STATUS OF THE MICROWAVE POWER TRANSMISSION COMPONENTS FOR THE SOLAR POWER SATELLITE (SPS)

William C. Brown
Raytheon Company
New Products Center
Waltham, Massachusetts 02254

ABSTRACT

The status of key microwave components in the transmitter and reception portion of the solar satellite (SPS are reviewed.

Introduction

As shown in Figure 1 the major microwave components of the Solar Power Satellite (SPS) may be considered to be the transmitting antenna, the microwave beam, and the receiving array which collects the microwave power and converts it back into DC power at the Earth's surface. The development of the SPS concept has presented many challenges to the microwave component engineer who must work closely with the systems engineer to integrate suitable components into an overall system that operates at high efficiency and reliability. This paper reviews the progress that has been made in the decade since the conception of the SPS with special emphasis upon the space or transmitter portion of the system.

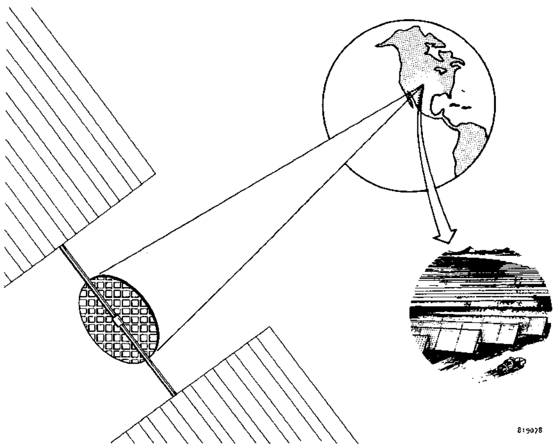

Fig. 1. Schematic of power from space system. Sun's radiant power is converted into microwave power in a synchronous satellite and beamed to earth for reconversion into ordinary power.

The emphasis is so placed because the need for an efficient ground collecting device has been filled by the rectenna device which simultaneously collects and rectifies the incoming microwave power while being relatively insensitive to the direction of the incoming beam or to minor spatial variations in its phase and amplitude. The rectenna is in a relatively well advanced state of development where its overall efficiency is in excess of 85%. Methods for fabricating it at high volume and low cost have been investigated.[1]

By contrast, many problem aspects of the space portion of the system remained unresolved until a recent program (1978-1980) under the sponsorship of the Department of Energy and NASA operating through the Jet Propulsion Laboratory and Marshall Space Flight Center investigated several alternative microwave generators including the magnetron used as an amplifier with the addition of external circuitry. In the experimental investigation of the magnetron surprising discoveries of low noise and potentially very long life were made.

The investigation went much further, however, and included integrating an ordinary microwave oven magnetron into a radiating unit involving a section of slotted waveguide array, and with arrangements to have the phase and amplitude of the radiated power follow phase and amplitude references. A large amount of experimental data was then taken on phase and amplitude tracking under conditions of large external and internal disturbances, on broadband noise, and on starting transients. In addition optical observations were made of filament temperatures so low that projected life times of tens of years could be made.

The study also made projections of electrical and physical size, efficiency, power output to mass ratio, and other characteristics of a passively cooled SPS space magnetron. Finally, it studied the interface between the radiating unit and other portions of the SPS microwave system. In particular it was found that the amplitude tracking feature on the magnetron would permit interfacing the magnetron bank directly with the solar photovoltaic array and eliminate nearly all of the power conditioning which would normally be necessary.

From the viewpoint of the impact of the findings of this study upon the SPS reference system, the system integrator was able to project a 25% decrease in the mass of the satellite, a reduction in cost of at least that amount, and a considerable reduction in complexity and risk.[2] Another significant benefit is that the projected SPS magnetron could be easily assimilated into the existing production capability for microwave oven magnetrons.

Principles of Operation and Interface Considerations

The schematic of the magnetron directional amplifier (injected locked magnetron) is shown in Figure 2. When the single port magnetron device is combined with a directional device such as a ferrite circulator it reacts to an externally injected signal by locking on that signal in frequency but 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.

