Adapting Microwave Techniques to Help Solve Future Energy Problems

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Abstract—The relationship between microwave techniques and the growing concern for future sources of energy is reviewed. The relationship is specifically explored in the use of a microwave beam to efficiently transport power from an array of solar photovoltaic cells in space to the earth's surface. The transition from a laboratory technology of microwave power transmission to a 10-GW 23 200-mi transmission system is examined in detail.

Introduction

ELECTRICAL power is such a desirable form of energy that its demand is expected to increase fivefold by the year 2000. Unfortunately, the present methods of generating electrical power pollute the environment and consume natural resources at a prodigious rate [1]. Within the past 20 years, however, three new technologies have been developed which can work together to provide continuous and pollution-free electrical power derived from a nearly inexhaustible source of energy, the sun [2], [3].

The first of these technologies is the solar photovoltaic cell, invented in 1954. This device transforms the sun's energy directly into electrical power without the necessity of a thermal cycle or any moving parts and with potentially high reliability and long life. The second technology is our newly won space capability, which permits transfer of the solar photovoltaic cell to space where it can be illuminated by the sun with close to 99-percent duty cycle if the cell is placed in a synchronous, equatorial orbit. This arrangement removes the limitation of low duty cycle (typically 10 percent) and the need for outsized arrays and electrical storage facilities when the solar cell is used in a terrestrial environment. The third technology is the efficient free-space transmission of power by microwave beam. This latter technology allows the electrical power generated in space to be coupled to the earth with high efficiency if a wavelength of about 10 cm is used. At this wavelength the normal atmospheric attenuation is about 2 percent, becoming as great as 6 percent in torrential downpours.

Transferring power from a space satellite is an entirely new application [4] for microwaves, which will challenge the microwave engineer with its technology requirements while providing him with a new opportunity to contribute to man's quality of life. The various microwave technologies that are involved are: 1) the efficient conversion of dc power into microwave power; 2) the antenna technology of forming a narrow, efficient beam of microwaves and efficiently absorbing that beam on the earth's surface; 3) the conversion of the microwave power back into dc power at the earth's surface.

The basic technology of efficiently transferring power by microwave beam has been under study for a number of years, receiving both government and private support [5]–[8]. Because of this work and associated activity on the components of the system, the development of microwave power transmission has now reached the point where most knowledgeable people who have followed the development believe that efficient transfer of large amounts of microwave power by microwave beam is not only possible, but also practical for a number of applications that have been considered.

The incorporation of a microwave beam transmission link into the satellite solar power station, however, represents a new application orientation of the power transfer system. In the past, the transmitter portion of any proposed system has either been ground based or, if in a satellite, its weight represented only a small portion of the total satellite weight. Getting rid of the heat resulting from losses in the generator, while important, has not been critical, nor has reliability been a matter for which years of uninterrupted operation have been required.

In studying the subject of adapting microwave techniques to a system which brings power from space, it is soon found that the system is so large and assumes characteristics so different from any other existing microwave system that the subject cannot be intelligently discussed without a comprehensive preliminary study and the establishment of a preliminary baseline design for the system. Such a study has been undertaken and completed by a four-company team comprised of personnel from Arthur D. Little, Inc., Raytheon Co., Grumman Aerospace Corp., and Textron, Inc. [4], [9], [10].

This study not only examined the technical feasibility of the concept, but also explored its economic feasibility, land-use requirements, safety aspects, and proposed timetable for building an operational system. It was found that its economic feasibility depended upon transportation costs, which in turn depended upon the weight of the satellite portion of the system and also upon a major reduction in the cost of solar cells. The cost of the microwave power transmission portion of the system was low relative to these two other costs. Land use was determined not to be a major problem or cost.

The safety aspects appear to be limited to the immediate region of the incoming beam, or to a land area of about 100 km^2, which is large enough to include a substantial guard ring around the edge of the beam. With such a guard ring the power density at the perimeter is reduced to levels considerably below the present safety standards for continuous exposure. At the center of the beam the power density would still be well within the short-time exposure standards and would represent no hazard to the structure of airplanes flying through the beam or to passengers within an airplane with metal skin. The perimeter of the ground area would be fenced to exclude humans and large animals. Maintenance personnel working inside the area would be suitably protected.

