Millimeter Wave Technology for Space Power Beaming

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Abstract—**This paper reports on the design and development of millimeter wave rectennas and power beaming systems. It includes a brief discussion on the history of power beaming, the basic components of a high frequency power beaming system, the advancement of millimeter wave rectenna technology, and possible terrestrial, space and lunar applications.**

INTRODUCTION

THE IDEA of power transmission at microwave frequencies was first introduced by W. C. Brown in the 1960's. Under US Air Force funding, Brown led the pioneering research effort and demonstrated an *S*-band (2.45 GHz) power beamed helicopter platform in 1964. Since then Brown's excellent work has continued to improve his systems, achieving extremely high system efficiencies at 2.45 GHz [1].

In 1968 P. Glaser launched his work on the Solar Power Satellite (SPS) which involved the design of large power satellites that converted solar energy to RF and beamed it to large 2.45 GHz rectennas on earth. Research on the SPS concept continued through the 1970's. That work included a demonstration directed by R. M. Dickinson at Goldstone in 1975 in which 30 kW of power was beamed a distance of one mile.

NASA continued to work on power beaming, broadening its focus from aircraft to include space applications. It was recognized that higher frequencies would reduce the sizes of power beam antennas and rectennas in space. Mr. Brown performed a study of a 20 GHz rectenna and published his findings in a NASA report [2].

In 1988 we undertook to develop a rectenna at 35 GHz. This effort was initiated to develop the technology for a high altitude microwave platform (SKYLINK). The frequency of 35 GHz was chosen because of its characteristic dip in the atmospheric attenuation spectrum. Our first 35 GHz rectenna was working at 50% efficiency level in June of 1988. With this result we concluded that the availability question for the major technology component of a system for SKYLINK had been answered. We knew that the other parts of the system were readily accessible. A ground station high power source called the gyrotron had been developed in the early 1980's at hundreds of kilowatts and 35 GHz parabolic dishes were available in sizes ranging from 4 to 60 meters in diameter.

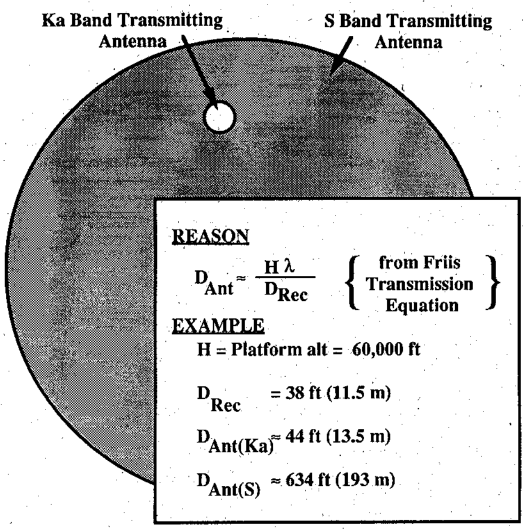

Fig. 1. Ground station comparison for *S* and *Ka* bands.

A year before this effort had started, the Canadian Stationary High Altitude Relay Platform (SHARP) program successfully flew the 4.5-meter wingspan SHARP-5 airplane for 20 minutes at low altitude powered only by microwave energy [3]. This was a historical event in microwave power beaming. The SHARP program operated at the same frequency (2.45 GHz) as Mr. Brown had in his pioneering efforts. For the SHARP airplane to go to high altitudes (21 km or 69 000 ft), however, the ground antenna would have to exceed 85 meters in diameter with a correspondingly large jump in rectenna size if an efficient system were to be constructed. A comparison of antenna size of *S* and *Ka* bands is shown in Fig. 1. As can be seen, the reduction in antenna size is considerable. If a balance is taken between the sizes of transmitting antenna and rectenna, the 35 GHz rectenna will also show the same reduction in size. For example, an efficient 35 GHz SKYLINK system with a flying platform at 60 000 ft would have a ground antenna and airplane rectenna diameter of approximately 13 meters. These dimensions are small enough to suggest that an economical SKYLINK system could be implemented with existing technologies.

After we had our first 35 GHz rectenna working, we began reviewing NASA requirements for power beaming. It became apparent that for space-to-space applications