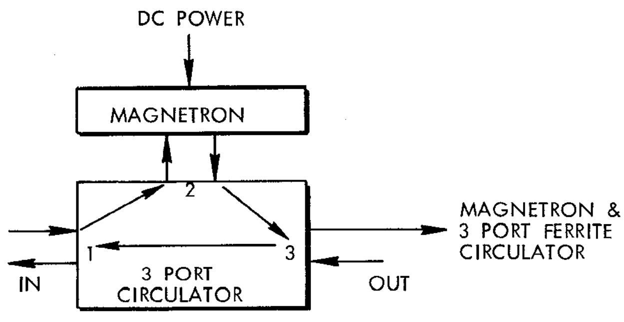

Fig. 2. Magnetron directional amplifier using magnetron and ferrite circulator.

As shown in Figure 3, the magnetron directional amplifier is given the ability to follow amplitude and phase references by means of comparator circuits at the output of the directional amplifier and feedback loops which control actuators that change the phase and amplitude of the output. In particular, the power output of the magnetron is controlled by varying the magnetic field imposed upon the tube by means of a buck-boost coil. This latter feature makes it possible to operate magnetrons in parallel with each other directly from a hard voltage bus directly connected, except for a high power circuit breaker and a rotary joint, to the photovoltaic array itself. Only a fuse and a low value of resistance are interposed between the magnetron and the high voltage bus. The schematic shown in Figure 4 is a not excessively simplified schematic of what the amplitude control feature makes possible. An important corollary of the amplitude control principle is that with appropriate logic circuits at a central control point the solar photovoltaic array can be operated at or near its most efficient operating point. Or, in another operational format, the SPS can automatically adjust itself to follow the changes in load dictated by the exigencies of the earth distribution system.

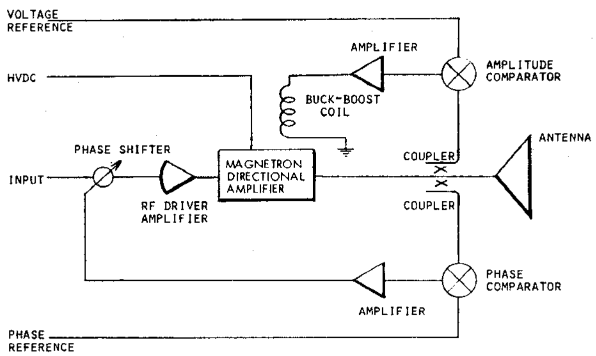

Fig. 3. Schematic showing how the phase and the amplitude of the magnetron directional amplifier output is controlled by phase and amplitude references and feedback control loops.

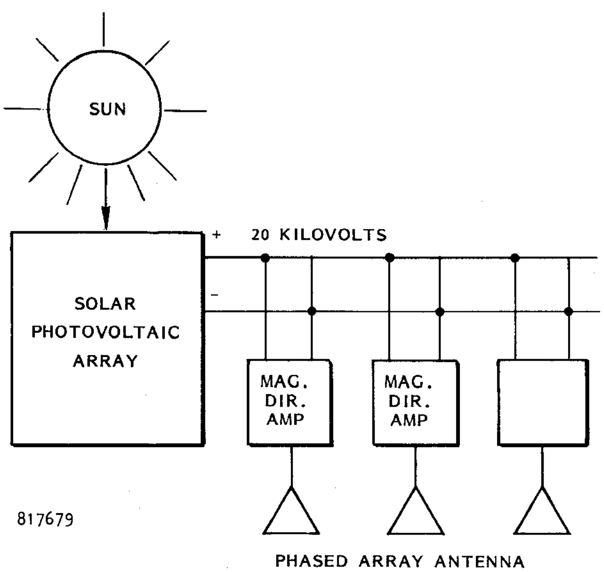

Fig. 4. Schematic showing interface of magnetron directional amplifier modules with solar array.

A major constraint on the design and power handling capability of the SPS transmitter is the necessity to reject to space any heat which results from inefficiencies in the microwave generator. Studies were made on how the large one kilometer diameter area available for the radiation of this heat could best be broken down into individual tubes with their own passive radiators to minimize the mass of the system. The results of this investigation are shown in simplified form in Figure 5. Each tube and its radiator is associated with a section of slotted waveguide radiator. The waveguide radiator size is quantized and this in turn quantizes the size of the radiating fin on the magnetron. Typically the fin is about 15 inches in diameter and radiates 0.56 kilowatts at 300^{o} Centigrade. It is projected to be made from pyrographite, a well-known material that has twice the heat conductivity of copper but only 25% of its density. At the intended 85% efficiency the tube will generate 3.2 kilowatts of power. A typical mass projected for the tube and radiator combined would be 1.0 $\pm$0.2 kilograms or approximately 0.3 kilograms per kilowatt of microwave radiated power.