The proposed timetable for building an operational system

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is in the 15–20-year time period. The recommendation at the present time is not to make a commitment to the construction of such a system but to do some of the preliminary planning and long lead time technology to keep open the option of building such a system, in the event that sociological and technological developments during the next decade make this approach to a future source of energy an attractive alternative to other approaches.

The four-company study evolved a baseline design which was considered feasible from an engineering point of view. This baseline design will be used in this paper, recognizing that it will be modified by subsequent study but that it has generally established many properties and characteristics of the system.

The microwave power transmission portion of this study was primarily concerned with the transition between a free-space power transfer technology that has been established at a low power level in a terrestrial laboratory to a very high power level in a system primarily located in space. This transition is not an easy one because of the demands of the system for high efficiency and reliability, augmented by the requirements imposed by space as an operating environment for the transmitter. Fortunately, however, there are many design resources in the form of new materials, and in sophisticated antenna and device technology which can be combined to fulfill the exacting requirements of the system. This paper will discuss that transition.

System Requirements

A condensed list of the system requirements on microwave power transmission is given in Table I. A detailed explanation of the development of the system requirements is outside the scope of this paper. However, a brief discussion may be useful in understanding the main features of the system. The level of power, for example, is set by the level at which the capital cost per kilowatt is minimal. The value of efficiency, which includes interchange of dc and microwave power at both ends of the system, was chosen as a realistic goal. The transmission distance is set by the requirement that the earth and the microwave transmitter be in synchronous rotation. The frequency is largely determined by the desire to keep incoming attenuation in the earth's troposphere during very heavy rainstorms to less than 0.5 dB. Long life is an economic necessity as well as a requirement for high reliability. Light weight is required because of the cost of transporting material from earth into space. The narrow-beam requirement is a property of the system optics. The cost figure was arbitrarily set to be consistent with the results of a cost study that has been made of the various elements of the system.

Present Laboratory Technology

The starting point in applying microwave power transmission to the Satellite Solar Power Station (SSPS) is the well-advanced technology of microwave power transmission as it now exists in the terrestrial laboratory [5]–[7]. To discuss this technology it is convenient to divide a microwave power transmission system into its three principal elements as shown in Fig. 1. These elements are: 1) conversion of dc power into microwave power, 2) the forming of the microwave beam and free-space power transmission, 3) capture of the microwave power and conversion to dc power at the receiving end. Each element has its own efficiency, and the overall efficiency is the product of the three separate efficiencies. The efficiencies are defined to adequately handle any interfaces between the elements.

TABLE I

Requirements of the Microwave Power Transmission System

High power	$3 - 15 \times 10^{9}$ watts
High efficiency	68%
Transmission distance	22,300 miles
Frequency	2 - 4 GHz
Passive radiation of all waste heat	
Long life	30 years
Light weight in space	< 2 lb/kW
Narrow beam	3×10^{-4} radians
Pointing accuracy	2.8×10^{-6} radians
Acceptable cost	< $200/kW
Minimum radio frequency interference	

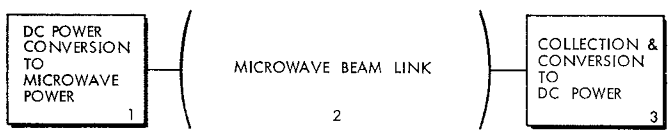

Fig. 1. Elements of a free-space microwave power transmission system.

TABLE II

Microwave Power Transmission Efficiencies

	Efficiency Presently Demonstrated[a]	Efficiency Expected with Present Technology[a]	Efficiency Expected with Additional Development[a]
Microwave Power Generation Efficiency (η_g)	76.7[b]	85.0	90.0
Transmission Efficiency from Output of Generator to Collector Aperture (η_t)	94.0	94.0	95.0
Collection and Rectification Efficiency (Rectenna) (η_r)	64.0	75.0	90.0
Transmission, Collection, and Rectification Efficiency ($\eta_t \eta_r$)	60.2	70.5	85.0
Overall Efficiency ($\eta_g \eta_t \eta_r$)	26.5[c]	60.0	77.0

[a] Frequency of 2450 MHz (12.2-cm wavelength).

[b] This efficiency was demonstrated at 3000 MHz and a power level of 300-kW CW.