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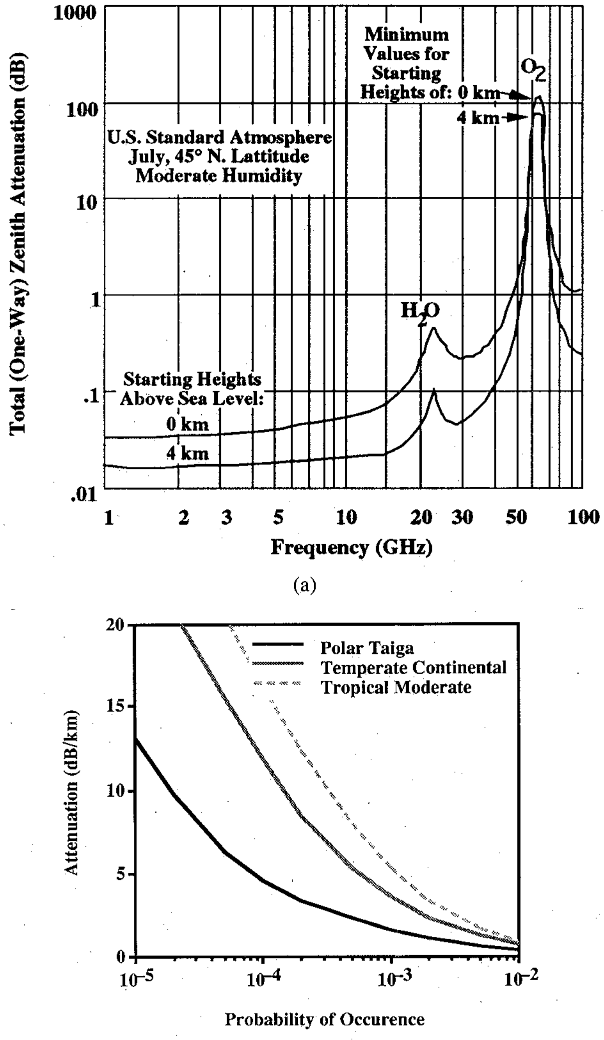
and transmitting on or to lunar surface, rectennas at higher frequencies were desirable. We are currently developing a 94 GHz rectenna and plan to go higher in frequency, possibly to 300 GHz. In this paper we will review the issues involved in millimeter wave rectenna development, discuss various power transmission issues, present the possible scenarios for power beaming from earth-to-space and space-to-earth as well as lunar transmission systems, and review the technologies that will make these systems feasible.

MILLIMETER WAVE RECTENNA DEVELOPMENT ISSUES

The issues in the millimeter wave region differ from those in the *S*-band due to the sizes of diodes and passive components. In addition, printed circuits have problems at higher frequencies due to losses and etching tolerances. In the following sections we will describe the salient features and issues of the millimeter wave rectenna technology and some of the solutions we have generated to overcome the problem of the rectifying structure [US patent 5 068 699].

Operating Frequencies: The operating frequencies between ground and space are set by the available attenuating windows in space (e.g., 35 and 94 GHz, etc.) as shown in Figure 2a. The chart indicates one-way attenuation for vertical passage as a function of frequency. For instance the total attenuation of a 35 GHz beam originating at sea level and traversing vertically through the atmosphere in clear weather is less than 0.3 dB. Attenuation will increase with inclement weather (rain), but its time-averaged effect on the operation of a high frequency power beaming system can be tolerated. Fig. 2(b) shows rain attenuation at 35 GHz on a probability base for three geographical regions on earth. As can be seen, rain attenuation will not cause a problem for any large percentage of the time with the exception of the tropical moderate region. For space-to-space transmission the choice of frequency will be determined more by the source than the rectenna. That is, for higher frequencies of 94 GHz and beyond, a rectenna could be developed as MMIC, a well defined basis of manufacture for many devices today. Unfortunately, the solid state sources operating at this frequency range can not provide over a watt of power. Of course gyrotrons capable of hundreds of kilowatts are available at these frequencies, but their use in space seems unlikely at this time.

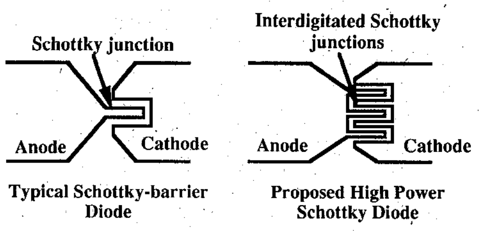


(a)

(b)

Fig. 2. (a) Vertical atmospheric attenuation versus frequency. (b) Rain attenuation at 35 GHz.

Diode Features: The major factor in diode considerations is that as frequency increases, the diode dimensions must decrease to insure that the junction capacitance does not present too low an impedance during reverse bias. For a 35 GHz diode the C_{jo} is about 0.07 pf which corresponds to a reactance of 65 Ω. The other major parameters are breakdown voltage V_b, series resistance R_s, and barrier voltage E_b. R_s determines the loss mechanisms, V_b the maximum reverse voltage (maximum power) the diode can handle and E_b the minimum power required for diode turn on. Typical values for these parameters as well as package parasitics are shown in Fig. 3 for a GaAs diode. (L_p is the inductance associated with the beam leads and C_p the package capacitance.) The dynamic range of a typical GaAs diode in a rectenna circuit is illustrated in Fig. 4(a) which shows the results of a LIBRA run for a range of input power levels. The lower limit of the curve is set by E_b and the upper end by V_b. Since loss is a major factor which presents a thermal management problem, it would appear that a decrease in *Rs* would be desirable. However, a decrease in *Rs* would raise C_{jo}, showing an interdependence of the two parameters, so that only a balance between these parameters can be obtained. Fig. 4(b) shows the behavior of the voltage across the diode as time passes. Note the dc shift of the diode voltage so that it is limited to 0.2 V and not clamped at the junction voltage (0.7 V) as anticipated. The phenomena is characteristic of the diode being used at this frequency due to energy storage in the inherent capacitors and determines the performance of the overall circuit. Figure 3 also shows a proposed diode where a set of realizable optimum param-



