Status of the Microwave Power Transmission Components for the Solar Power Satellite

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Abstract —**During the 1970–1980 time period a substantial advance has been made in developing all portions of a microwave power transmission system for the solar power satellite (SPS). The most recent advances pertain to the transmitting portion of the system in the satellite and are based upon experimental observations of the use of the magnetron combined with a passive directional device to convert it into a highly efficient directional amplifier with excellent low-noise properties and potentially very long life. The ability of its microwave output to track a phase reference makes it possible to combine it with many other radiating units to provide a highly coherent microwave beam. The ability of its output to track an amplitude reference while operating from a dc power source with varying voltage makes it possible to eliminate most of the power conditioning equipment that would otherwise be necessary.**

I. Introduction and Historical Background

As SUGGESTED in Fig. 1 the solar power satellite (SPS) is a concept in which a large photovoltaic array is placed into geostationary orbit above the equator where it is exposed to sunlight for more than 99 percent of the time during the year. The power derived from the sun is transmitted to earth by a microwave beam at a frequency which penetrates the earth's atmosphere with only small losses under the most adverse weather condition. At the earth it is converted back into dc electrical power. The advantage of the concept as a source of base load electrical power is that it is the only approach that is free from expensive energy storage or particulate, gaseous, or radioactive residues.

Over a decade has passed since the first paper on the SPS concept was published by Glaser [1] and nearly a decade since the first publications on this subject in [2]. The four principal technologies involved, space transportation, solar photovoltaic cells, large space structures, and microwave power transmission, have all progressed in the elapsed time interval. The purpose of this report is to review the status of microwave power transmission technology as it relates to the SPS. This is a particularly appropriate time to do so because the three year SPS Concept and Evaluation program administered by the Department of Energy and National Air and Space Administration [3], [4] has been completed. The studies sponsored by this program have led to the specific design of the microwave power transmission system that will be discussed in this paper. However, these recent studies depended in a large measure upon a microwave power

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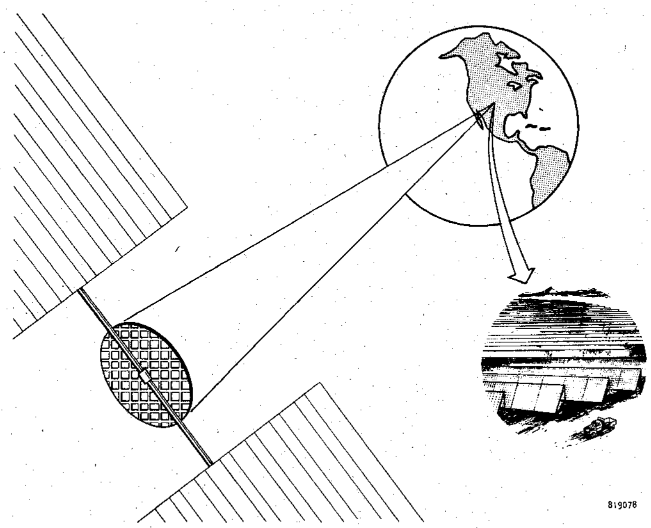

Fig. 1. Schematic of power from space system. The sun's radiant power is converted into microwave power in a synchronous satellite and beamed to earth for reconversion into ordinary power.

transmission technology base that was built up prior to the DOE/NASA concept development and evaluation program. As background information it may be useful to review the progress that was made in various areas of technology that relate directly to the SPS.

Progress in the overall efficiency of a microwave power transmission system is of special importance to the SPS, whose economic attractiveness is directly impacted by efficiency. Overall efficiency is defined as the ratio of dc power output at the receiving terminal to dc power input at the transmitting terminal. Using this definition, the efficiency was 26 percent in 1970 [5]. That efficiency figure was raised to a certified 54 ± 1 percent in the 1975 experiment [6] illustrated in Fig. 2. If the experiment were to be repeated today with existing technology the efficiency would reach 70 percent. Although the distance of transmission in the laboratory was not great, the microwave transmission efficiency is independent of distance if the transmitting and receiving aperture areas are scaled up directly with the distance of transmission [7]. Hence, this laboratory experiment, if it were upgraded to use current component technology, would be indicative of the 65-percent overall efficiency projected for the SPS system which transmits power over a distance of 23 000 miles, and which uses large apertures to achieve this efficiency. In turn, the large apertures of the SPS permit the handling of very large

