EXPERIMENTAL THIN-FILM, ETCHED-CIRCUIT RECTENNA

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ABSTRACT

The design and experimental evaluation of a 2.45 GHz thin-film etched-circuit rectenna based upon the use of Mylar or Kapton F film is discussed. Efficiencies of 85% and DC power output to mass ratios of one watt per gram have been achieved.

INTRODUCTION

"Rectenna" is a functional abbreviation of the terms "rectifier" and "antenna" that denotes a special class of receiving antenna used in free-space microwave power transmission systems.

The rectenna is made up of contiguous receiving cells each smaller in dimension than a wave length and each terminated with a rectifying device. The output DC power then flows into a common load resistance. The resulting structure has a theoretical capture efficiency of 100% while maintaining a directivity that is characteristic of the aperture of a single cell. The rectenna has a long development history and has now reached an overall efficiency level (incident microwave power to DC power out) of over 85%.

From a structure point of view the rectenna was first developed along the lines of individual bar-type elements that plugged into DC collecting busses. More recently the bar type elements have been joined to each other as shown in Figure 1 to form the foreplane of a two-plane rectenna format in which the other plane is a simple flat metallic reflector.[1] The foreplane carries out the functions of power collection, filtering, rectification, and DC power bussing. It is a stand-alone microwave structure in most respects. However, it needs the help of a reflecting plane to enable it to absorb all of the incident microwave power.

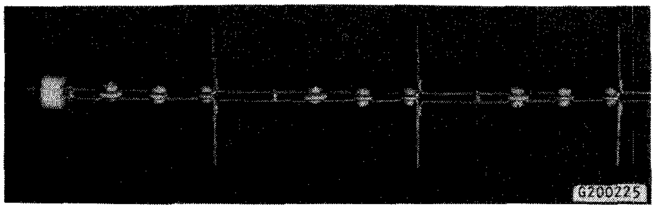

Fig. 1. State-of-the-art of the rectenna foreplane prior to thin-film, etched-circuit format.

The two-plane, bar-type construction is quite satisfactory for many applications. However, for microwave powered platforms in the earth's atmosphere and for space operations, a different type of construction is needed to maximize the ratio of power handling capability to mass. Lower construction cost is also an objective.[2,3]

This paper describes a new foreplane construction format that is based upon the use of etched microwave circuits on two sides of a thin film of insulating material, and discusses the properties and test results of a specific design at 2.45 GHz. The appearance of this new format is shown in Figure 2.

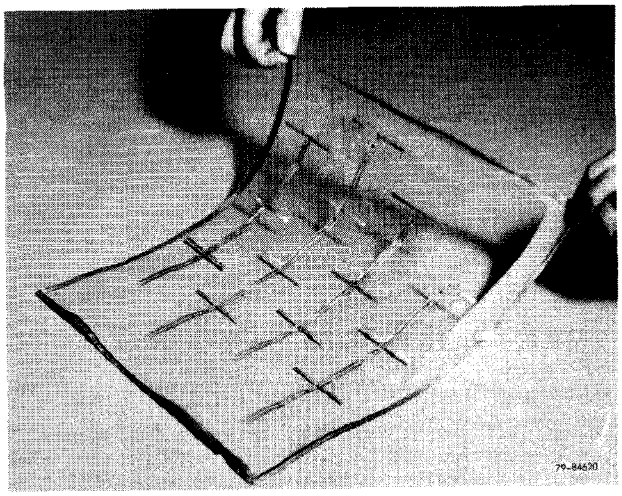

Fig. 2. Rectenna foreplane made in the new thin-film etched-circuit format. Film used was one mil Mylar with adhesive bonding it to copper circuits 1.4 mil thick.

Rectenna Description and Operation

The rectenna using the new format of Figure 2 is fabricated from a laminated material consisting of a thin film of dielectric material of suitable electrical and mechanical properties, bonded between two thin sheets of 1 once copper (1.4 mil thick). Art work and masks for the microwave circuits are made for both faces. Standard photoetching processes, without the need to provide for interconnects between the two surfaces, are used to produce the rectenna foreplane shown in Figure 2. One of the two forms of packaged diodes shown in Figure 3 is then bonded to the etched circuit, one per each repetitive cell.

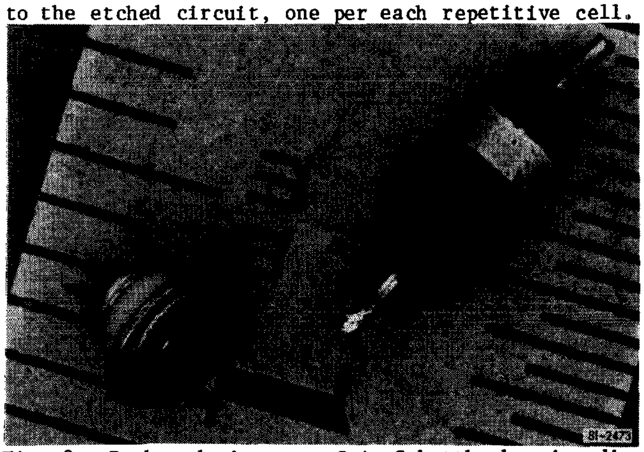

Fig. 3. Packaged microwave GaAs Schottky barrier diodes used on the thin film rectenna. Both miniature glass and ceramic packages were used.