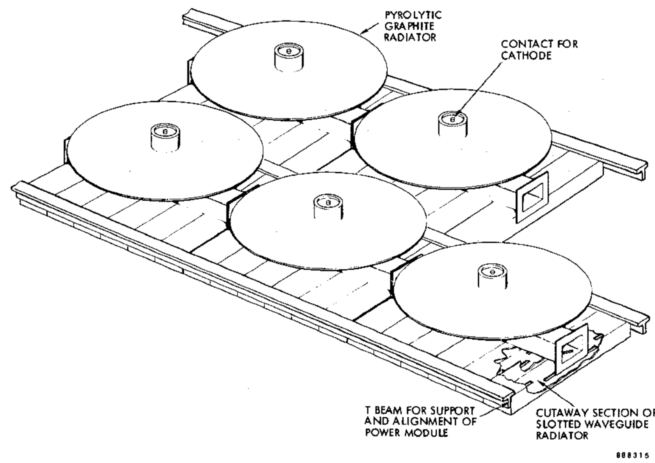

Fig. 5. Basic concept of assembly of packaged magnetron directional amplifier and slotted waveguide units into a power module.

Experimental Data

Experimental data were taken either from the complete radiating unit shown in Figure 6 or with a waveguide water load replacing the slotted waveguide radiator. The unit as shown consisted of a microwave oven magnetron, a ferrite circulator, a 30 inch square slotted waveguide section, phase and amplitude comparator circuits, feed back circuitry, and actuators to cause phase and amplitude to follow a reference. The arrangement follows the schematic of Figure 3. The experimental data taken at a frequency of 2.45 GHz follows.

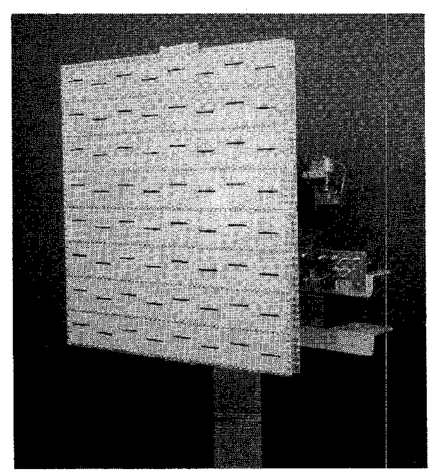

Fig. 6. Test bed for the phase and amplitude tracking investigation. Shown with slotted waveguide load, other load option is waveguide water load.

Phase Control. The output phase followed the fixed phase reference within ±1° when the output power was changed from 500 to 900 watts as shown in Figure 7 and under a condition of ten watts of microwave drive power.

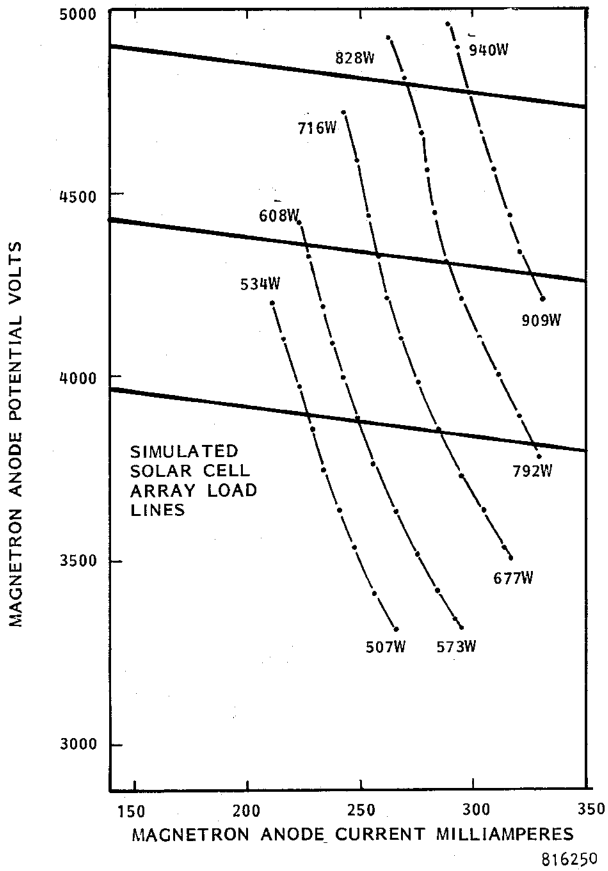

Fig. 7. Experimental data on the amplitude control system shown in Figures 3 and 6.