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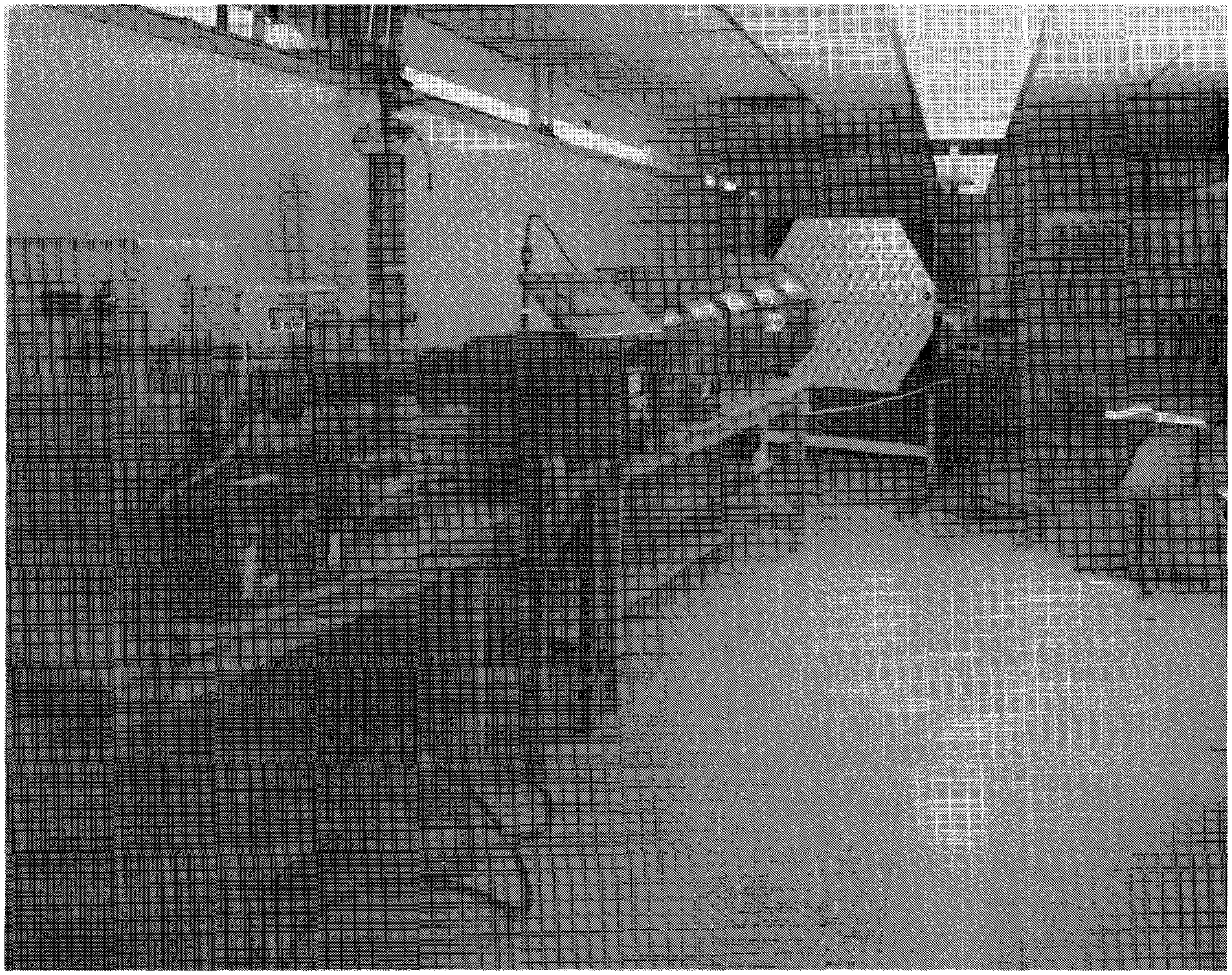

Fig. 2. Test of overall dc-to-dc efficiency in the Raytheon Laboratory. The ratio of the dc power out of the rectenna to the dc power in to the magnetron generator was 0.5418+0.0094 probable error. Efficiency of 54 percent was certified by JPL Quality Assurance Division.

amounts of power, typically 5 GW of dc power output at the earth. The large size of the receiving aperture also keeps the maximum microwave power density incident upon the earth to about 25 percent the density of sunlight at the earth's surface.

Progress in the distance of transmission and amount of power transmitted is of particular importance to those who find it difficult to scale the modest power levels and transmission distances of a laboratory experiment to those in the SPS. Prior to 1975, the maximum dc power out of any microwave power transmission system was 100 W and the maximum distance of transmission was 25 ft [8]. In 1975, over 30 kW of dc power was obtained from a system that transmitted power over a distance of 1.6 km [9] at the Venus site of the Jet Propulsion Laboratory facility at Goldstone in the Mojave Desert (Fig. 3).

Very significant progress was also made in the efficiency and ruggedness of the rectenna, the receiving device which simultaneously absorbs the microwave power and converts it into dc power. In 1970, the maximum overall capture and rectification efficiency of the rectenna was 40 percent [5]. In 1975, it had reached 84 percent [6], [9]. In 1978, carefully checked efficiencies of 90 percent had been obtained from individual rectenna elements [10]. Because microwave collection efficiencies for the rectenna are theoretically 100 percent and have been measured at over 98 percent, it may be concluded that an overall efficiency of at least 88 percent could now be obtained from a full-size rectenna.

A major contribution to rectenna efficiency and reliability was the [6], [8], [10] development of efficient and reliable Schottky-barrier diodes as rectifiers. Diode efficiencies as measured apart from circuit losses outside the diode were 92 percent. Extensive life tests were run on 200 rectenna elements containing 200 diodes, and 800000 diode hours were accumulated without a failure for those rectenna elements that produced individually 6 W of power output or less [10]. The proposed level of power in the SPS rectenna is less than 2 W per rectenna element.

As additional background information a set of representative characteristics of a single solar power satellite are given in Table I.

In applying the existing microwave power transmission to the SPS it was found that the rectenna technology could