Is = 100 pA
Rs = 4 Ohms
Cjo = 0.07 pF
Vbr = 7 V
Lp = 0.2 nH
Cp = 0.03 pF

Is > 1 nA
Rs < 2 Ohms
Cjo < 0.1 pF
Vbr > 10 V

Fig. 3. Millimeter wave Schottky barrier diodes.

eter values are presented. Fig. 4(c) is the results from a LIBRA simulation for a circuit using these parameters. Note the higher power handling capability of the diode. For the higher frequencies of 94 GHz and beyond indium phosphide (InP) is being considered as the semiconductor material. The ratio of majority to minority carriers is 40 for InP while only 12.5 for GaAs. For higher frequencies electrons, which have less mass than the holes, are the desired carriers.

Hybrid Versus MMIC: A hybrid rectenna circuit consists of an etched thin-film printed-circuit board with a bonded diode. MMIC is the presently growing technology of uniting microwave circuitry and IC technology. The essential difference between these two technologies is the degree of etching tolerance which MMIC provides over the hybrid approach. MMIC tolerance is one micrometer, whereas printed-circuit board tolerance is at best twelve micrometers. Etching out the input filter and the antenna system becomes more difficult at higher frequencies of 94 GHz and beyond. Manufacturing diodes and bonding these small devices also become increasingly difficult at higher frequencies. In fact, at higher frequencies the bonding joint may introduce reactances that may not be correctable. For these reasons, it has been concluded that hybrid technique is adequate at 35 GHz, and possibly 94 GHz; beyond this range of frequencies MMIC technology must be employed. A hybrid rectenna is cheaper than a MMIC counterpart, since the latter requires that the whole rectenna surface be made of GaAs or InP. Bonding diodes in the hybrid is not a costly procedure since bonding machines do exist which may be able to bond up to a thousand diodes an hour [4]. For the 35 GHz rectenna program, the hybrid approach is the better choice.