From a circuit point of view (see Figure 4), 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. There the circuit connections may be either in series or parallel, depending upon the laod conditions. 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.

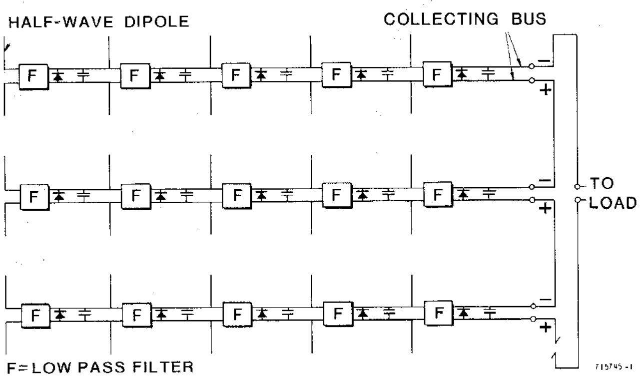

Fig. 4. Circuit schematic of rectenna foreplane. It carries out the functions of microwave power collection, microwave filtering, rectification, and DC power conduction.

In more detail, each rectenna element consists of a two-stage, low-pass filter, followed by a rectifier circuit. The rectifier circuit consists of a single diode, a section of microwave transmission line, and large bypass capacitor whose physical location from the diode determines the length, and therefore the equivalent inductance of the transmission line. The bypass capacitor also serves to filter out harmonic components from the DC power collecting busses. Finally, it serves to effectively short a quarter wavelength section of transmission line to the left (in Figure 4) of each dipole antenna and thus prevents coupling of power from the antenna to the adjacent rectenna element. This simplifies understanding the rectenna and permits a testing procedure involving only one rectenna element.

The low-pass input filter serves a number of functions. It serves as a buffer between the half-wave rectifier circuit and the antenna, storing energy, and making the rectenna appear as a constant impedance to the microwave beam. This buffering is essential to obtaining the high overall efficiency of 85%. The lowpass filter also serves to attenuate the flow of harmonic power from the rectifier circuit to the dipole antenna. The second section of the input filter is also frequently used as an impedance matching device, particularly at low microwave input levels where it is desirable to use a higher DC load resistance to reduce the impact of the voltage drop across the Schottky barrier upon efficiency.

The necessity for the rectenna to passively radiate any heat that is generated through any operational inefficiency stresses the desirability of both highly-efficient operation and operation at high temperature; the latter because of the 4th power relationship between the quantity of heat radiated and the temperature. These considerations have resulted in a decision to use the GaAs Schottky barrier diode because of its higher efficiency and ability to operate at high temperatures. Special heat-sink GaAs diodes have been developed for this application. These diodes are currently packaged but it is anticipated that eventually the passivated chips will be bonded directly to the copper conductors to reduce both cost and weight.

Rectenna Weight and Power Handling Capability

Each rectenna element, in the most recent format of 2 mil Kaption F film, weights 0.8 grams. Each element can conservatively produce two watts of power to provide a power output-to-weight ratio of 2.5 kilowatts per kilogram. This should conservatively translate into one kilowatt per kilogram for the entire rectenna when the reflecting plane and spacers are added. Since each rectenna element occupies about 50 square centimeters, the ratio of power output to area of the rectenna is 400 watts per square meter.

If it were desired to operate the rectenna at lower power densities and still retain the ratio of one kilowatt per kilogram, the present design could be changed in a number of ways to reduce weight of the foreplane per unit area. Or, as might be the case in microwave powered high altitude aircraft, the rectenna could be deployed to have some forced convective cooling and thereby greatly increase the amount of power that could be handled by each rectenna element. The present limitation of two watts per element is based upon radiation cooling into a 30°C environment.

Test Arrangements and Results

It is customary to develop a new rectenna approach at the single rectenna element level. The resulting design can then be incorporated into the full scale rectenna. The testing of the rectenna element is done in a closed system where the incident and reflected microwave power can be accurately measured in addition to the DC power output. As shown in Figure 5, the individual rectenna element is mounted about two centimeters from the inside surface of a door which can be closed over the end of an expanded waveguide. Microwave energy propagated down this waveguide then simulates free space radiation of the rectenna element. Efficiency measurements can be made to a probable error of about 1.5%.