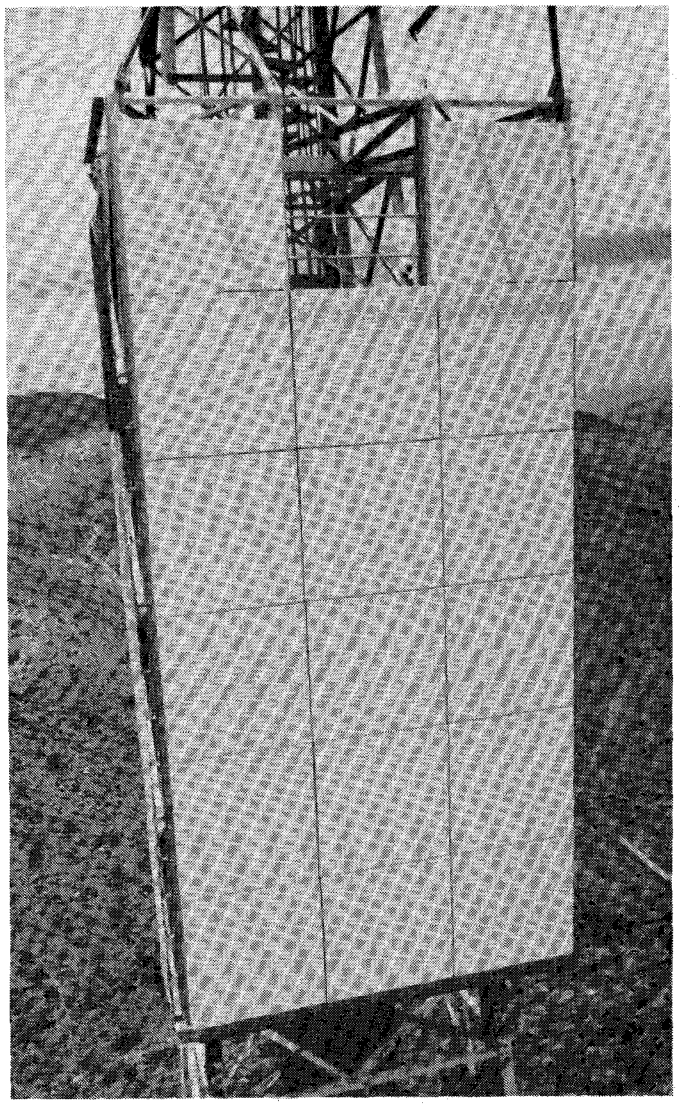

Fig. 3. Photo of the 25.4-m^2 rectenna at the Venus site of the Goldstone Facility of the Jet Propulsion Laboratory. Power was transferred by microwave beam over a distance of 1 mi and converted into over 30 kW of CW power which was dissipated in lamp and resistive load. The rectenna efficiency was 82 percent.

TABLE I
REQUIREMENTS AND CHARACTERISTICS OF THE MICROWAVE POWER TRANSMISSION SYSTEM FOR THE SPS

DC Power Level at Output	3 to 8 x 10^9 watts
Overall DC to DC Transmission Efficiency	62-67%
Transmission Distance	22,300 miles
Frequency	2.45 GHz
Life of Components	30 years
Beam Width	3 x 10^{-4} radians
Pointing Accuracy	2.8 x 10^{-6} radians
Desired Method of Radiating Waste Heat	Passive
Transmitting Aperture Size	0.8-1.2 kilometers diameter
Receiving Aperture Size	7 to 10 kilometers diameter

be applied directly with little modification. However, a severe challenge was encountered in the satellite portion of the SPS because of the many difficult requirements imposed upon an acceptable system. These requirements and how they were met will be discussed in the next section.

II. THE COMPONENTS AND ARCHITECTURE OF THE TRANSMITTING ANTENNA

The design of the SPS transmitting antenna has imposed a set of severe requirements which must be met simultaneously. These requirements relate to efficiency, mass, methods for radiating waste heat, life of components, reliability and redundancy, radio frequency interference, launching of a coherent beam, and interfacing with the solar photovoltaic array.

Perhaps the severest requirement imposed by space operation is that any heat resulting from the inefficiencies in the power conditioning and in conversion of dc power into microwave power must be radiated directly into space. This necessity implies that the efficiency of the power conditioning and energy conversion processes be carried out as efficiently as possible and that the heat radiation occur at an elevated temperature to take advantage of the fourth power relationship between the quantity of heat that is radiated per unit area and the temperature. The leverage of high device efficiency and high operating temperature upon the amount of microwave power that can be radiated per unit area are shown in Fig. 4. Clearly, at this time, solid-state generators cannot compete because of their inability to operate at high temperatures. The SPS reference system is based upon a maximum microwave power radiation density of 30 kW/m^2.

A secondary but important aspect of the heat radiation process is that for life and reliability reasons radiation processes should not involve the flow of heat by liquid or vapor processes to a radiating surface. On the other hand, flow by conduction to a radiating surface requires a cross section of material and, therefore, mass through which the heat can flow. This latter consideration imposes a practical upper limit on the mechanical and electrical size of an individual microwave generator because of the high cost of transporting mass to synchronous orbit.

Meeting the heat dissipation requirement while simultaneously meeting all of the other requirements represented such a difficult problem that it was not until an investigation into this area by the DOE/NASA concept development program was completed recently that strong confidence developed in believing that it could be done. The system that has emerged and in which the magnetron directional amplifier is a key element will now be described [11].

The composition of the complete transmitting antenna is sufficiently complex to attempt a simplified description. For reasons having to do with launching the beam with a high degree of coherency, with freedom to radiate waste heat over the entire area of the transmitter, and eliminating microwave skin losses in waveguide runs, the transmitting antenna is designed as an active phased array, that is, the generation of microwave power is distributed over the surface of the transmitting aperture. There are, therefore, many radiating units that consist of a microwave genera-

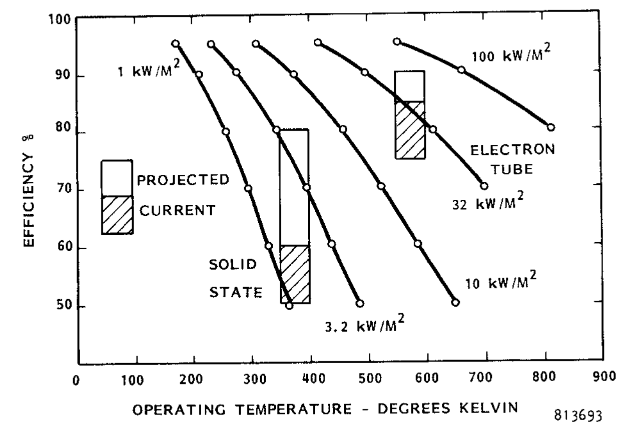

Fig. 4. Contours of microwave power output density as function of efficiency and operating temperature of microwave generators. Comparative positions of solid-state devices and electron tubes are shown.

