half-wave dipole, suitable input filters, and a rectifier circuit. The outputs of the rectifiers can then be combined into one or several loads without loss of efficiency. A laboratory version of such a rectenna is shown in Figure 1.

The capability of the rectenna to absorb the incident radiation approaches 100 percent efficiency so that the overall efficiency of the rectenna array is critically dependent upon the efficiency with which the received microwave power is converted into DC power within the rectenna element itself. The overall rectenna element efficiency has been increased from 50% to over 90% since its introduction, as shown in Figure 2.

Much of the recent interest in the development of the rectenna element has resulted from the concept of transmitting large amounts of solar-derived electrical power from space satellites to the earth.[3] For this application, literally billions of these elements are necessary, and requirements for high-efficiency and low-cost manufacture are basic. Recent activity therefore, has focused on optimizing the efficiency of structurally simple elements as shown in Figure 3 which employ but a single Schottky barrier diode in a half-wave rectifier circuit.

Efficiency optimization requires adequate measurement techniques and facilities and an insight into the detailed behavior of the complex electrical device which can be obtained from mathematical modeling and computer simulation.

Measurements of Efficiency and Losses Of Rectenna Element

Confidence in efficiency measurements of the rectenna element requires an accurate measurement of the microwave power input, the DC output, and the major losses in the device. The cell area occupied by the rectenna element in the rectenna may be simulated by a closed test fixture so that the efficiency of the rectenna element and the matching to it can be studied independently of the rectenna. Two kinds of test fixture are used. The one normally used is an expanded waveguide fixture to simulate directly the cell area for the rectenna element, which is balanced structure with respect to the ground plane. The other is a special test fixture which splits the element in half so that a ground plane may be used and the element may be tested with a coaxial input. The ground plane is a heavy plate into which special kinds of instrumentation may be attached without affecting the performance of the element.

An important form of instrumentation associated with the ground-plane test fixture is a thermistor bridge with which the losses in the diode may be measured. The output voltage of the thermistor bridge is calibrated with measured DC power input, and the valid assumption is made that the heat sinking of the microwave power and of the DC power are identical. In this manner, the dissipation of microwave power in the diode can be measured to within 1%, or within 0.1% of the microwave input into the rectenna element.

It is now possible to prepare a "balance" sheet in which the microwave power whose calibration is traceable to the National Bureau of Standards is compared with the total sum of the DC power output, the power dissipated in the diode, and an estimate of other circuit losses based in part on measurement. This balance, which is within 1% over a power range of one to eight watts is shown in Figure 5. Figure 5 also shows the various percentages of the absorbed power which are presented by DC power output (rectenna element efficiency), diode losses, and circuit losses. The diode losses are seen to vary from 8% at high power levels to over 30% at the lowest power levels measured. The same diode and the same circuit impedance were used.

Computer Simulation of the Rectenna Element

The computer simulation program[4, 5] provides a great deal of detailed information about the behavior of the rectenna element. The associated mathematical model is identified as a cascade of lumped-element circuit meshes in which the diode appears as a highly non-linear circuit element with the variation of both its internal resistance and capacitance with impressed voltage being adequately accounted for. The mathematical model breaks down any sections of transmission line with distributed parameters into a sufficient number of cascaded circuit sections of lumped-circuit elements to make the model valid at frequencies about six times the fundamental. A simplified version of this network is shown in Figure 6. The time behavior of certain current and voltages identified in Figure 6 appear in Figures 7 and 8. The data indicate a conduction period of about 110 degrees, an unspiked current flow during the conduction period, and a relatively uncomplicated behavior of the voltage impressed across the diode.

The computer simulation program also has direct readouts of diode dissipation, other circuit losses, and DC power output. The results for the simulation of the ground-plane model are shown in Figure 5. There is generally good agreement between the experimental measurements and the predictions of the computer simulation program.

Development of an Efficient Diode Rectifier

The development of the GaAs Schottky barrier diode[6] as a high power rectifier has contributed significantly to the improved efficiencies shown in Figure 1. Losses in the diode result directly from (1) the voltage drop across the Schottky barrier itself (which is equivalent to the brush drop in a DC motor) and (2) the series resistance which is a function of the contact area and the thickness and doping density of the epitaxial layer. GaAs has an advantage over other materials because of its lower resistivity. An optimum diode and rectenna design involves the tradeoff between losses in the Schottky barrier, losses in the series resistance during the conduction period, and losses in the series resistance during the non conduction period (which occur because of charging current to the diode capacitance) and results in a specification of the junction area, the doping density of the epitaxial material, and an impedance operating level. The optimum design is different for each power level.