[c] This value could be immediately increased to 45 percent if an efficient generator were available at the same power level at which the $\eta_t\eta_r$ efficiency of 60.2 percent was obtained.

Table II indicates the efficiencies that have been achieved for the three elements. Additional columns of efficiencies reflect the best that could be achieved with present technology and what could be expected after additional research and development to improve the efficiencies.

The typical tools used in the laboratory [6], [7] are shown in Fig. 2. An off-the-shelf magnetron in the 2.4–2.5-GHz ISM band excites a dual-mode horn whose special properties are that it has negligible sidelobes and radiates a beam which is Gaussian in both the near and far field. A specially designed

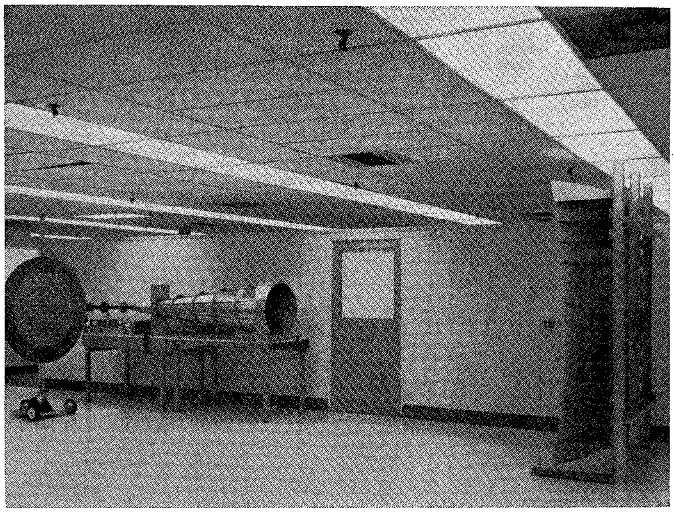

Fig. 2. Laboratory setup for demonstrating free-space microwave power transmission consists of microwave generator, dual-mode horn for launching the beam, ellipsoidal reflector for changing the divergent beam to a convergent beam, and a rectenna for intercepting the beam and converting the microwave power into dc power. In the setup shown, an efficiency from the output of the magnetron to the dc output of the rectenna is limited to 50.5 percent, principally because the microwave beam is larger in diameter than the rectenna at the point of intersection. An efficiency of 60.2 percent was measured with the rectenna placed a few feet in front of the horn where 94 percent of the energy measured at the horn input was intercepted.

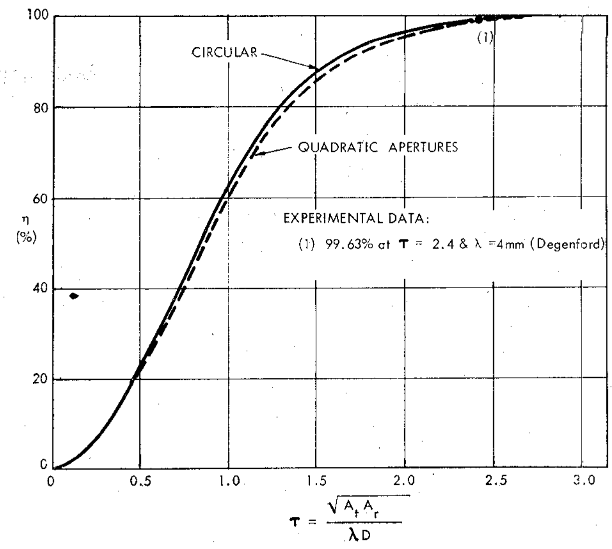

Fig. 3. Microwave beam transmission efficiency as a function of τ.

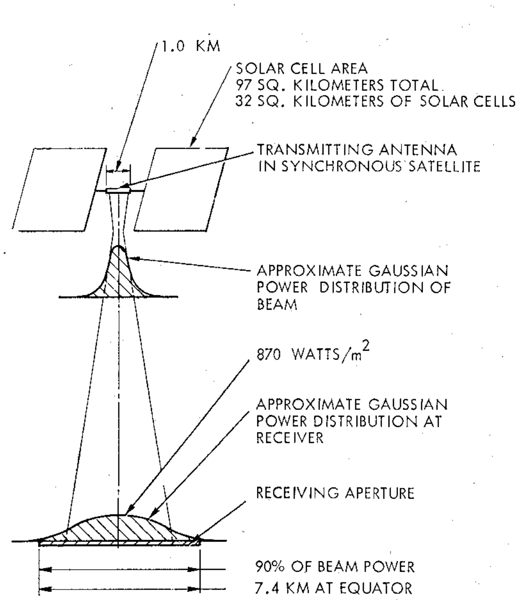

Fig. 4. Dimensions and essential physical features of the SSPS for a 10 000-MW system. Radiation wavelength of 10 cm is assumed.