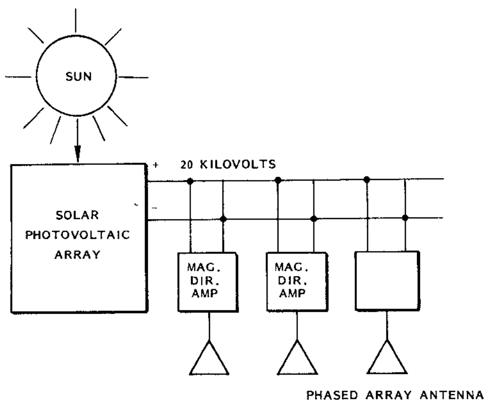

Fig. 5. Schematic showing interface of magnetron directional amplifier modules with solar array.

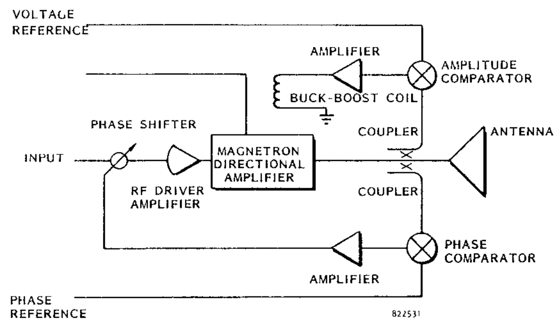

Fig. 6. Schematic showing how the phase and the amplitude of the magnetron directional amplifier output are controlled by phase and amplitude references and feedback control loops.

tor, its cooling radiator, a section of slotted waveguide radiator, and other elements. The radiating units are combined into power modules which are the smallest entities that can be replaced. The power modules make up a subarray, and the subarrays make up the completed antenna.

The radiating units are so designed and integrated with the balance of the system that they will radiate coherently with other radiating units on their microwave output side, and operate properly when connected in parallel across a high voltage bus on their dc input side. The ability of the magnetron directional amplifier to interface directly with the solar array is shown in Fig. 5. The ability to interface directly with the solar array, except for major circuit breakers, is of key importance in eliminating otherwise necessary power conditioning equipment whose development for space use would be a major undertaking and whose use would represent additional mass and heat losses to be disposed of in the SPS satellite.

The arrangement shown in Fig. 5 is made possible by the single high voltage terminal which is a characteristic feature of the magnetron directional amplifier and by the use of an automatic voltage matching feature of the magnetron directional amplifier. The voltage matching feature follows from the feedback arrangement shown in Fig. 6, in which the amplitude of the microwave output is compared with a reference amplitude and any resulting error signal is then fed into a closed-loop control system employing an operational amplifier to cause current to flow in a buck–boost coil which adds or subtracts to the residual field across the magnetron that is supplied by a samarium–cobalt permanent magnet. The change in magnetic field in turn changes the voltage–current characteristic of the magnetron so that the hard voltage bus causes the correct amount of current and power to flow into the tube to give the desired microwave power output.

The power output reference is a dc voltage that is supplied from a central logic center which can perform a number of functions by specifying the power output at which various areas of the transmitting array should operate. It can, for example, control the power distribution across the array and, therefore, the side lobes of the antenna pattern; it can cause the solar photovoltaic array to be operated at its most efficient point, or conversely, it can cause it to be operated inefficiently to match the power requirements of the earth's power distribution system; and it can be used to program the buildup of transmitted power as the satellite comes out of an eclipse by the earth.

To experimentally evaluate the amplitude control feature a large amount of data was taken on a magnetron directional amplifier that incorporated the common microwave oven magnetron. The performance was highly satisfactory, as shown in Fig. 7. In taking the data, the hard bus voltage was simulated by a power supply with a voltage regulated output. The data was taken with 100 Ω inserted between the tube and the power supply to simulate the resistance of a fuse and possibly some small inductance to limit the initial current flow should a short occur within the tube. The power dissipated in the resistance represented less than 1 percent of the power input to the tube.

Fig. 7 shows the range of current and voltage over which the tube will operate while performing as an amplifier with a nominal gain of 17 dB. It is noted that the output power is kept within ±3 percent of the constant value of power output at which the reference is set. Fig. 7 also shows representative voltage–current characteristics of the solar array and how the curves of constant power output from the magnetron directional amplifier intercept these characteristics to establish an operating point.

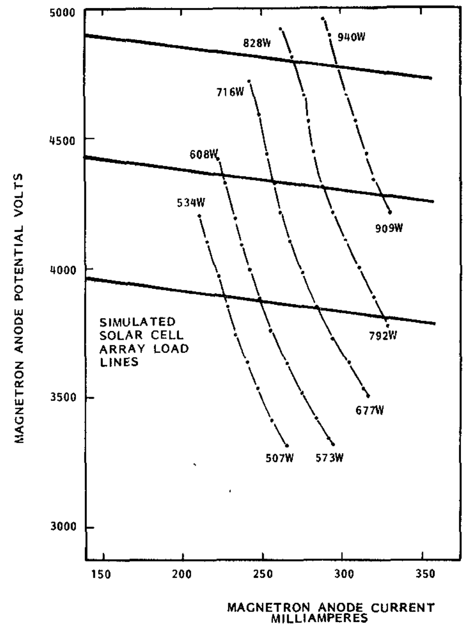

Fig. 7. Experimental data on the amplitude control system shown in Fig. 6, illustrating the achievement of nearly constant power output contours despite large changes in the power supply voltage applied to the magnetron anode.

