A 35 GHz Extremely High Power Rectenna For The Microwave Lightcraft

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Abstract. A rectenna has been designed to provide DC energy for the propulsion engines of the Microwave Lightcraft. It uses very high density sub-arrays to convert the microwave energy in a beam of power density 4 kW/cm^2 with an efficiency of 56 %. Each sub-array consists of an ensemble of very short dipoles and Schottky diode elements deposited on and within a semiconductor substrate. The substrate sits down on a low-loss wafer carrier which also performs the function of water cooling. The rectenna design permits the periodic reflection and focussing of the beam to maintain a plasma nose-cone in front of the vehicle. In addition, the rectenna is capable of transmitting stored energy to this 'air-spike' region to maintain that plasma in the event of a loss of beam power.

INTRODUCTION

A microwave-powered vehicle meeting a number of inter-continental and space transportation needs has been proposed [1]. A microwave beam is transmitted from a phased array of size 1 km by 1 km to the Lightcraft at a distance of about 1200 km. The DC power for the oscillators of this transmit array is generated by a large solar cell array, both solar cells and oscillators being co-located on a solar power satellite (SPS) in a low earth orbit (LEO) at an altitude of about 500 km. The 35 GHz beam is focussed on the rectenna of the 15 m diameter spacecraft, as shown in Figure 1. The primary function of the rectenna is to collect the microwave energy in the beam and convert it to useable DC electrical energy for the propulsion engines located around the periphery of the lenticular-shaped vehicle. The beam would power the Lightcraft from its liftoff to various altitudes up to 100 km, depending on the mission. The phasing of the beam and the trajectories of the vehicle and SPS are such that the beam remains at broadside to the major dimension of the vehicle.

Broadside travel (in the direction of the beam) is made possible by the generation of a plasma nose-cone or 'air-spike' in front of the vehicle, replacing the mass of a traditional physical conical forebody normally used for streamlining an aerospace vehicle. The central (1.5 m diameter) portion of this air-spike will absorb and reflect the microwave beam, leaving the outer section of the beam incident on the rectenna. The air plasma is induced and supported by a portion of the microwave beam energy incident on the Lightcraft. A secondary function of the rectenna is thus the periodic reflection and focussing of the beam to this air-spike region. In addition, the rectenna is capable of transmitting stored energy to the air-spike to maintain that plasma in the event of a loss of beam power.

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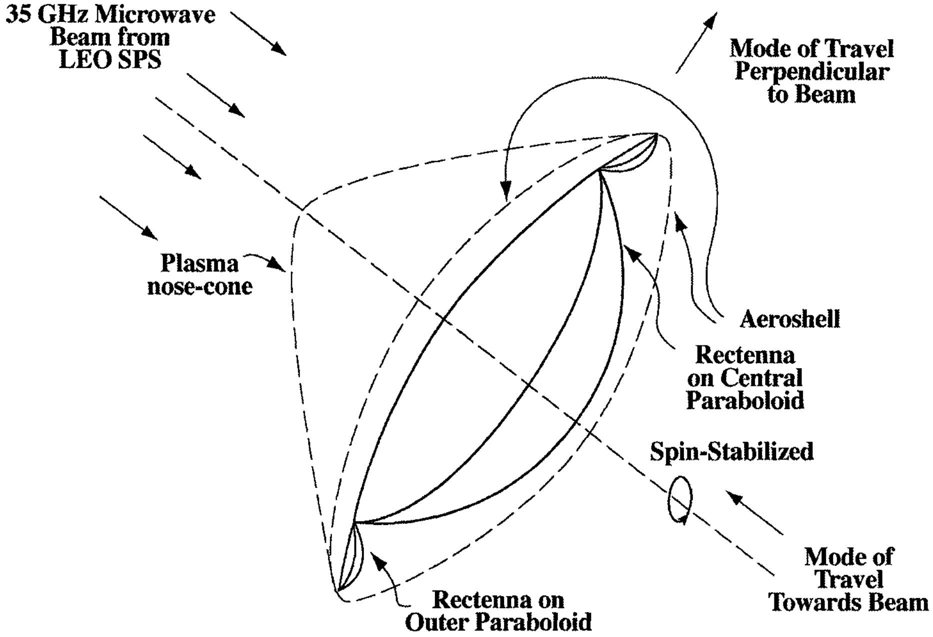

Figure 1 Microwave Lightcraft Powering System

RECTENNA DESIGN

Primary Function Design Considerations

For this extremely high power (EHP) application, normally-used rectenna designs, as shown in Figure 2, run into trouble. In these designs, each rectenna element collects the energy incident over an area a little more than a half-wavelength square surrounding that element. It accomplishes this using a resonant half-wavelength dipole antenna at the centre of the area allotted to that element, and a reflector plane behind the rectenna array.