ellipsoidal reflector is available for refocusing the microwave beam into an initially convergent beam. The receiving device located on the platform on wheels is a rectenna, a device which simultaneously absorbs and rectifies the incident microwave radiation. The rectenna principle [11], which breaks down the large aperture into many small apertures and terminates each one with a rectifier, is vital to any long-distance transmission system since it removes the high directivity and pattern-matching problems of conventional large-aperture devices.

The technology of the microwave beam itself has been theoretically investigated by Goubau and others [8], [12]–[14]. Goubau [12] has provided a curve (see Fig. 3) which shows the efficiency as a function of the parameter τ. τ is defined as

$$\tau = \frac{\sqrt{A_t A_r}}{\lambda D}$$

where

- A_t area of transmitter aperture;
- A_r area of receiving aperture;
- λ wavelength of radiation;
- D distance separating transmitting and receiving apertures.

Fig. 3 shows that the efficiency can be very high and that it is independent of distance in a lossless propagation medium, providing that the aperture areas are scaled with the distance. Because of this scaling aspect, the experimental checks in a laboratory, such as the one [14] shown on Fig. 3, are applicable to any distance. The relationship shown in Fig. 3 assumes an optimum illumination distribution pattern which closely approximates a truncated Gaussian for values of τ corresponding to high efficiency. It also assumes a spherical phase front at the apertures with a radius of curvature equal to the distance D between the apertures.

General Factors Involved in Applying Microwave Technology to the SSPS

The size of the transmitting and receiving aperture areas for the SSPS can be determined with the aid of Fig. 3. It should be noted that the minimum total aperture area occurs when the two apertures are equal in area. However, it appears that there is a better economic tradeoff if the size of the transmitting antenna is set at about 1 km in diameter. This is large enough to accommodate the passive radiation of the waste heat which will be generated in the dc–microwave conversion process. If a 1-km-diameter transmitting antenna and a radiation wavelength of 10 cm are assumed, then the overall physical dimensions of the microwave power transmission system for the SSPS will be as shown in Fig. 4.

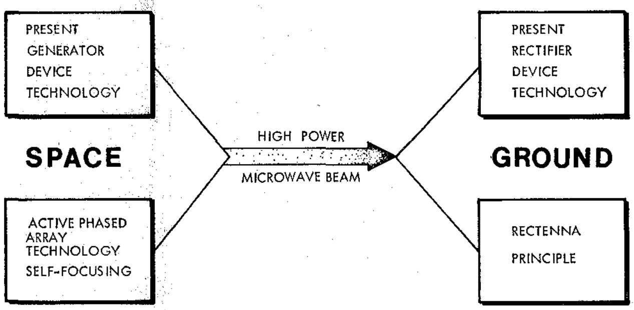

Fig. 5. General approach to meeting requirements imposed on the microwave power transmission system in the SSPS.

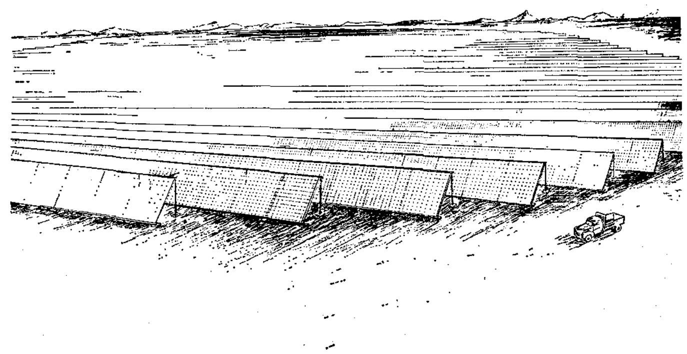

Fig. 6. Artist's sketch of the SSPS rectenna, the electronic device that captures the energy from the microwave beam and simultaneously converts it into dc power for distribution on a conventional power grid. The rectenna need not be accurately pointed toward the transmitting antenna for efficient operation, and its operation is independent of any distortion of the microwave beam as it passes through the earth's atmosphere.