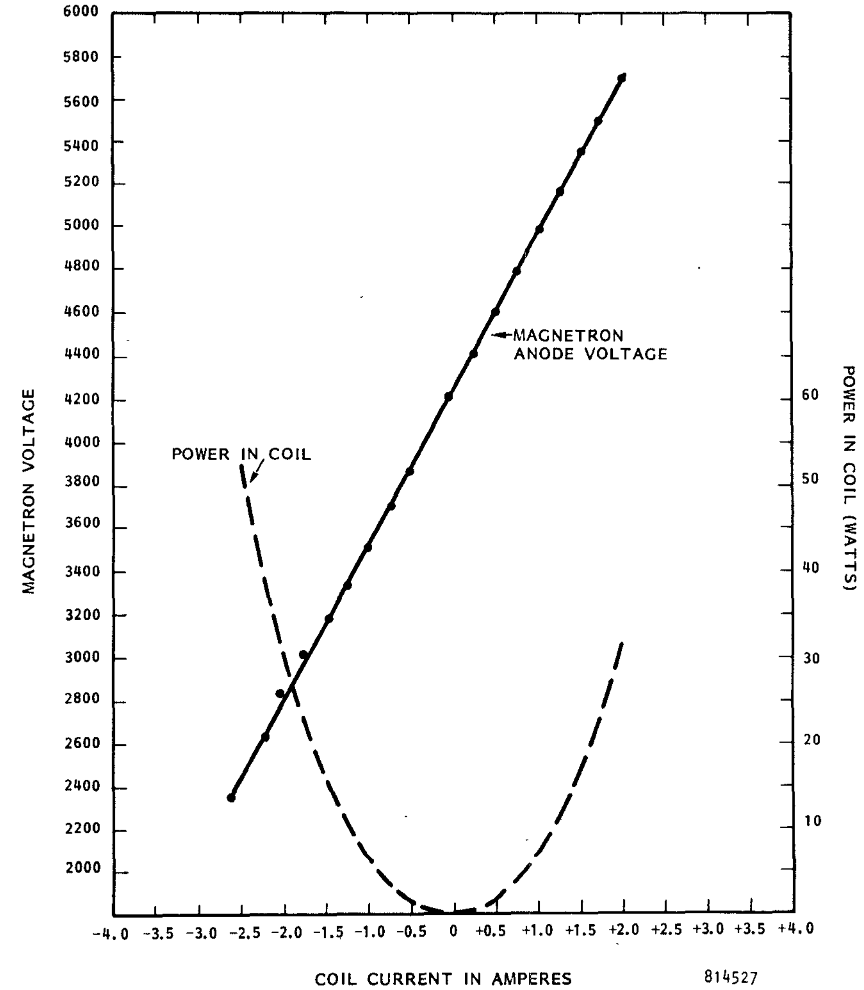

Fig. 8. Magnetron anode voltage and power dissipated in buck–boost coil as function of current in buck–boost coil.

Experimental data on the current and power in the buck–boost coil that are required to change the operating voltage of the magnetron are shown in Fig. 8. It is noted that only 10 W, or about 1 percent of the dc power input to the magnetron, is required to change the voltage over the range of 3400–5000 V or a ratio of 1.47. This wide range would seem to be an adequate ratio for any expected variation in the voltage output level of the solar cell array. The space magnetron proposed for the SPS system will operate at a power level of about 4 kW or about five times the level of the microwave oven magnetron, and is expected to absorb about 30 W in the buck–boost coil. The buck–boost coil will be incorporated into the magnetron package so it will not represent an additional separate component to be developed and produced.

While the amplitude of the microwave power output is being controlled the phase of the output is simultaneously tracking a reference phase transmitted by coax cable or stripline from a more central source. If the output phase is not tracking the reference then the error signal actuates some form of phase shifting device at the input of the magnetron directional amplifier to compensate for the phase shift that is going on inside of the magnetron directional amplifier and is being caused by changes in operating conditions imposed upon the magnetron. In the experimental investigation a mechanically moveable phase shifter was used for convenience, and the output phase was held to within $\pm 1°$ over the entire performance chart in Fig. 7.

The phase shift that occurs internally in the magnetron directional amplifier is the result of using the magnetron as an amplifier with the aid of an external passive directional device such as a ferrite circulator or a "magic T", as shown in Fig. 9. When used in this manner, the magnetron directional amplifier reacts to an externally injected signal by locking on that signal in frequency and changing its output phase relative to that of the injected signal by an amount that is proportional to the difference in frequency between the injected signal and the free running frequency of the magnetron and to the half-power of the ratio of the output power of the magnetron to the power of the injected signal. The free running frequency of the tube is dependent upon the current and voltage at which the tube is operated, upon its temperature, and upon change in dimensions with life, if any.

The operating range over which the tube can be operated and still remain locked on frequency will depend upon the drive level. For the data of Fig. 7 a 10-W drive was used and the nominal power gain was 17 dB.