For the Lightcraft application, the incident power collected by such a rectenna element would be around 3 kW. Because of the small active semiconductor areas necessary for 35 GHz operation of the rectenna diodes, these normal concepts place extremely high electrical power requirements on the rectification needed at each element.

In the present application, the dipole length and element separation are reduced from the order of a half-wavelength (4 mm) to around 50 µm. This high density of dipoles allows for a decrease in the power handling requirements of each diode by 4 orders of magnitude.

Rectennas normally use input and output circuit filters on each side of the diode for improved conversion efficiency, as shown in Figure 2. Owing to the difficulties involved in their implementation in the restricted area of the EHP design, the circuit filters have been relinquished. Output filter resonance of the diode junction capacitance is now provided by the appropriate spacing of the reflector plane behind the rectenna. The absence of input circuit filtering results in a reduction in rectification efficiency of less than 10 %.

Figure 2 shows a linearly-polarized (LP) rectenna. Such a design has serious disadvantages when motion of the transmitter or rectenna occurs. The rectenna would have to 'polarization-track' any rotation of a moving LP power beam, or alternatively, accept a 50 % power loss in a circularly-polarized (CP) beam. For the EHP Rectenna [2], a dual polarization format is employed, enabling all the power in a CP beam to be collected. The rectenna elements are laid in bands on paraboloidal surfaces within the Lightcraft, as shown for the central paraboloid in Figure 3. The x-polarization rectenna element at any location is oriented up the surface towards the rim, while the y-polarization element lies around the surface. Detailed modelling of this configuration shows that if the reflector and inter-element spacings are made specific functions of band position, matching of the beam to the rectenna can be achieved over the entire paraboloid with a single impedance level design. The rectenna does, however, require alignment between the beam direction and the axes of the paraboloids and manufacturing process variations in dipole and reflector spacings over the surfaces.

A 'sub-array' approach, Figures 3 and 4, is proposed to obviate part of the difficulty in manufacturing a large, curved-surface rectenna at 35 GHz. Each rectenna sub-array consists of an ensemble of antenna and Schottky diode elements deposited on and within a semiconductor substrate (wafer). Planar diodes are proposed to keep heat

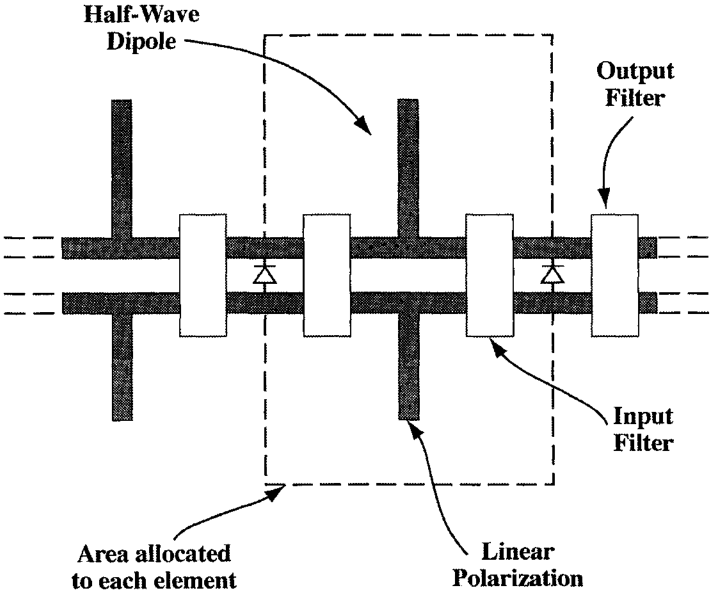

Figure 2 Normal Rectenna Design

dissipation close to the surface of the wafer. Each sub-array is surrounded by lossy material reducing stray reflections, diffractions and transmission of the high power beam in the regions between sub-arrays. This lossy material forms part of the rectenna water-cooling 'jacket' and is itself water-cooled. The space between sub-arrays is kept to a minimum to prevent a significant reduction in power collection.