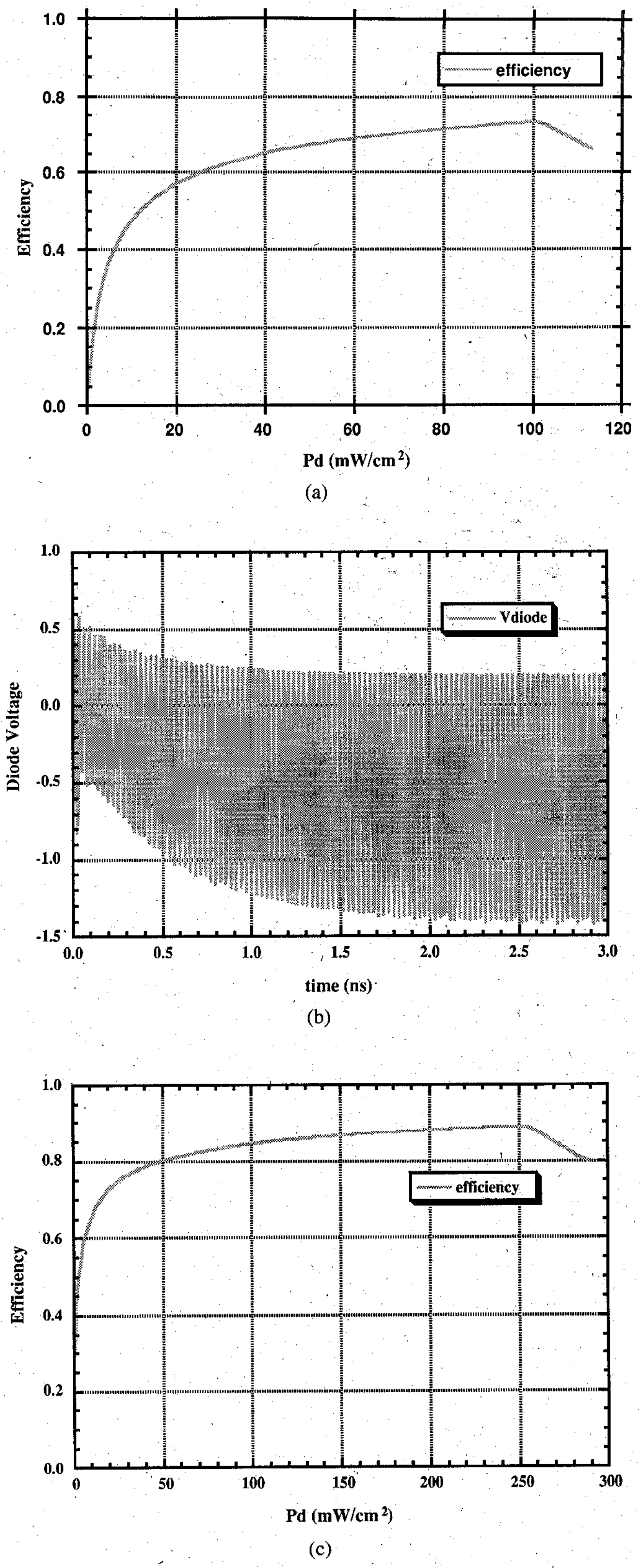


Fig. 4. (a) 35 GHz Rectenna with Off-the-Shelf GaAs Diode. (b) 35 GHz Rectenna Diode Voltage. (c) 35 GHz rectenna with high power diode.

Losses in Rectenna: The losses in the rectenna are the power reradiated due to the mismatch with the antenna, loss in the network and transmission lines, and the loss in the diode. For a 70% efficient microstrip rectenna the largest loss will probably be the radiated power due to mismatch which may be as much as 20%. Diode loss will comprise from 5 to 10% of the dissipated loss. Fig. 5 shows the relation between diode loss and dc out obtained from a SPICE run. (Average loss in the diode calculates out to be 5%.) Losses in the lines are typically 0.2 to 0.3 dB per wavelength. Half of this type of loss is due to conduction and the other half is due to the radiation and dielectric losses. Dissipated losses in the lines and diodes are the major concern because of the thermal problems they introduce.

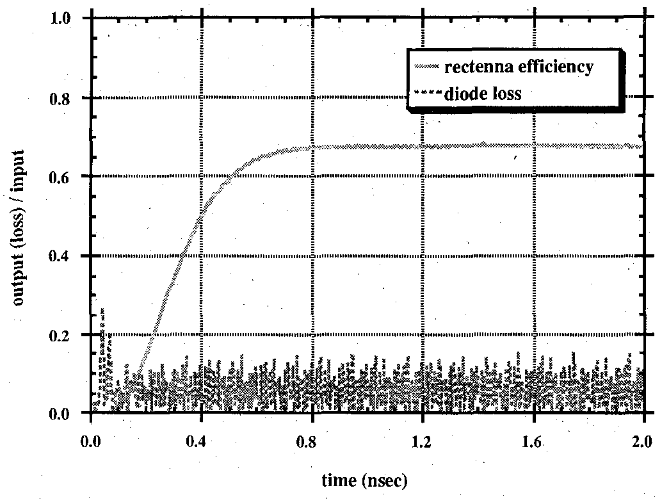
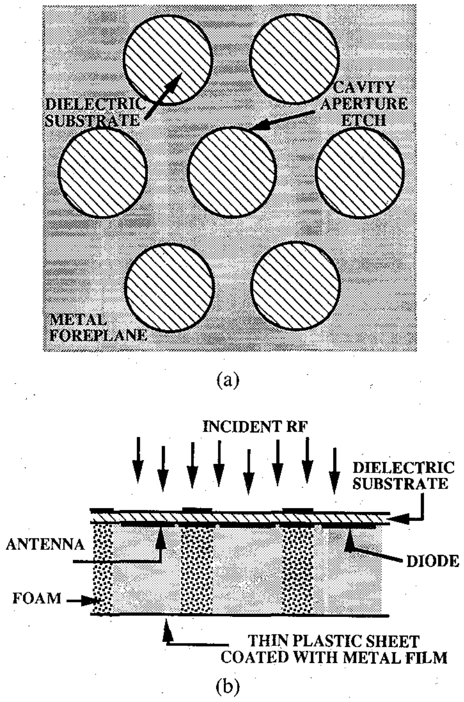


Fig. 5. Rectenna output and diode loss.