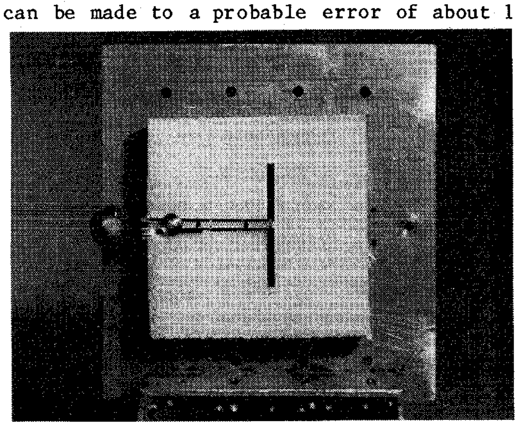

Fig. 5. Testing of rectenna element in closed system. Element is mounted one inch above metallic door which serves a reflecting plane. Door is then closed over end of expanded waveguide section which simulates a free-space environment. Incident and reflected microwave power can be accurately measured. Other measured parameter is DC power output.

Figure 6 shows efficiency test results of the rectenna element as a function of the absorbed microwave power level for two types of film, Mylar and Kapton F. The efficiencies given in Figure 6 should be interpreted as the efficiencies of the rectenna element because the inefficiency caused by mismatch and associated reflected power has been subtracted to give the power absorbed by the rectenna element. However, over a wide range of incident power levels, the load resistance can be changed to result in a good match of the rectenna element to the incident power.

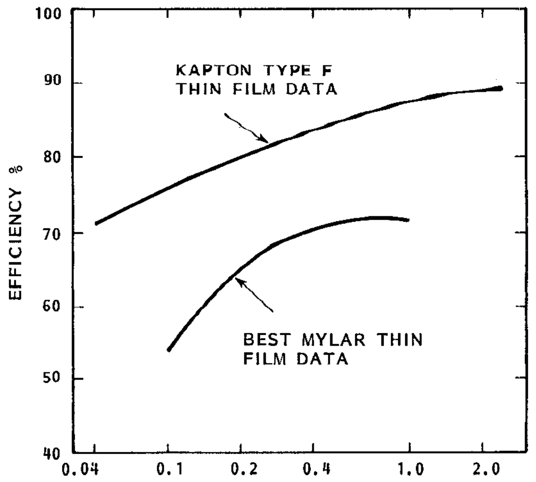

Fig 6. Rectenna element efficiency as function of absorbed power for two different dielectric films, Mylar and Kapton F. Shown are composite data for different load resistances. Reflected power for some data points is less than 3%.

The high efficiency of 85% at the higher input power levels, shown in Figure 6 for the Kapton F film, are particularly pertinent to high power because the power inefficiency that has to be radiated away in the form of heat is low while the Kapton material along with the GaAs diode can operate at high temperatures.

The substantial differences in efficiency between the Kapton and Mylar films correlates well with dielectric loss measurements made on the two films. The dielectric loss in the film affects the rectenna element efficiency mainly through its use in the capacitors in the low-pass filters (see Figure 7). The loss is especially evident at the low input power levels, where it is necessary to operate at higher load resistance to minimize the impact of the Schottky barrier voltage drop upon efficiency. But this increases the corresponding voltage across the filter capacitors and the losses are correspondingly greater.

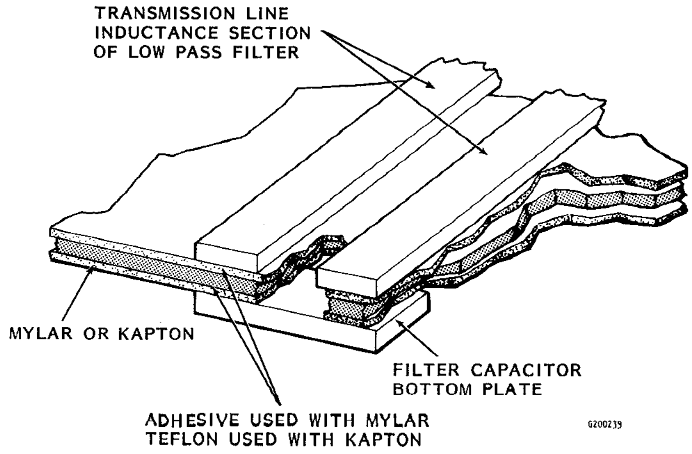

Fig. 7. Cutaway view of rectenna element construction in region of capacitor for low-pass filter section. Low dielectric losses in the film and adhesive are critical to high efficiency.

It was suspected and confirmed that the dielectric loss of the adhesive used to bond the copper to the Mylar was large, but it was also found that the loss in the Mylar was significantly higher than stated in the literature. On the other hand, the loss in Kapton was found to be relatively low and the Teflon used as the adhesive further reduced the composite loss in the dielectric.

Kapton and Teflon laminate is also thermally superior to Mylar, so that the diodes can be operated at a higher temperature and more heat can be radiated from the structure to increase the power rating of the rectenna. If the rectenna foreplane should be exposed to the sun (as is expected in many applications), the Kapton's high resistance to deterioration from ultraviolet radiation would make it more suitable than Mylar.

Conclusions

A new rectenna format, making use of a thin dielectric film and etched copper circuits that are bonded to the film, has been developed. The efficiency and the ratio of power handling capability to weight are high. Anticipated applications are in microwave powered high altitude atmospheric platforms and for power transmission in space.

Acknowledgements

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