Although there are many design resources which contribute to the successful structuring of a microwave power transmission system for the SSPS, the most important tools are combining the present generator device technology with adaptive and active-phased-array concepts in the transmitter [15] and the solid-state rectifier with the rectenna principle in the receiver, as shown in Fig. 5. Such combinations of devices and antenna principles not only remove the power limitation restriction of the individual device, but also introduce new principles which make the construction of very large-aperture transmitting and receiving antennas practical.

In the following material, the adaptation of current rectenna technology to the ground portion of the SSPS system will be discussed first. This will be followed by a discussion of the adaptation of dc–RF energy conversion technology to the SSPS transmitter, and the interface between the conversion devices and the transmitting antenna. Finally, the approach to forming a sharp beam with low side-lobes and scatter will be discussed.

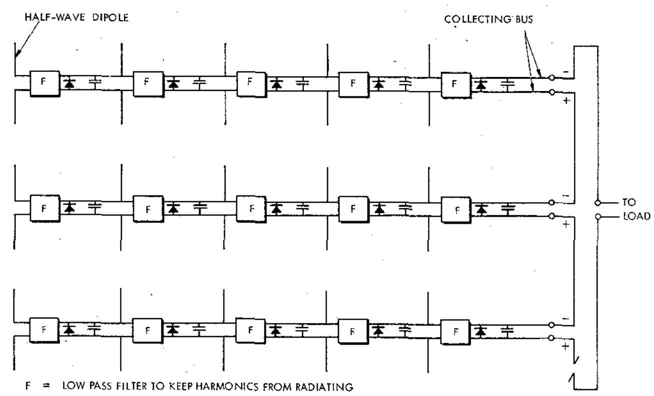

Fig. 7. Interconnection arrangement of half-wave dipoles, wave filters, rectifier circuits, and collecting buses in the SSPS rectenna.

Adaptation of Present Rectenna and Rectifier Device Technology to the SSPS

An artist's sketch of the ground rectenna located on the earth at a latitude of 40° is shown in Fig. 6. The face of the stepped rectenna is placed approximately normal to the direction of the microwave beam; however, this orientation is not critical. The rectenna itself consists of a two-level structure: the back level is an open-mesh metal screen and the front level consists of many half-wave dipoles, their associated rectifier circuitry, and dc bus lines. In this application, an effort has been made to design a rectenna of maximum simplicity and minimum cost.

Fig. 7 shows a schematic of the present baseline design of the top level of the rectenna. There are a large number of half-wave dipoles which absorb the microwave power. The absorbed power first passes through a microwave low-pass filter, which prevents radiation of harmonic energy and enhances the overall efficiency of the rectenna element, and then passes into a simple half-wave rectifier circuit where it is converted into dc power. A 20–40-pF capacitance provides ample storage for a ripple filter. The position of the capacitance is also used to tune the rectifier circuit and could also be used as a microwave short, a quarter-wavelength from the next half-wave dipole to the right to prevent loading of that dipole by circuitry to its left. The two sides of the line also function as dc buses, taking the dc power out of the system.

This circuitry is currently being developed at the level of the individual rectenna element using techniques which can be easily converted into stripline configurations. Fig. 8 shows the actual laboratory rectenna element, while Fig. 9 shows experimental results. The present overall rectenna element efficiency of 80 percent and the output of several watts are made possible by the gallium arsenide Schottky-barrier diode. It is expected that the overall efficiency of the rectenna element can be substantially improved toward the 90-percent objective level.

Table III lists some of the statistics of the rectenna. Rectenna costs have been estimated on the basis of material and labor costs for an item which can be highly automated. As an example of the need for extreme automation, the number of diodes in one SSPS rectenna array would require a year's production at a rate of manufacturing of 18 000 diodes/min. Yet the amount of material required would be less than 4000 lb because of the very small chip size in the diode.