The test bed with which experimental data were taken for amplitude and phase control behavior and for noise measurements is shown in Fig. 10. The test bed consists of the magnetron directional amplifier which combines a magnetron with a ferrite circulator, phase and amplitude control circuitry, and either a section of slotted waveguide as shown in the figure or a waveguide water load for output power measurements. The microwave driver for the magnetron directional amplifier was either a 10-W traveling wave tube, or another magnetron when low-level noise

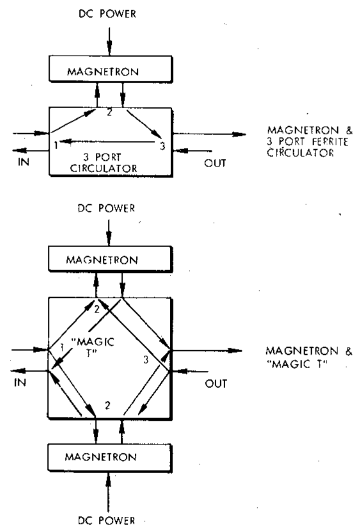

Fig. 9. Directional amplifier approaches using a magnetron combined with (a) a ferrite circulator, and (b) a "magic T."

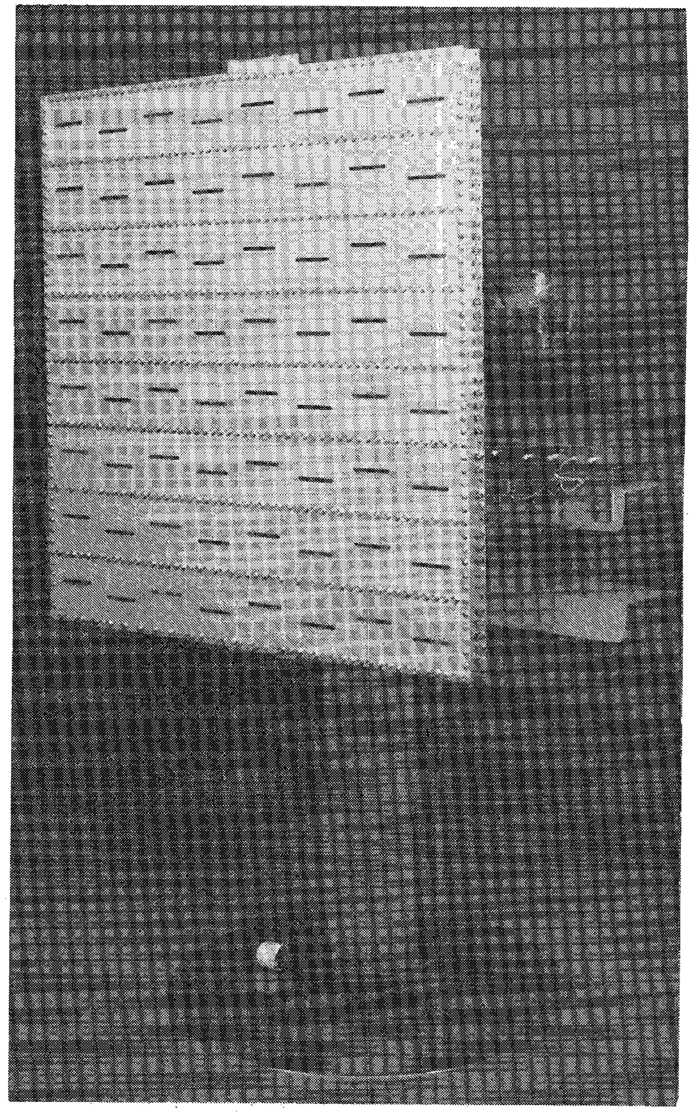

Fig. 10. Test bed for the phase and amplitude tracking investigation, shown with slotted waveguide load as an option.

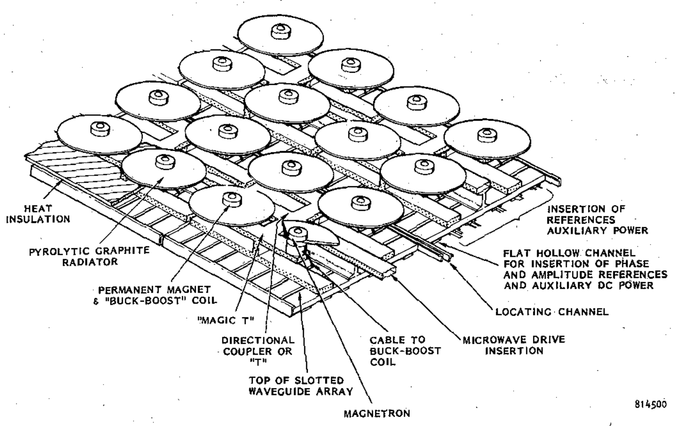

Fig. 11. Assembly architecture for the magnetron directional amplifier in the antenna subarray. Two subsections are shown. Microwave drive and all references and auxiliary power are inserted from the "backbone" of the subarray. The array has two distinct temperature zones. The zone at the top of the illustration is used to radiate the heat. The zone at the bottom is used for mounting of solid-state components.

measurements were to be taken. The slotted waveguide array used a novel fabrication technique in which thin (0.020-in thick) sheet aluminum was folded up to form the sides and back of a parallel array of waveguides. A slotted face plate was then welded to the parallel array to complete the assembly [12].

The proposed architecture of the power module for space use is shown in Fig. 11 [11]. It is made up of a number of radiating units as previously described. The power module has two thermal zones. One is a high temperature zone of about 300°C and is for the purpose of radiating waste heat into space. The other thermal zone is much cooler and is associated with the location of any solid-state devices that are needed in the control circuitry or for other purposes. The phase and amplitude references are channeled across the face of the slotted waveguide radiator. In Fig. 11 the magnetrons are shown with a radiating fin attached. The radiating fin is a tapered disk of pyrographite, selected for its combination of very desirable properties [11]. It has the heat conductivity of copper; but its density is only one quarter that of copper; it has an emissivity of 0.92 or nearly that of a black body, and it has a very low vapor pressure. In Fig. 11, the radiating unit consists of two magnetrons operating in to a "magic T" as in Fig. 9(b) rather than a single tube with a ferrite circulator.