At the higher power levels shown in Figure 4, a diode design having a doping density corresponding to a V_{br} of 60 volts and a zero-bias capacitance of 3.7 picofarad, and an impedance level of 120 ohms provides an optimum efficiency. At low power levels, the Schottky barrier losses become so predominant that operation at a higher impedance level is mandatory and the materials used in the junction become important. A GaAs-W Schottky barrier is to be preferred to a GaAs-Pt because of its significantly lower voltage drop.

Rectenna Element Life Test Evaluation

Another essential requirement for most applications of the rectenna is long life and high reliability. For this reason, the rectenna shown in Figure 1 has been used to run an interesting life test in which the elements at the center of the 100 rectenna element array have been run at the 8-10 watt level while those on the edge have been run at only 0.2 watt, because of the Gaussian illumination pattern of the incoming microwave beam. Over 800,000 diode hours have now been accumulated, corresponding to over 4000 hours of array operation. The results of this life test are shown in Figure 9. Since the first 150 hours of operation, only five diodes have failed, and four of these failures occurred simultaneously under high overload caused by operator error.

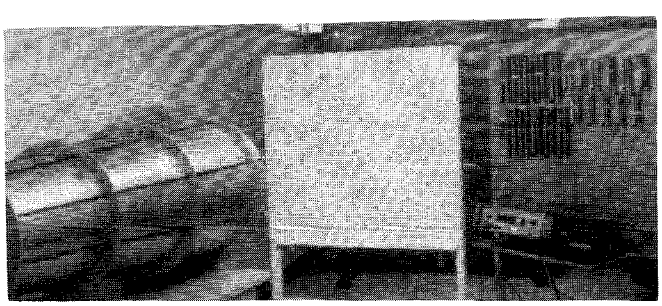

Figure 1. A laboratory type rectenna containing 199 rectenna elements, each consisting of half-wave dipole and rectification circuit. Also used for life test.

Acknowledgements

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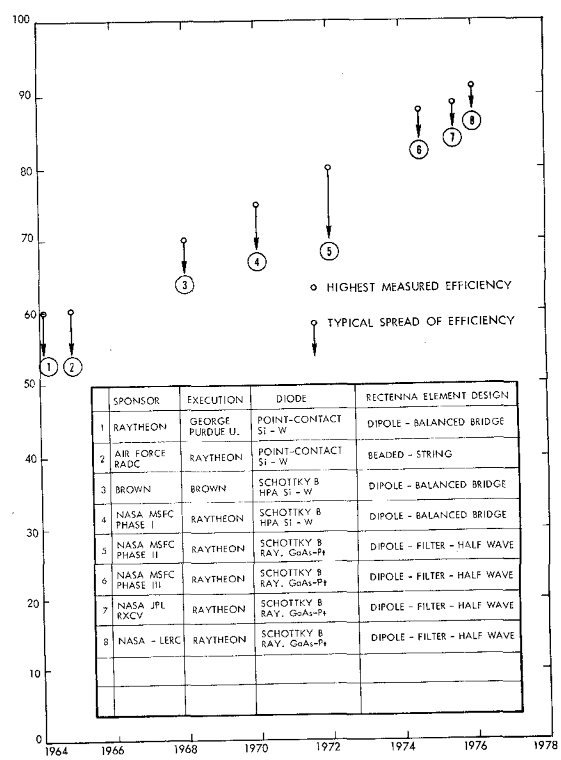