Low-dielectric constant, low-electrical loss enclosures carry filtered de-ionized water along narrow channels at the surface of the wafer. The use of microchannel liquid cooling [3] has been proposed for the rectenna [4]. In the variant proposed here, these channels of water would flow directly over the anode metallization of each diode active area. The channels would traverse the entire sub-array and carry away the heated water for discharge from the vehicle. The serpentine channels pass at right angles to the dipoles and across the diodes they cool, to minimize the effect of the high-dielectric water on antenna performance. The width of each microchannel would be around 10 μm, the length of the diode active area. The height of each channel would also be small, between 10 and 20 μm. This would reduce the volume of coolant needed from normal microchannel requirements, and keep the effect of poor-thermally conducting channel walls to a minimum. Reliability problems related to the direct contact of water with the anodes would be limited by the use of a top gold metallization. If migration of the water into the passive regions of the wafer is a problem, an inert liquid coolant could be used. Viscosity considerations may also preclude the use of water in such narrow microchannels.

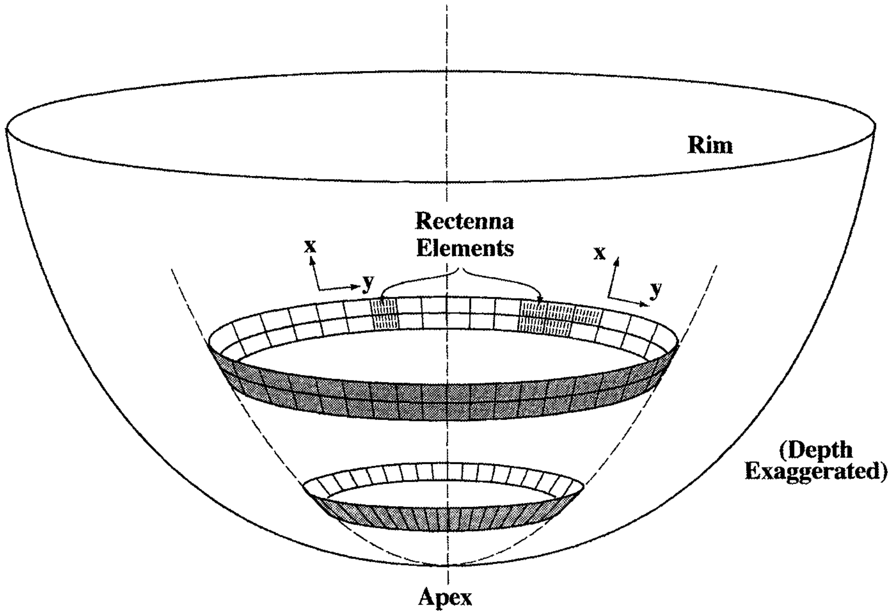

Figure 3 Bands of Rectenna Elements on Central Paraboloid

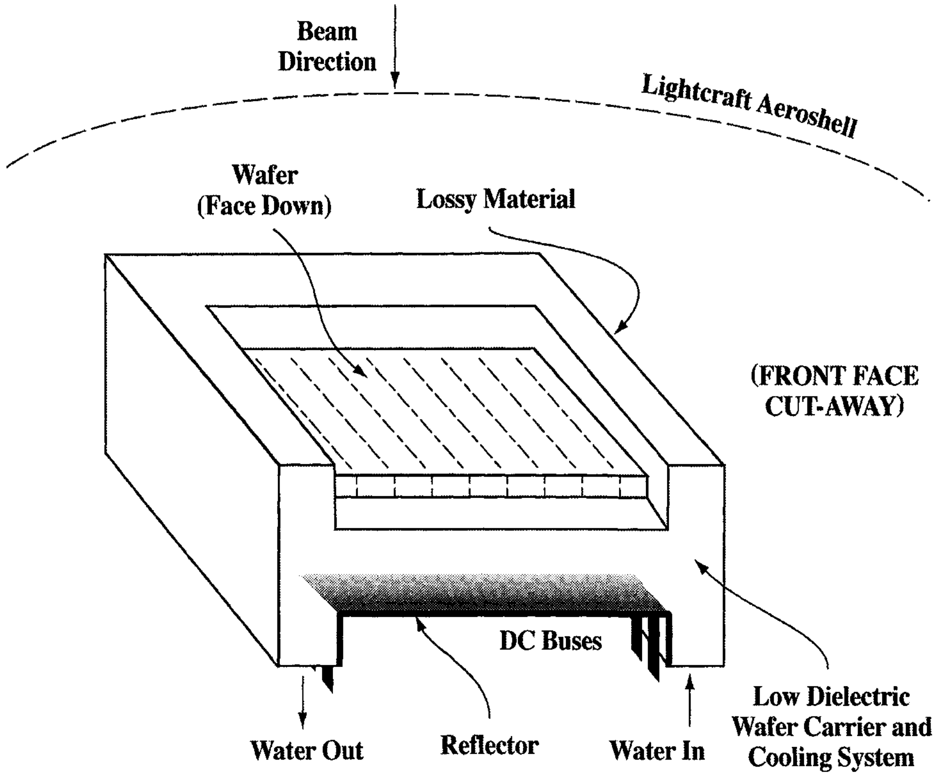

Figure 4 Three-Dimensional View of Sub-Array Structure

Electrical models for a rectenna element have been implemented using the circuit analysis program p-SPICE. The results of these simulations are shown in Figure 5 for two candidate wafer materials, GaAs and SiC, at active region temperatures of 250 °C. From the curve for GaAs, it is seen that an inter-element spacing of 61 μm (75 mW input power) results in a microwave-DC efficiency of 56 %. The rectenna circuit designs used for these calculations are not considered optimal. The importance of the cooling system is illustrated in Figure 6 where efficiencies are seen to drop significantly as the diode / surface metal temperature rises.

First-generation prototypes of the EHP Rectenna structure have been built and tested at 6 GHz. These devices use discrete (surface mount) Si Schottky diodes and are capable of power outputs up to 50 mW for each element. The array density is, however, limited by the size of these diode packages to inter-element spacings of 1 cm or greater.

