PERFORMANCE CHARACTERISTICS OF THE THIN-FILM, ETCHED-CIRCUIT RECTENNA

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ABSTRACT

Measurement of DC power output, temperature rise of the rectifying diode as measured with the fluoroptic temperature probe, and efficiency have been made on the thin-film, etched-circuit rectenna foreplane as a function of incident microwave power and velocity of laminar air flow parallel to rectenna. When the rectenna is illuminated with 2.45 GHz microwave power, DC power output densities of 1 kw/M^2 and DC power to weight ratios of 4 kw/kg have been obtained with air velocity of 10 ft/sec at sea level density and diode temperature rise of 100°C.

INTRODUCTION

A rectenna is the device used at the receiving end of a free space microwave power transmission system to absorb the incident microwave energy and to convert it into DC power. The device performs both of these functions with a high overall efficiency of 85% to 91% depending upon power level densities and construction format. It also has directive properties similar to a half wave dipole so that large aperture areas show little change in capture efficiency over substantial variations in angle of arrival of the incoming microwave power.

For 100% collection efficiency the rectenna must be a two-plane system but all of the microwave circuitry, rectification, and DC bussing can be carried out in the foreplane depicted in Figure 1. The other plane is the reflecting plane, a metallized surface approximately one quarter wavelength behind the foreplane.

From a circuit point of view (see Figure 1), the rectenna foreplane consists of a large number of repetitive circuits called "rectenna elements," all joined together by transmission lines that serve to collect the DC power from the individual elements and to conduct the power to the edges of the array. At certain locations along their length those collecting busses also serve as short sections of microwave transmission line representing inductances in low-pass filter circuits and in the rectifier tank circuits. The transmission lines also serve to radiate and conduct away heat generated in the diodes during the rectification process. (See Reference 1 and 2 for circuit details.)

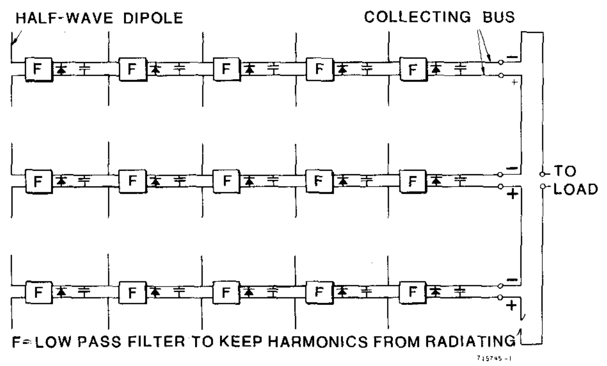

Fig. 1. Circuit schematic of rectenna foreplane. It carries out the functions of microwave power collection, microwave filtering, rectification, and DC power conduction.

The thin-film, etched-circuit rectenna foreplane is a new, light weight, flexible format designed for use on aircraft or space vehicles.[1,2] As shown in Figure 2, it weighs 0.25 kilogram per square meter. It can produce conservatively one kilowatt of DC power output per square meter when used on an airplane wing for a power to weight ratio of 4 kw/kg. It is highly flexible and can be wrapped around small diameter rolls for ease of storage and for deployment in space. The rectenna is designed for use at 2.45 GHz. The rectenna element density is 200 elements per square meter.

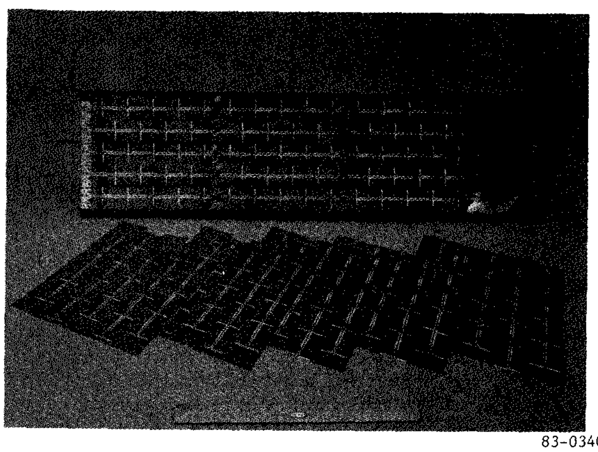

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Fig. 2. Five 25-element thin-film, etched-circuit rectenna sections and a rectenna covered airplane wing are exhibited.

Figure 3 indicates the construction of the thin-film, etched-circuit rectenna foreplane. Most of the etched circuitry is on the top surface. Only etched areas for the bottom plates of the capacitors are on the bottom surface. Kapton F is used for the dielectric material because of its resistance to deterioration from ultra violet light, its high temperature tolerance, and its low loss dielectric properties.

The diode is mounted across the transmission line (Figure 1) at the appropriate location.