Thermal Management: Fig. 6(a) and (b) show the layout of the surface and side. This layout was designed so that the cooling will take place on the front surface. The rectenna surface has been laid out with holes for the antenna elements and conducting surfaces between holes for cooling either by convection or radiation (black body) and some portion where RF currents flow around the perimeters of the holes. The holes take up about 50% of the total surface. In the side view (Fig. 6(b)) it can be seen that the rectenna network and diode are located very close (~ 10 mils) to the outer surface. Thermal paths between the diode and the outer surface are thus provided. For the high flying platform at 60 000 ft (SKYLINK) convection can account for more than 0.1 W/cm^2 for raised temperatures of 50°C and aircraft speeds of 200 miles/hr or 89 m/sec. For space applications radiation can also be 0.1 W/cm^2 if emissivity of close to unity and raised temperatures at 100°C and ambient temperatures lower than 100°K are assumed. Since our calculations indicate that no more than 10% of the losses will be dissipated, this cooling level should be adequate to support rectenna system receiving power densities up to 1 W/cm^2 or 10 kW/m^2.

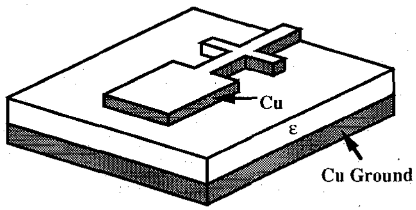
Rectenna Layout: Fig. 7 shows two different approaches to implementing the rectenna circuit on a dielectric board. The first and perhaps the more popular approach is the microstrip, where two planes are involved in the transmission, and the other is the coplanar stripline, where transmission takes place on a single etched plane. Selecting either approach dictates the antenna to be used—patches for the microstrip and dipoles or loops for the coplanar. Our first rectennas were formed using patch antennas where over 50% efficiencies were measured. Subsequently, however, we chose the coplanar approach because of the gain in efficiency. Dipoles, when backed by resonant structures, can have aperture efficiencies greater than 80% while patch antenna efficiencies may range from 40 to 80%. These circuits were tested using a low power solid-state (Gunn) oscillator and a power meter. A 50 W TWTA was also used in those tests involving higher power densities. Fig. 8 shows the measurement procedure. A power meter equipped with an open waveguide detector was first used to determine the power level at a given distance from the source for a range of frequencies (typically 34 to 36 GHz). Open waveguide (WR-28) was used because of its well-known characteristics—i.e., its broad beam pattern. The rectenna circuit would



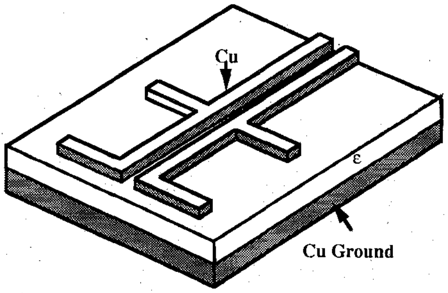
(a)

(b)

Fig. 6. (a) Outer surface of rectenna panel. (b) Cross section view of rectenna panel.



Microstrip Patch Antenna and Circuit



Coplanar Strip Antenna System

(Drawings not to scale)

Fig. 7. Microstrip and coplanar strip circuits.

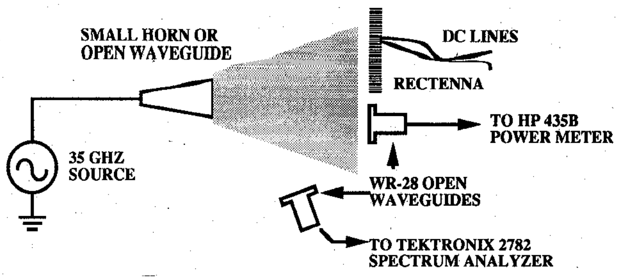


Fig. 8. 35 GHz Rectenna test setup.

then be placed in the same location and the dc output recorded for the same range of frequencies. Efficiency was defined as dc power out divided by RF power incident on the rectenna. As a practical means of measurement, the power seen by the rectenna was determined as the magnitude of RF power density recorded multiplied by the ratio of the actual antenna size of the rectenna to that of the open waveguide. This ratio is just the ratio of the physical sizes multiplied by the ratio of aperture efficiencies. For simplicity aperture efficiency of 75% was used for the open waveguide. (Waveguide aperture efficiencies can range from 60 to 90%. It should be noted that in our calculations we assumed a mean value for the aperture efficiency.)

$$\eta \equiv \text{rectenna } \textit{RF-to-dc} \text{ conversion efficiency}$$

$$\eta = \frac{P_{\mathrm{dc}}(\text{dc power out})}{P_{\mathrm{RF}}(\text{RF power incident on the rectenna})} \times 100$$

where

$$P_{\mathrm{RF}} = P_d(\text{power density}) \times A_e(\text{rectenna aperture})$$

$$P_d = \frac{P(\text{measured with open waveguide})}{A_{\mathrm{ewg}}(\text{effective waveguide aperture})}$$

$$A_e = \epsilon_a(\text{aperture efficiency}) \times A_p(\text{physical area})$$

It should be noted that the margin for error is not negligible due to some uncertainties in the measurement. For instance ten percent margin may be applied to the values shown on the chart. The following table lists the results of some of these circuits.