The power module which consists of a number of radiating units is considered to be the unit which can be removed as an entity for servicing if that should be necessary. In turn several power modules comprise a subarray, and the subarrays compose the radiating antenna. The purpose of the subarray level is primarily to establish the reference phase which is then transmitted by cable or stripline to the radiating units.

The reference phase is established by the retrodirective array principle which eliminates mechanical misalignment of the transmitting antenna as a factor in both misalignment and scatter of the microwave beam. A pilot beam that is radiated from the center of the ground rectenna illuminates the SPS transmitting antenna with a reference phase front. This reference phase front is compared with a "clock" reference phase at a phase comparator location in each subarray. The relative phase of the two references is then conjugated, and it is the conjugated phase that is used as the reference phase for the power modules with that particular subarray.

III. Low Noise and Long Life Characteristics of the Magnetron Directional Amplifier

The radio frequency interference potential of the SPS system has been the principle objection to the SPS by some interest groups. It will continue to be an important factor but the seriousness of the situation has been substantially mitigated by recent noise measurements that have been made on the magnetron directional amplifier that used the ordinary microwave oven magnetron as a test vehicle [11], [12]. The measurements have indicated that the CCIR[1] noise emission requirements of -154 dBw/m^2/4 kHz can be met for random noise at frequencies outside of the band of 2.4–2.5 GHz that is reserved for industrial scientific, and medical applications of microwaves. And there is some hope that with additional effort harmonic radiation can also be held low enough to meet the CCIR requirement.

The low noise level found in the common microwave oven magnetron was one of the two important discoveries encountered in the assessment of the magnetron directional amplifier for the SPS. It was found that the ordinary microwave oven magnetron selected at random and run from a well-filtered dc power supply and with the external source of filament power removed after it was used to start the tube operation characteristically had a spectral noise density (noise in 1-Hz bandwidth) that was 160 dB below the carrier at frequencies removed from the carrier by more than 20 MHz. Without any tube development, and without any filters in the microwave output but with special external microwave circuitry on the mechanical support for the cathode, spectral noise densities as low as 196 dB below the carrier were found at frequencies (other than harmonics) removed 50 MHz or more from the carrier [11].

Table II translates these low noise measurements into the level of noise radiation that would be received on the earth from one SPS radiating 7.5 GW of carrier power and compares this level with the demanding CCIR requirements for such noise radiation. A safety factor of over 40 dB is indicated after using the very conservative assumption that the full gain of the antenna aperture associated with each magnetron directional amplifier at the power transmitting frequency of 2.45 GHz also applies to frequencies outside of the guard band.

The signal-to-noise level measurements on the directional amplifier indicated that they were independent of the gain level over the 10–26-dB range to which observations were limited [12]. This would be expected from theory and also from the observation that the magnetron operated

[1]International Radio Consultative Committee Regulation on Limits of Power Flux Density from Space Station.

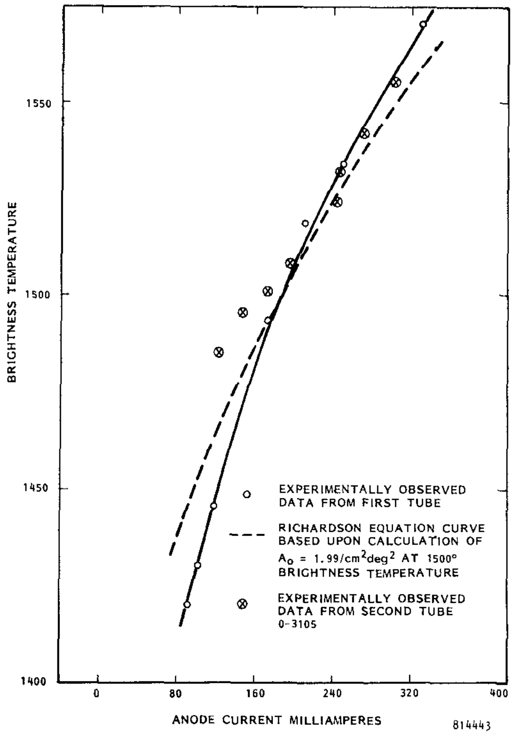

Fig. 12. Experimentally observed and theoretically predicted relationship between cathode temperature and anode current for microwave oven magnetron.

TABLE II
COMPARISON OF RADIATED NOISE AS MEASURED ON LABORATORY MAGNETRON DIRECTIONAL AMPLIFIER AND CCIR REQUIREMENTS BASED ON RADIATED POWER AT ISM BAND (2.4–2.5-GHz) EDGES

Total noise radiated power in 4 KHz bandwidth from 7.5 gigawatt transmitter on basis of experimentally measured carrier to noise ratio of 160 dB referenced to 4 KHz band.	7.5×10^{-7} Watts
Radiated power density per square meter at Earth in 4 KHz band assuming uniform radiation over a hemisphere	0.93×10^{-22} W/M^2
Safety factor over CCIR requirements (-154 dBw/M^2/4 KHz)	66.3 dB
Safety factor after taking gain of radiating apertures into account (0.29 square meters)	45.5 dB

as a free running oscillator exhibits the same high signal-to-noise ratio. In fact, a magnetron oscillator is used as a driver when sensitive noise measurements are made because of its superior noise qualities to that of the 10-W TWT driver that is normally used as a microwave driver.