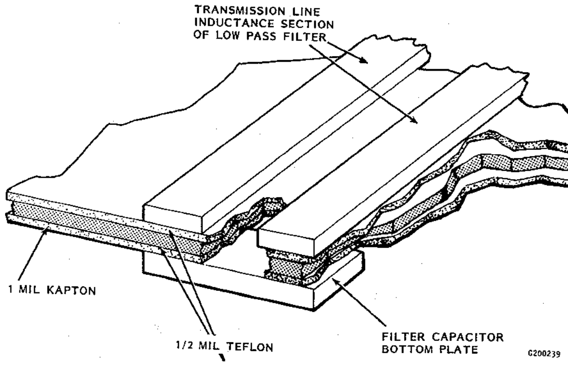

Fig. 3. Rectenna element construction in region of capacitor for low-pass filter section. Low dielectric losses in the film are critical to high efficiency.

Test Arrangement and Test Results

This paper discusses test results on power handling capability and efficiency of the rectenna foreplane when subjected to low-velocity convective air cooling at sea level air densities. These conditions are equivalent to cooling obtained at typical airplane flight speeds and air densities at altitudes of 40,000 feet and more.

The tests were made with the test configuration shown in Figure 4. The velocity of the air stream flowing across the rectenna was calibrated with a hot wire anemometer. The temperature of the diode was monitored during operation with a probe of a fluoroptic thermometer that was mounted at the diode case with precaution to shield the probe from the air stream. The great advantage of the fluoroptic thermometer is that it does not interact with the microwave field and does not conduct heat away from the source it is measuring.

It must be noted that this test arrangement does not allow accurate measurement of the capture efficiency of either the 25 element rectenna or the single element. The unknown edge effects are much too large for this purpose. However, it has been well established from other research that the experimentally measured capture efficiency approaches the 100% theoretical capture efficiency to within 1%.(3) The tests reported here were for the purpose of establishing the power handling capability of the rectenna under typical operating conditions encountered in an airplane or balloon.

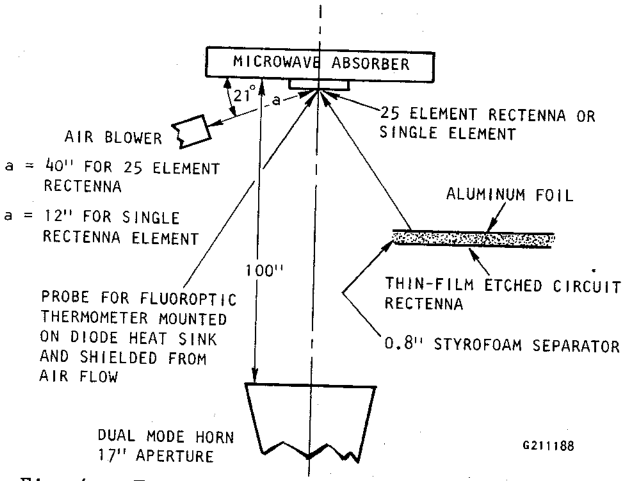

Fig. 4. Test arrangement for measuring DC power output and diode temperature rise of 25 element or single element rectenna as function of laminar air flow velocity and incident mircowave power.

A number of tests were made with the test arrangement of Figure 4. The first test was a measurement of one of the 25 element rectenna foreplane sections in Figure 2. The airstream flow was set at 15.8 ft/sec (10.8 mi/hr). The incident microwave power was varied and the total DC power output and the temperature of the diode of the central rectenna element observed. The data is shown in Figure 5. The total power output of 123 watts corresponds to an average of 4.9 watts for each of the 25 diodes. The highest diode temperature of 88°C is far below the 200°C operating temperature considered safe for GaAs diode operation.

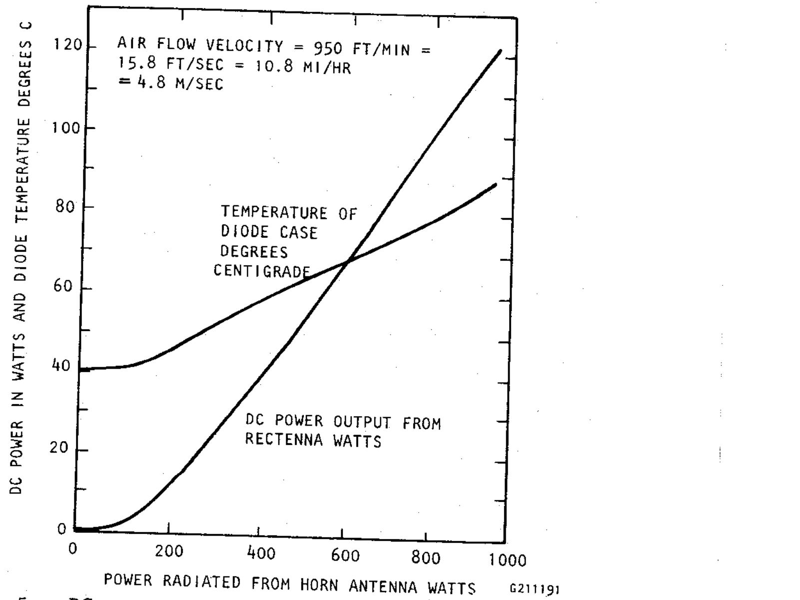

Fig. 5. DC power output of 25 element rectenna and case temperature of center diode as function of total power radiated.