Circuit	Rectenna Efficiency
Rectangular Patch 1	61%
Rectangular Patch 2	72%
Cross Patch	57%

Combining Antennas: For higher frequencies it may be necessary to combine antennas either in parallel or series to produce enough voltage to exceed the junction voltage of the diode. (Fig. 7 shows two dipoles in parallel connection in a coplanar layout.) As frequency increases, antenna length decreases, hence generating less voltage for a given field. Either solution involves impedance transformations prior to the diode. A study of coplanar series and parallel elements is currently being conducted using a Wiltron 360 Vector Network Analyzer, a high frequency test fixture, and custom-designed transitions.

MILLIMETER WAVE SOURCES AND ANTENNAS

Depending on the type of application, a wide range of sources are available to provide the RF at *Ka*-band and higher. Proper selection of the source would include careful consideration of various issues associated with the system in mind. For instance a ground station located at an environmentally favorable place can afford to have a high power source that requires regulated water cooling. This approach, however, may not be favorable for providing RF power in a space-based system where thermal management is the critical issue. Whatever the application, there are sources currently available to meet the system requirements.

Gyrotrons: Until recently obtaining hundreds of kilowatts of power with a single source at millimeter wave frequencies was near impossible. This barrier was overcome with the advent of a new class of oscillators known as gyro-devices, where the cyclotron resonator replaces the physical resonator as in conventional tubes. The gyrotron, which falls into this category, is a microwave vacuum tube operating on the principle of interaction between an electron beam and microwave fields. Coupling is achieved by the cyclotron resonance condition, which permits the beam and microwave circuit dimensions to be large compared to a wavelength. This unique feature circumvents the power density problem encountered in conventional klystrons and traveling wave tubes at millimeter wavelengths. Gyrotrons capable of generating 200 kilowatts CW at 35 GHz have been built and are currently being used by various groups. Technologies exist for the development of high power gyro-devices capable of delivering even greater power at millimeter and submillimeter wavelengths. Table I shows gyro-devices available (or under development) at various frequencies.

Other Sources: Although gyrotrons can deliver hundreds of kilowatts at high frequencies, their use in space-based systems may be difficult and limited. With projected efficiencies of 40 to 50%, and with system efficiencies being correspondingly less, these devices will pose serious thermal problems in space. Current technology may not be able to provide adequate cooling for such systems. It may be necessary to consider some alternatives. An obvious choice would be to use an array of lower power TWT's. Such sources have been space-proven, with new or improved tubes entering the market quite regularly. A 100 W tube, for instance, can be selected as the basis for a large transmitter array. Dozens of these tubes can be combined to feed a single dish in space. Power combining can include various techniques to optimize size, weight, and cooling parameters. Mallavarpu and Puri of Raytheon recently reported on a three-dimensional combining circuit for TWT's with greater than 90% com-

TABLE I
GYRO-DEVICES

Frequency	Tube Type and Performance
35 GHz	GYROTRON-200 kW CW
94 GHz	GYRO-TWT-100 kW CW
110 GHz	GYRO-TWT-500 kW pulsed
140 GHz	GYROTRON-400 kW CW (1 MW CW unit under development)
160 GHz	GYROTRON-500 kW pulsed unit under development
280 GHz	GYROTRON-1 MW CW unit under development
100-300 GHz	QUASI-OPTICAL GYROTRON-1 MW CW unit under development

bining efficiency from 2 to 8 GHz [5]. Known as a spatial field power combiner, this device may be scaled up to operate at higher frequencies. It can also be used with solid state modules. Another choice could be the use of Extended Interaction Oscillators (EIO's). Outputs up to 500 W are available at *Ka*-band. However, these devices require water cooling, and hence special attention must be given to their use in space. Finally, solid state devices can be used to provide the power. IMPATT oscillators providing 5 to 10 W are currently available. Efficient combining schemes can tailor the total output power to the desired level. Each module can be used to feed an element in a transmitter array. Other available solid state devices are the GaAs FET's and HEMT's. Several semiconductor foundries have developed single FETs capable of delivering 0.1 W at *Ka*-band. Such devices can be combined as described above. To inprove efficiency (to greater than 90%) and maximize the output of each device, techniques used in making class D and E amplifiers (more commonly used at lower frequencies) may be incorporated. At very high frequencies MMIC devices should be employed. With such small devices micro heat pipes can be used to facilitate better thermal management. As a final note the selection of the RF source should be made with overall system efficiency and thermal management issues in mind.

Antennas: Advances in manufacturing precision cassegrain antennas have also contributed to the feasibility of high frequency power beaming. A wide range of steerable tracking antenna systems are currently available. These systems, which consist of reflector panels with surface accuracies better than 0.025 mm, can operate up to 500 GHz. They also offer pointing and tracking accuracies of two arc seconds rms (each axis) [6]. Standard reflector diameters range from 7 to 20 meters.