Amplitude Control. To obtain this data a "hard bus" was simulated by means of a voltage regulated power supply. Figure 7 shows the ability to track a preset amplitude reference over a wide range of input voltage and current under this condition. In general the amplitude reference was followed within ±3% over the entire range of locked operation. The control circuit is simple; its basic control ratio is described by a first order differential equation. Neither lead nor lag compensation was added to change the order. Nevertheless, the response time was less than two milliseconds and the residual error 2 or 3%. Most data were taken with a 100 ohm resistor interposed between the tube and the voltage regulated power supply. The corresponding power loss was about 1%. Figure 7 shows data taken with an 800 ohm resistor to simulate slope of solar array. Reference following was better with the 100 ohm resistor because of higher system gain. The control system was also used to suddenly reduce magnetic field for turn on of tubes.

Noise Output. Spectral density noise (noise in 1 Hz bandwidth) from the output of an unmodified microwave oven magnetron was measured to be 175 dB below the carrier at the edge of the ISM band, or 50 MHz from the operating frequency of the tube. This is a very low noise level and special equipment with high sensitivity had to be built to make such measurements. There is reason to believe that such low noise levels should not interfere with communications.[3] However, it was found possible to reduce the noise further, to 195 dB below the carrier, by adding special microwave filters on the mechanical support of the cathode. No filters in the output were used for any of the measurements.

Experimental data involving life of cathode and efficiency of tube were also obtained from other experiments.

Low Filament Temperature for Long Life. When operated under conditions that produced the low noise, temperatures as low as 1850° Kelvin were measured on the carburized thoriated tungsten filaments of several magnetrons assembled with optical windows. Based on extensive engineering and life test data on such filaments such a temperature in the projected space tube design would be associated with 50 to 100 year life.[4]

Efficiency. Carefully measured overall efficiency (ratio of microwave power output to DC power input) of 82 ±1% was achieved on a microwave oven magnetron operated with higher values of magnetic field than normal.[4] The normal operating efficiency of the microwave oven magnetron is 65 to 70%.

Summary of the SPS System Characteristics

The proposed DC power output at the Earth from the SPS for most economical operation is somewhere between three and ten gigawatts. The proposed efficiency with which this power is transferred is between 60 and 70%. The frequency of operation is 2.45 GHz, corresponding to the center of the band reserved for ISM (industrial, scientific, medical) applications. Attenuation and scattering effects at this frequency in the Earth's atmosphere are normally one or two percent but never greater than 10% under the most adverse weather conditions.

The distance of microwave transmission is over 23,000 miles. To obtain 90% aperture to aperture transmission efficiencies, a transmitting aperture of one kilometer and a receiving aperture of ten kilometers are used. The transmitting aperture is sufficiently large to be able to radiate all the dissipation losses associated with eight gigawatts of radiated microwave power, assuming an 85% efficiency figure for the microwave generator.

The power from such a large antenna is radiated coherently into a narrow beam with only small side lobe and scattering losses by using the principle of the retrodirective array in which a pilot beam located in the center of the ground rectenna establishes a reference phase across the transmitting antenna. This reference phase is then compared with a local clock phase and the conjugate of this phase used to establish the reference phase for use by the magnetron directional amplifier or other generator.

The rectenna on the ground collects the energy at nearly 100% efficiency and converts it into DC power with 85 to 90% efficiency.

References

1. W.C. Brown, "The Design of Large Scale Terrestrial Rectennas for Low Cost Production and Erection". Proceedings of the 1978 IEEE MTT-S International Microwave Symposium, IEEE Cat. #78CH1355-7 MTT, pages 349-351.

2. "Satellite Power Systems (SPS) Concept Definition Study", Rockwell International SSD 80-0108-7, Contract NAS8-32475 DPD 567 MA-04, October 1980.

3. W.C. Brown, "Satellite Power Systems (SPS) Magnetron Tube Assessment Study", Final Report, Contract NAS-8-33157, July, 1980. Raytheon Report No. PT-5653.

4. W.C. Brown, "Microwave Beamed Power Technology Improvements", Final Report, JPL Contract No. 955104, May 15, 1980. Raytheon Report No. PT-5613.