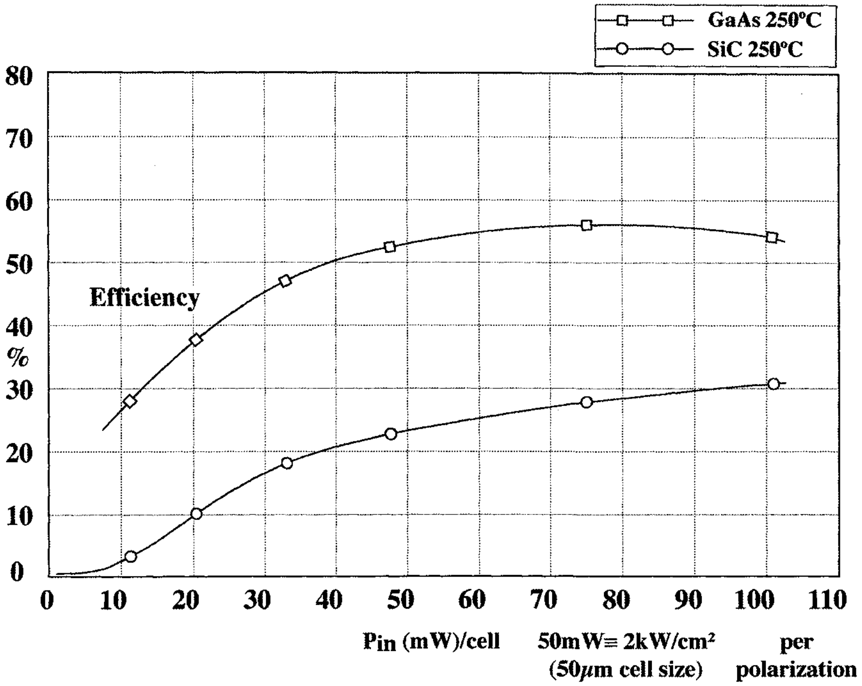

Figure 5 Rectenna Efficiency With Power Level

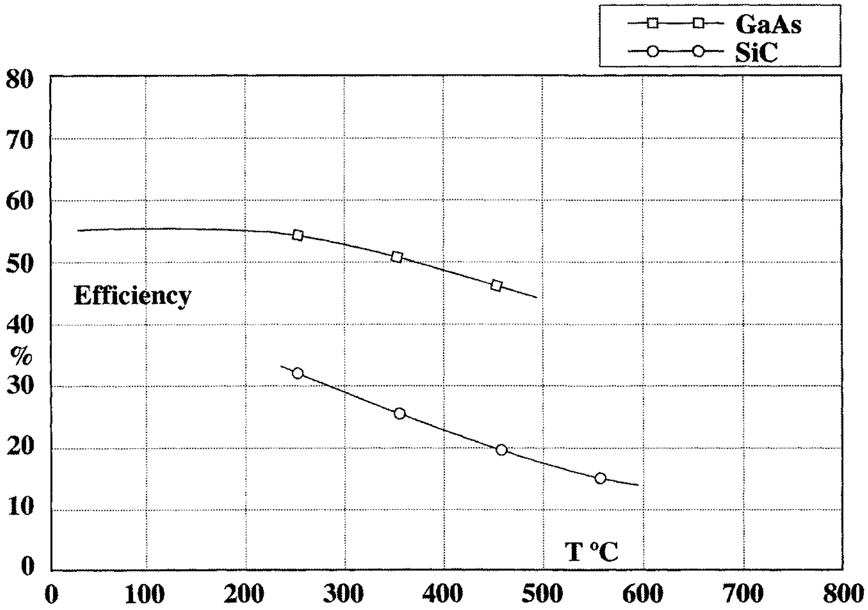

Figure 6 Rectenna Efficiency as a Function of Diode Temperature

Secondary Function Design Considerations

Redirection of Power Beam

The use of the rectenna, rather than a dedicated switching surface, for the reflection of the power beam to the air-spike is attractive for reasons of construction, weight etc. It has been proposed [5] that by switching the DC load impedance of the rectenna from its normal value (engine as load) to a short circuit, the reflective properties of the paraboloidal rectenna surface during the short-circuit period can be used. The power beam could then be focussed on the air-spike region. From exponential diode theory, it has been shown [2] that the reflected wave amplitude ratio and phase are approximately identical to those from a perfect reflector, over the varying beam amplitudes and angles of beam incidence of the paraboloid. The rectenna sub-arrays will then reflect a large percentage of the incident power to arrive in phase at the focus of the paraboloid.

Emergency Maintenance of Air-Spike

The sub-array format of the rectenna may be used to maintain the air-spike region in the event of a loss of the incident powering wave from the SPS. The essential features of such a system are shown in Figure 7. A number of solid-state microwave oscillators is located around the periphery of the central rectenna paraboloid. The DC energy to drive these sources is obtained from the stored energy in superconducting field coils around the outside of the vehicle [1]. The normal function of these coils is to provide the DC magnetic field required for the propulsion engines. This DC power is fed to the oscillators through power processing and protective switch gear running continuously under low-load conditions and monitored during flight.

The microwave oscillators are frequency- and phase-locked to each other and provide the source of injected RF power to each sub-array. They also run and are monitored continuously. A plurality of sources is used to provide sufficient power to feed the large number of sub-arrays, facilitate the routing of that primary power and to provide redundancy.

If the powering beam is lost, each sub-array switches immediately from its rectenna function to a transmit function. DC/RF switches, powered from the DC energy source, connect the sub-array to a DC voltage and the injected microwave signal. The DC voltage reverse-biases the rectenna diodes into avalanche breakdown, creating a set of RF transmission lines shunt-loaded at regular intervals by antenna elements with Schottky diodes across their terminals, reverse-biased into avalanche breakdown. Each shunt diode then acts as an IMPATT amplifier on the injected microwave signal. The sub-array then performs as an antenna of equivalent aperture with, however, additional RF power gain [6]. When each band of sub-arrays is correctly phased, a concentrated beam at the paraboloid focus will result, Figure 7.