Another approach would be to use an array of antennas as shown in Fig. 9. This approach would be favorable in a system where thermal management is a critical issue. Output from a TWT can be distributed to several elements, or if employing solid state technology, each module can feed an antenna element. Thousands of such elements can be arrayed to provide high power at high frequencies.

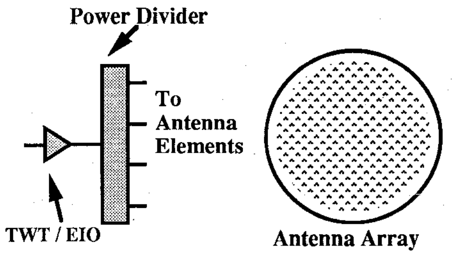


Fig. 9. Transmitter/antenna array.

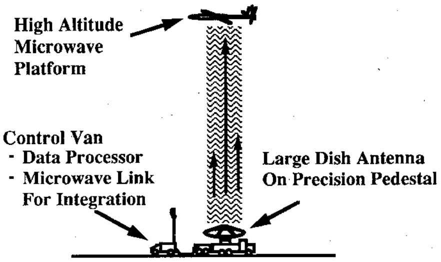


Fig. 10. Ground-to-platform power beaming system.

APPLICATION

There are many scenarios of power beaming in space; we will present three as representative of space applications.

SKYLINK: SKYLINK is a concept that features an electric powered UAV (Unmanned Aerial Vehicle) that can maintain its operation indefinitely (mean time between failure of components). The UAV is powered by beaming microwave energy at 35 GHz from a ground station as shown in Fig. 10. The SKYLINK concept can be applied to many varied missions from low altitude (5000 ft) to very high altitude (100 000 ft). The hundreds of kilowatts that can be made available on the platform is more than adequate for propulsion and multiple payloads. The antenna size is dependent upon the platform altitude, size, and system efficiency requirement, but could range from 3 to 15 meters in diameter. As shown in Fig. 10, a 35 GHz gyrotron of 100 kW or more can feed a cassegrain dish which beams power to the rectenna on the flying platform. The cassegrain subreflector is transparent to the frequency of a tracker mounted at the dish focal point which tracks a beacon transmitting from the platform.

Space Power Beaming System: Fig. 11 is an illustration of power transmission system on the lunar surface. This is an illustration showing power transmission on the surface for the long (14 days) lunar nights. Power can be relayed from earth, solar satellite on the sunny side, or a nuclear power station to the power relay station. In order to practically implement power beaming to lunar rovers with a maximum distance in line of sight of 10 km, a higher frequency must be employed. For example, 300 GHz transmission would require a rectenna with a diameter of at least one to two meters. The source would have to be a gyrotron for this scenario.

Power Beaming from a Nuclear Plant in Space: Fig. 12 is an illustration of a space-based power beaming system. Since this scenario may involve large distances for

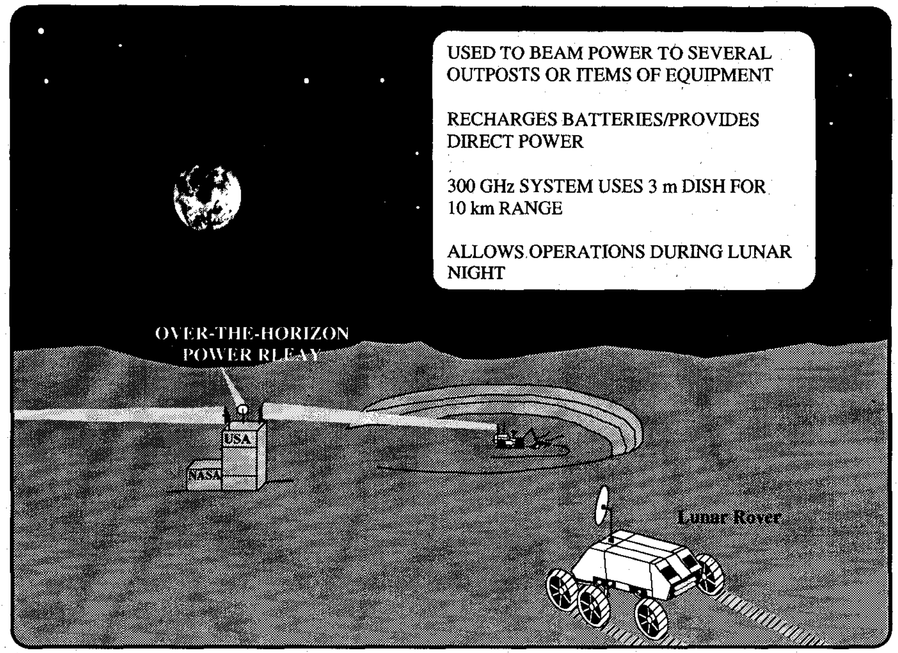


Fig. 11. Lunar Station Power Beaming System.