The second set of tests was made on a single rectenna element. The tests were divided into two parts. The first part did not make use of microwave power. Instead, a known amount of DC power was injected into the diode to be dissipated in the diode. The temperature rise of the diode was then observed as a function of the air velocity of the cooling stream and the DC power dissipated in the diode. These data are shown in Figure 6(a).

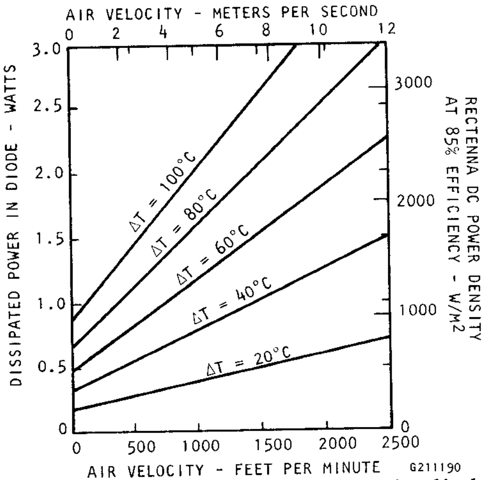

Fig. 6. (a) Power dissipated in single diode as function of air velocity and diode temperature (b) Rectenna DC power density at 85% efficiency.

The second part involved illuminating the diode rectenna element with different amounts of microwave power. The temperature rise of the diode was again noted as a function of the air velocity and the DC power output.

The temperature rise in the diode could now be used for two purposes. From the first set of data as given in Figure 6(a) the power dissipation in the diode could be determined. From the second set of data the DC power output for the same temperature rise could be noted. Since nearly all of the dissipation of the rectenna element takes place within the diode, the efficiency of the rectenna element can be approximated by the following expression.

$$\text{Rectenna Element Efficiency} \cong \frac{\text{DC Power Output}}{\text{DC Power Output} + \text{Power Dissipated in Diode}} \quad (1)$$

With data obtained in this manner the efficiency of the rectenna elements is shown as a function of DC power output and DC load resistance in Figure 7.

The data in Figure 6(a) can be used to develop equation 2 for diode dissipation as a function of air velocity and temperature rise of the diode case. The equation has two components. One component is that associated with convective cooling. The other is associated with residual cooling at zero air velocity and is assumed to be largely radiative cooling. Note that the linearity of the data and the low Reynolds number associated with the air velocity indicates laminar air flow at all time.

$$W = 1.125 \times 10^{-5}\Delta T_1 V + 0.009\Delta T_2, \text{ where} \quad (2)$$

W = power dissipated in diode

V = air velocity in feet per minute

ΔT_1 = increase in temperature of diode case above ambient air temperature

ΔT_2 = increase in temperature of diode case above temperature of sink for radiated power

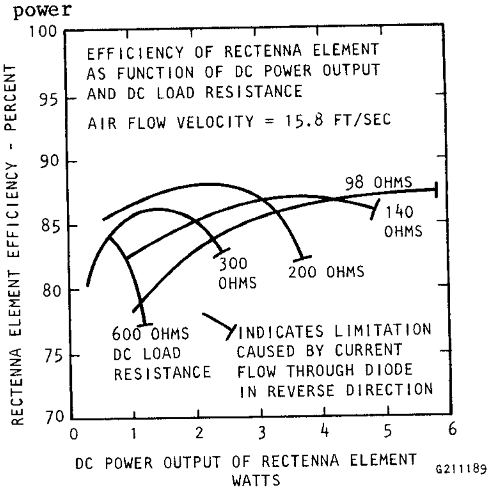

Fig. 7. Efficiency of rectenna element as function of DC power output and DC load resistance.

Now if we know or make an estimate of what the rectenna element efficiency, n, is then we can multiply equation (2) by the factor $n/1-n$ to obtain the DC power output of each rectenna element. For an assumed efficiency of 85%, a typical value for the rectenna element operated in the one to five watt output region, this factor will be 5.7. The corresponding DC power for one square meter which contains 200 elements is shown in Figure 6(b) as a function of air velocity and diode temperature rise.

Equation (2) was derived from experimental data using mass flow rates of air at sea level density. If the term V in equation 2 is replaced by $V\rho/\rho o$ where V and ρ are the air velocity and air density at any altitude and ρo is the air density at sea level, the resulting expression is applicable to any altitude, and can therefore be applied to high altitude airplanes or balloons.

Conclusions

The new thin-film etched-circuit rectenna format has been evaluated for its power handling capability and a generalized expression developed for its application to microwave powered high altitude aircraft.

Acknowledgements

The technology development reported upon has been supported by the National Air and Space Administration through its Lewis Research Center and Wallops Flight Center.

References

1. W. C. Brown, "Experimental Thin-Film, Etched-Circuit Rectenna", Paper K-4, Digest of 1982 IEEE MTT-S Int'l Symposium IEEE Cat. No. 82CH1705-3.
2. "Design Definition of a Microwave Power Reception and Conversion System for Use on a HAPP," NASA CR 156866, March 1980.
3. W. Brown,"Electronic and Mechanical Improvement of the Receiving Terminal of a Free-Space Microwave Power Transmission System,"Raytheon Contractor Report PT-4962 NASA CR-135194, Aug 1977.