Adaptation of Present Microwave Generator Device Technology to the SSPS

The space environment imposes a severe requirement on the dc–microwave conversion process in that any waste heat due to inefficiency of operation must be disposed of by passive radiation. It follows that the power rating of the generator must be relatively low and that it must be run at a relatively high temperature since it represents the heat source at the center of a radiator whose radiation capability is proportional to the fourth power of the absolute temperature.

It also follows that the device should operate at a high

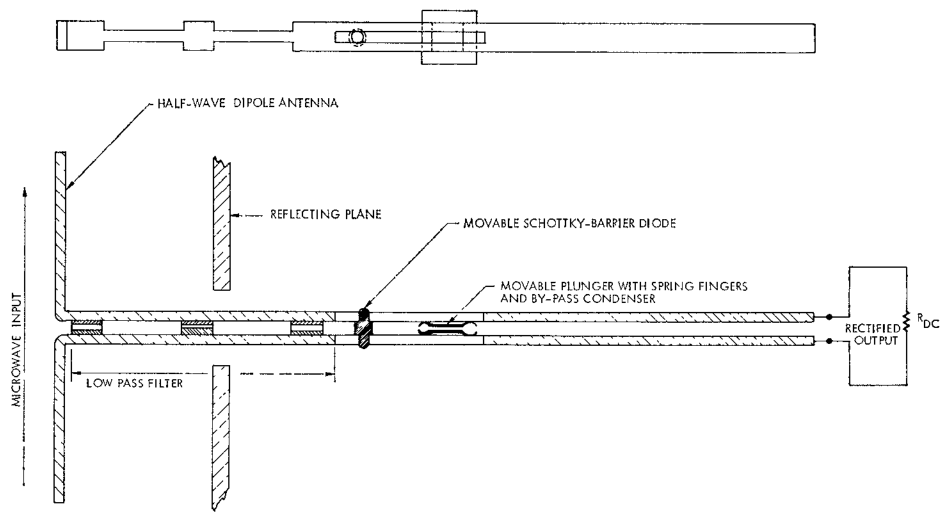

Fig. 8. Experimental rectenna element containing two sections: low-pass filter and half-wave rectifier using Schottky-barrier diode. Efficiency of 80 percent was achieved.

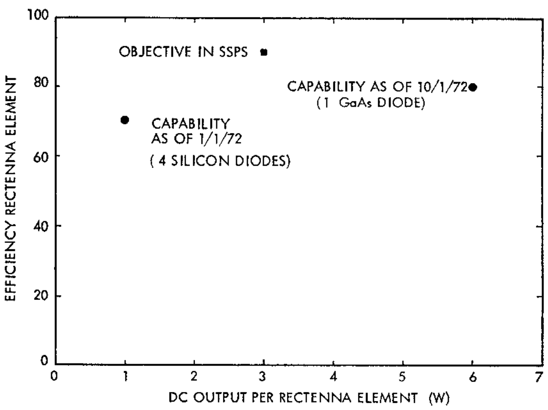

Fig. 9. A breakthrough in the power handling and efficiency capability of rectenna elements has recently been achieved. The objective power level has been exceeded.

TABLE III

STATISTICS ON RECTENNA

Wavelength	10 cm
Rectenna diameter	7.4 kilometers
Total area	43 x 10^6 square meters
Average power density	
10,000 megawatts dc	232 watts/square meter
5,000 megawatts dc	116 watts/square meter
Total number of rectenna elements	1.23 x 10^{10}
Rectenna element density	284/square meter
Maximum power per element	
10,000 megawatts dc	3.0 watts
5,000 megawatts dc	1.5 watts
Cost per Kilowatt of D.C. Output	
10,000 megowatts dc	$ 50.00/kW
5,000 megowatts dc	$100.00/kW

efficiency as well as at a high temperature since the useful output of a generator which is dissipation limited is proportional to the factor $n/(1-n)$ where n is the efficiency. Hence, a 90-percent efficient device has an output nine times its dissipation, an 80-percent efficient device has an output four times its dissipation, while a 50-percent efficient device has an output only equal to its dissipation.