	SPONSOR	EXECUTION	DIODE	RECTENNA ELEMENT DESIGN
1	RAYTHEON	GEORGE PURDUE U.	POINT-CONTACT Si - W	DIPOLE - BALANCED BRIDGE
2	AIR FORCE RADC	RAYTHEON	POINT-CONTACT Si - W	BEADED - STRING
3	BROWN	BROWN	SCHOTTKY B HPA Si - W	DIPOLE - BALANCED BRIDGE
4	NASA MSFC PHASE I	RAYTHEON	SCHOTTKY B HPA Si - W	DIPOLE - BALANCED BRIDGE
5	NASA MSFC PHASE II	RAYTHEON	SCHOTTKY B RAY. GaAs-Pt	DIPOLE - FILTER - HALF WAVE
6	NASA MSFC PHASE III	RAYTHEON	SCHOTTKY B RAY. GaAs-Pt	DIPOLE - FILTER - HALF WAVE
7	NASA JPL RXCV	RAYTHEON	SCHOTTKY B RAY. GaAs-Pt	DIPOLE - FILTER - HALF WAVE
8	NASA - LERC	RAYTHEON	SCHOTTKY B RAY. GaAs-Pt	DIPOLE - FILTER - HALF WAVE

Figure 2. Progress in optimizing efficiency of rectenna element

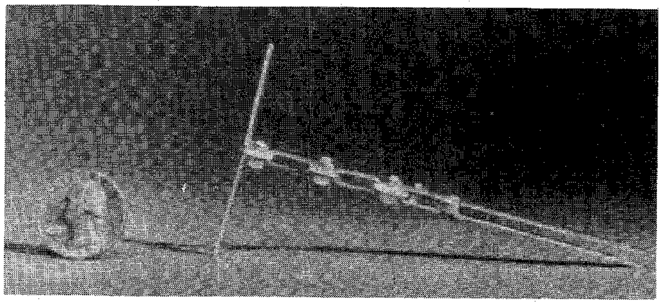


Figure 3. Rectenna element consisting of half-wave dipole, two-section low pass filter, Schottky-barrier diode, and rectification circuit

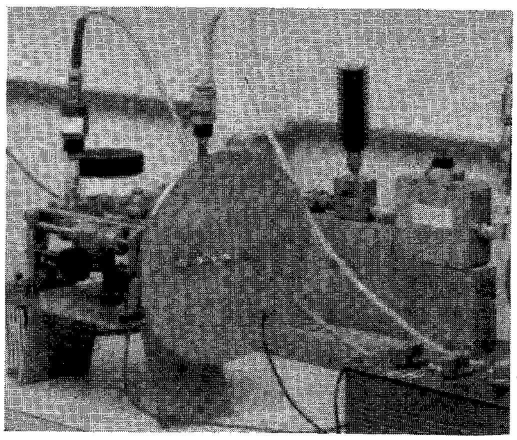


Figure 4. Ground-plane test fixture coupled to 50-ohm coaxial input. In operation, the element being tested has an rf shield over it.

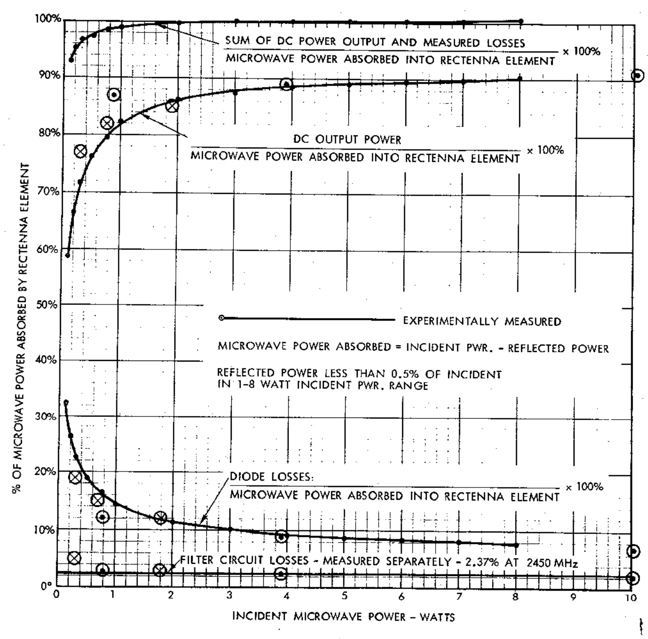


Figure 5. Experimental and computer simulation data for efficiency in RXCV rectenna element using ground-plane test fixture.