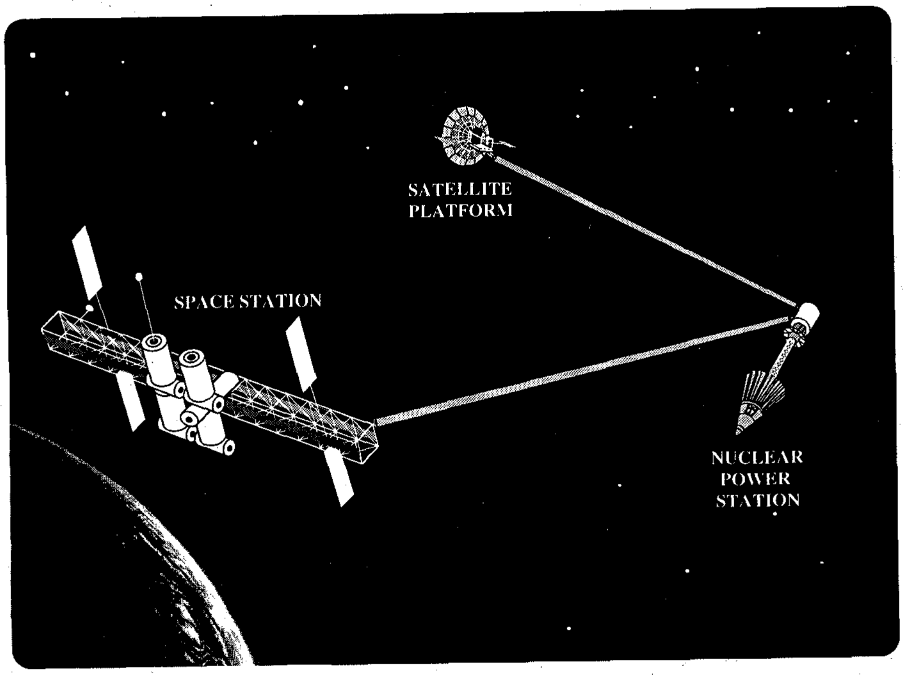


Fig. 12. Power beaming from a Space-Based Nuclear Power Station.

power beaming (100 000 km or more), operation in the higher frequencies (such as 300 GHz) are almost a requirement. If nuclear power is abundant, the inefficiency in a gyrotron system may be tolerated. However, transferring the heat generated in a gyrotron will still be a problem.

SUMMARY

A 35 GHz rectenna has been fabricated with an efficiency of 70%. A moderate panel of rectennas (12 cm × 12 cm) has been constructed and results agreed well with computer simulation. With this result, all the major components in the technologies necessary for a ground to space power beaming system at 35 GHz are available. Hybrid techniques can be used for 94 GHz rectenna, but for higher frequencies MMIC technology must be employed. As for the sources gyrotrons exist from 35 to 300 GHz with output power in the hundreds of kilowatts. This is the preferred source for ground based millimeter wave transmitter system. However, for transmitting in space, gyrotrons may not be a practical source. Therefore the need exists for a highly efficient ($>90\%$) solid state amplifiers (>5 W) to be used in a microwave array with 10 000 or more elements.

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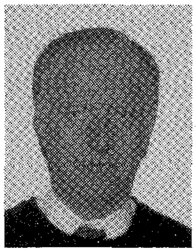

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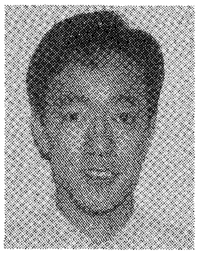
He spent ten years as a Microwave/Antenna Engineer where he was responsible for the design of tracking antenna systems and various microwave components. In addition he has been involved in studies and design of explosive generators, plasma switches, electron accelerators, high power microwave sources, high field electromagnet design, modeling and computer code development. Presently he is responsible for solid state amplifier development and design in the HF and UHF band and rectenna development in the *Ka* and *W* frequency bands.



James T. Cha (M'88) was born on June 21, 1963 in Pusan, Korea. He received the B.S.E.E. and M.Eng. degrees from Cornell University in 1985 and 1986, respectively.

From 1986 to 1987 he worked as an electrical engineer at Equipment Division Laboratories of Raytheon Company. He helped design and test both hardware and firmware for different transmitter systems, including an over-the-horizon radar system. Since 1988 he has been with ARCO Power Technologies, Inc., where he has been involved in the design and development of rectenna networks in the *Ka* and *W* frequency bands. His current engineering activities also include millimeterwave antenna networks and solid-state sources.