Although the existence of noise close in to the carrier is not as important in the SPS application as noise removed from the carrier, sensitive noise measurements have been made on the close-in noise and found to be very low as well [12]. A typical level for phase added noise in a 1-kHz band that is 10 kHz removed from the carrier is 110 dB below the carrier.

A second important discovery made in the course of the investigation was the potentially very long life, measured in terms of fifty to one hundred years, that a tube specifically designed for the SPS could provide [12]. This projected long life is based upon observations of the operating temperature of the filament of a microwave oven magnetron when the magnetron is operating under the same conditions that produce low noise. The life of a carburized thoriated tungsten filament is dependent upon the temperature, being much greater as the temperature is reduced [12], [13], [14]. The emission current density requirements to supply the anode current of the magnetron are fortunately low and consistent with the low temperatures needed for very long life. The problem would normally remain, however, of externally regulating the temperature of the cathode to give just the required emission and no more in the interests of achieving long life.

Fortunately there is an internal feedback mechanism involving electron back bombardment of the cathode that automatically accomplishes this temperature regulation. The experimental evidence of this is shown in Fig. 12 [12]. In this figure, the observed temperature of the cathode is plotted against the anode current of the tube. This experimental relationship is seen to follow the slope that is predicted by the Richardson–Dushman equation for temperature limited emission as a function of the absolute (Kelvin) temperature. The two curves were matched to each other at an absolute temperature of 1888 K which corresponds to a Brightness temperature of 1500°C in Fig. 12. It was assumed that the magnetron current and emission current density are related by a simple multiplying constant.

The relationship established in Fig. 12 was subsequently repeated on another tube by another observer and reported in [11].

IV. Conclusion

The recent joint assessment of the SPS concept by the Department of Energy and NASA indicates that no "show stoppers" of a technical, environmental, or societal nature have been found. However, it indicated the need to further reduce the ranges of uncertainty in such areas as system cost and radio frequency interference. The recent work based upon the use of the magnetron directional amplifier has made it possible to reduce in a favorable direction the uncertainty in both of these areas. It has also prepared the way for a specific program of limited technology development to keep the development of the microwave power transmission portion of the system apace with the development of the other components in solar photovoltaics and space transportation.

Acknowledgment

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References

[1] P. E. Glaser, "Power from the sun; its future," *Science*, vol. 162, pp. 857–861, Nov. 22, 1968.

[2] W. C. Brown, "Adapting microwave techniques to help solve future energy problems," *IEEE Trans. Microwave Theory Tech.*, pp. 753–763, Dec. 1973.

[3] "The final proceedings of the solar power satellite program review, DOE/NASA satellite power system concept development and evaluation program," July 1980, *Conf.-800491*.

[4] "Program assessment report, statement of findings. SPS concept development and evaluation program," Rep. DOE/ER-0085, Nov. 1980.
[5] W. J. Robinson, "Wireless power transmission in a space environment," *J. Microwave Power*, vol. 5, Dec. 1970.
[6] R. M. Dickinson and W. C. Brown, "Radiated microwave power transmission system efficiency measurements," Tech. Memo 33-727 Jet Prop. Lab., Cal. Inst. Tech., Mar. 15, 1975.
[7] G. Goubau, "Microwave power transmission from an orbiting solar power station," *J. Microwave Power*, vol. 5, no. 4, pp. 223–231, Dec. 1970.
[8] W. C. Brown, "Experiments in the transportation of energy by microwave beam," in *IEEE Int. Conv. Rec.*, vol. XII, pt. 2, pp. 8–17, 1964.
[9] R. M. Dickinson, "Evaluation of a microwave high-power reception -conversion array for wireless power transmission," Tech. Memo 33-741, Jet Propulsion Lab., Cal. Inst. Tech., Sept. 1, 1975.
[10] W. C. Brown, "Electrical and mechanical improvement of the receiving terminal of a free-space microwave power transmission system," Raytheon Contractor Rep. PT-4964 NASA CR-135194, Aug. 1977.
[11] W. C. Brown, "Satellite power system (SPS) magnetron tube assessment study," Contract NAS8-33157 NASA Contractor Rep. 3383, Feb. 1981.
[12] W. C. Brown, "Microwave beamed power technology improvements," Final Report JPL Contract 955104, Raytheon Report PT-5613, May 15, 1980.
[13] "Solar power satellite microwave power transmission and reception," NASA Conf. Publication 2141, pp. 219–220.
[14] W. H. Kohl, *Handbook of materials and techniques for vacuum devices*. Reinhold, 1967, pp. 487–491.

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SAW Oscillators in UHF Transit Satellite Links

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***Abstract*—A 375-MHz surface-acoustic-wave (SAW) resonator controlled oscillator was developed for application in the Transit satellite marine navigation system. The SAW oscillator, in a 2-in^3 hybrid package, contains a heater, voltage regulator, and divider and is a direct replacement for a bulk wave oscillator and its multiplier chain. A short term stability of $2E-10$ and an aging rate of $3E-8$/day were achieved at 75°C. Comparison tests showed that the accuracy of the navigation system with the SAW oscillator was equivalent to the accuracy using the bulk oscillator.**

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I. Introduction

THE APPLICATION of a surface-acoustic-wave (SAW) oscillator in a commercial Transit satellite marine navigator and the test results will be presented.

The MX1102 marine navigation system receives signals from the Transit satellites [1] in the UHF band at 400 MHz. The Transit satellites circle the earth in 107-min polar orbits at an altitude of 600 nmi. The orbits do not

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