• Experimental data
⊙ Computer simulation with theoretical diode
⊗ Computer simulation using measured diode characteristics

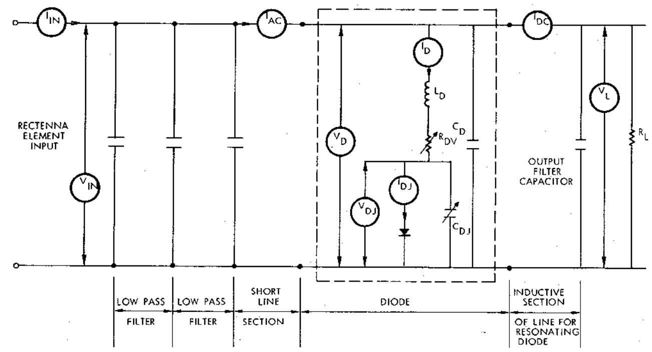


Figure 6. Simplified math-model schematic diagram for computer simulation

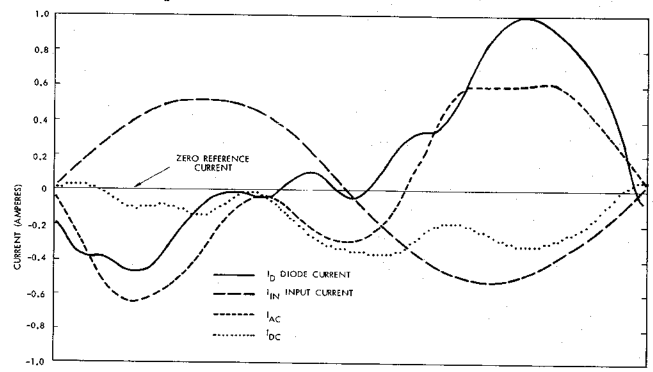


Figure 7. Time behavior of input current to rectenna element, diode current, microwave filter output current, and input current to rectifier tank circuit, as computed

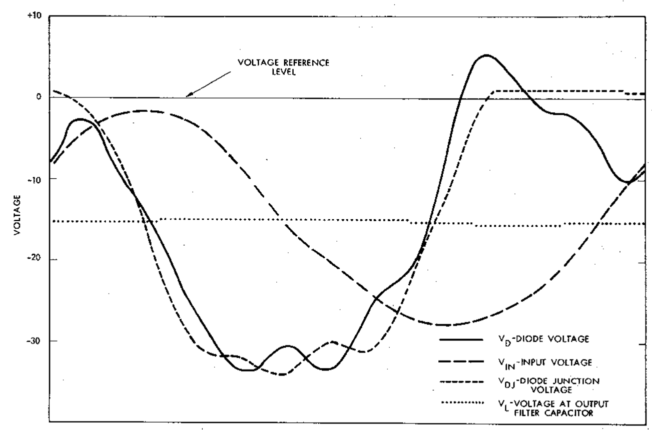
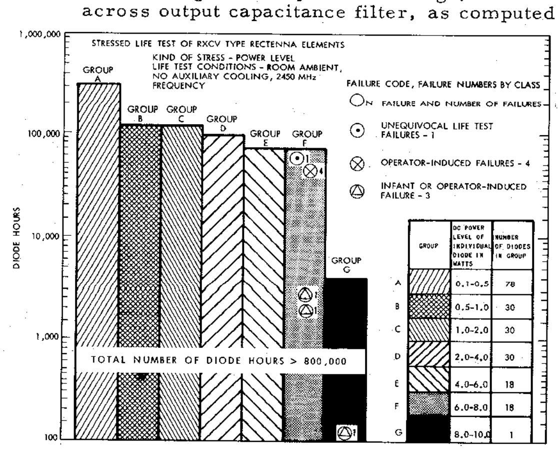


Figure 8. Time behavior of input voltage to rectenna element, diode voltage, diode junction voltage, and voltage across output capacitance filter, as computed



GROUP		DC POWER LEVEL OF INDIVIDUAL DIODE IN WATTS	NUMBER OF DIODES IN GROUP
A		0.1-0.5	78
B		0.5-1.0	30
C		1.0-2.0	30
D		2.0-4.0	30
E		4.0-6.0	18
F		6.0-8.0	18
G		8.0-10.0	1

Figure 9. Diode life test results using Test arrangement shown in Figure 1