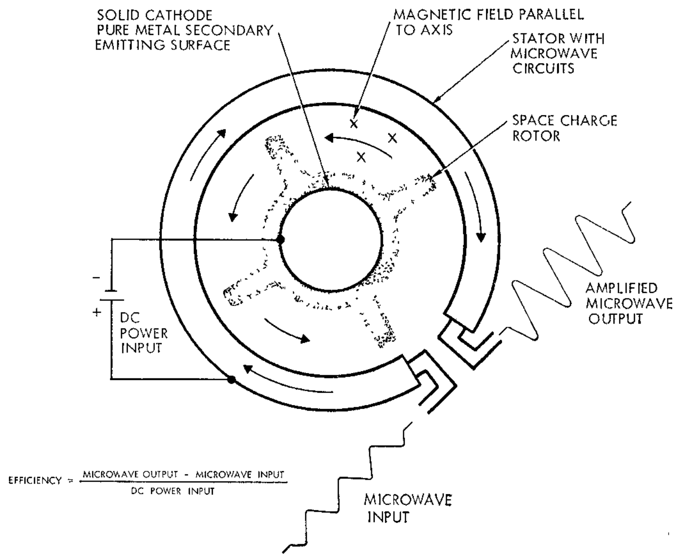

Fig. 10. Principle of operation of the Amplitron. Rotating spokes of space charge induce currents into the microwave circuit and provide efficient amplification of the microwave input signal. Dc–microwave conversion efficiencies of over 85 percent have been obtained from the crossed-field device.

The most efficient microwave generator devices available are electron tubes. Current solid-state devices are comparatively inefficient and incapable of operating at the high temperatures required for heat dissipation purposes. However, the current status does not proclude their application at some future time if breakthroughs in solid-state device technology should occur.

The electron tube which best meets the demanding requirements of the SSPS is the Amplitron [16]–[18] (sometimes called the continuous cathode crossed-field amplifier), which in this application combines a very high efficiency with an extremely long life because of the optional use of a pure-metal secondary emitting cathode. The operating principle of the Amplitron is shown in Fig. 10. While the efficiency and long-life cathode of the Amplitron do not necessarily preclude other device approaches, these features are of such importance that it is well justified to carry out the details of a baseline design using this device approach.

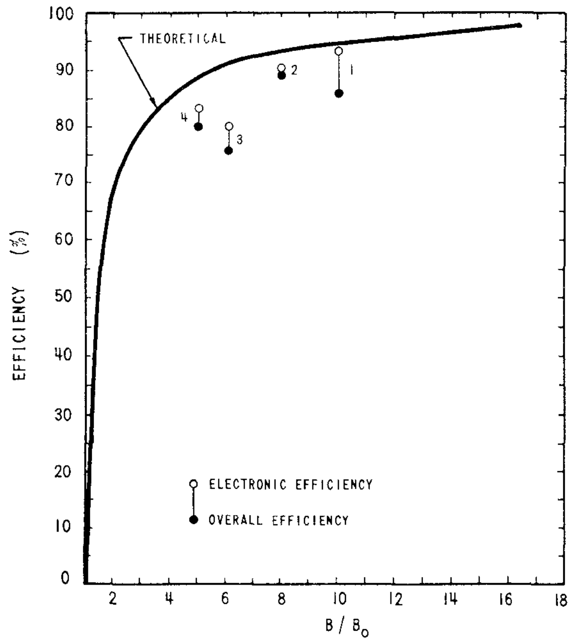

Fig. 11. Theoretical and observed efficiencies of magnetrons and Amplitrons as a function of the magnetic-field parameters. 1—8684-magnetron 915-MHz 25-kW CW shelf item; 2—1220-Amplitron 500-MHz low-power research item; 3—849-Amplitron 3000-MHz 200–400-kW CW not a shelf item; 4—622-Amplitron 3000-MHz 3-MW pulsed shelf item.