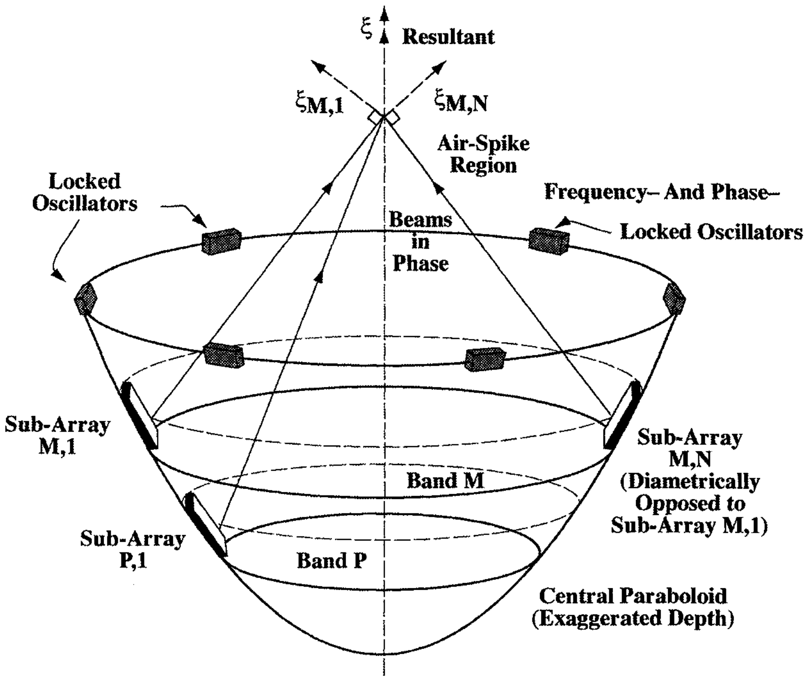

Figure 7 Paraboloidal Phased Array for Emergency Maintenance of Air-Spike

It is estimated that about 10^7 watts of CW power directed to the focus, are needed to maintain the air-spike. This represents about 80 mW per radiating amplifier-dipole element, for a 35 GHz transmit frequency. With IMPATT DC / RF conversion efficiency around 15 %, the DC requirement for this emergency function is around 7 x 10^7 watts. The energy stored in the Lightcraft field coils is estimated at around 10^8 joules and can thus only support the air-spike for 1.5 seconds. For the rectenna to perform this emergency function for the estimated 2 to 10 seconds necessary for speed reduction, the energy-storage capacity of the Microwave Lightcraft must be increased or some of the kinetic energy of the vehicle must be recoverable as DC electrical energy during the emergency.

CONCLUSIONS

A 35 GHz Extremely High Power Rectenna has been designed. Simulations suggest that an efficiency of 56 % or more is achievable for a monolithic GaAs rectenna at 250 °C in a 4 kW / cm^2 beam. Lower-power, lower-frequency hybrid prototypes have been built and tested successfully. Other applications for the technology are envisaged.

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REFERENCES

1. Myrabo, L. N., 'Microwave-Boosted Spacecraft', *Presentation Notes, 5th Advanced Space Propulsion Research Workshop,* Pasadena: JPL, May 18-20 1994.
2. Alden, A., 'A 35 GHz Extremely High Power Rectenna For The Microwave Lightcraft', *CRC Contract Report No. CRC-VPRS-00-03,* Ottawa: Communications Research Centre, March 2001.
3. Tuckerman, D. B., and Pease, R. F., 'Ultrahigh Thermal Conductance Microstructures for Cooling Integrated Circuits', *32nd Electronic Components Conference,* San Diego, May 1982, pp. 145-149.
4. Communications from E. Somerscales and L. Myrabo, January 1999.
5. Communications from L. Myrabo, January 1999.
6. Bayraktaroglu, B., and Shih, H. D., 'Millimeter-Wave GaAs Distributed IMPATT Diodes', *IEEE Electron Device Letters,* Vol. EDL-4, No. 11, Nov. 1983, pp. 393-395.