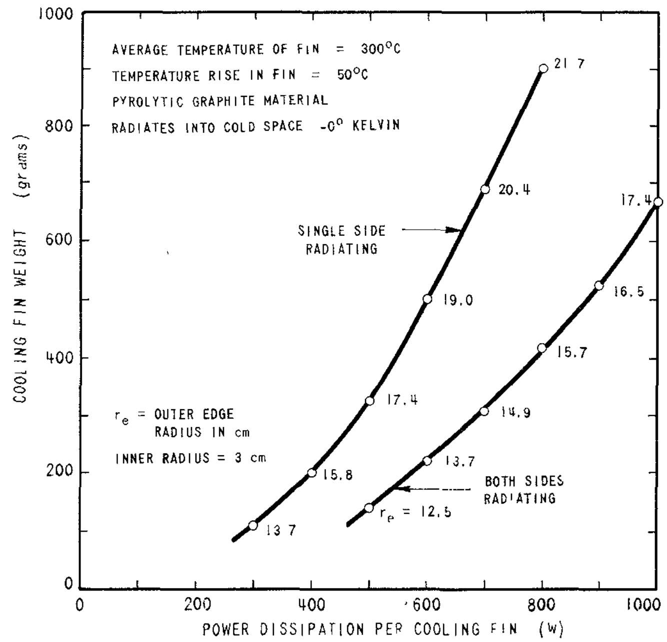

Fig. 12. Cooling fin weight as a function of power dissipation demand upon the cooling fin. Numbers along curves refer to outer edge radius of cooling fin in centimeters.

Fig. 11 shows the theoretical and observed efficiencies of selected Amplitrons and magnetrons [19]–[22]. (The magnetron is another device which makes use of the same efficient energy conversion mechanism.) It is noted that the theoretical conversion efficiency improves as a function of the B/B_0 ratio and that this relationship has been confirmed in operating tubes. B is the value of the magnetic field applied to the tube while B_0 is a design parameter directly proportional to the frequency for which the tube is designed. The frequency dependence of B_0 is important because, until recently, there have been no permanent magnet materials available with which to make practical tube designs at 3 GHz with B/B_0 ratios of 10. The most efficient tube shown in Fig. 11 does operate with a B/B_0 ratio of 10, but its frequency is 0.915 GHz [19].

Fortunately, a revolutionary permanent magnet material [23], [24] has been developed recently and is now in production. This new material, samarium-cobalt, makes possible high B/B_0 ratios in a 3-GHz tube with a weight which amounts to only a few ounces in the tube proposed for the SSPS application.

Long life can be attained in the Amplitron with the use of a thin layer of platinum serving as the cathode emitting surface. Platinum is used because it has the highest secondary emission ratio of any pure metal, and because experience obtained through the use of these cathodes in many Amplitron designs has shown no deterioration of the secondary emitting properties of the material as a function of life.[1] It is reasonable to expect that this kind of cathode would have extremely long life in the SSPS application—perhaps thirty years or longer. This scale of cathode life is in sharp contrast with thermionic cathodes, which have a limited life and which require some form of auxiliary heater with its own set of life problems and power requirements. There is one disadvantage to the secondary emitting cathode; the electrons which bombard the cathode and produce secondary electrons also heat the cathode. Hence the cathode itself must be equipped with a radiator for cooling purposes. Another requirement of the secondary emitting cathode is that there be an injection of microwave power into the input of the tube before the secondary emission process can begin. This requirement has been taken into account in the baseline design and will be discussed later.

It is proposed to use pyrolytic graphite for the radiators attached to the cathode and anode [25]. In the temperature range of concern, <300°C, pyrolytic graphite can be processed to have a heat conductivity 1.8 times that of copper, yet its density is only one-fourth that of copper. It has a natural emissivity of 0.92 and, at a temperature of 300°C in a vacuum, its evaporation rate is negligible.

Calculations of fin weight as a function of dissipation capability for a tapered circular radiator have been made and the results are shown in Fig. 12. If both sides of the fin radiate effectively, very low fin weights result. If the sun is shining on the radiator, then the effectiveness of the radiator is reduced; however, the sun's maximum incident power input is 1.46 kW/m^2 while the radiation capability of both sides of a pyrolytic graphite sheet at 300°C is 10.6 kW/m^2.

The weight and complexity of the Amplitron for the space application is reduced since no vacuum envelope around the tube is necessary. The microwave windows and vacuum-tight joints in the envelope are major considerations in the development and production of tubes for an earth environment.

The essential features of the Amplitron for this application from the viewpoints of heat flow and weight are shown in Fig. 13 where input and output circuit attachments and other features have been eliminated for simplicity. A parametric study of the weight of the tube as a function of its electrical

[1] A recent paper with a comprehensive discussion of platinum cathode life is J. F. Skowron, "The continuous-cathode (emitting-sole) crossed-field amplifier," *Proc. IEEE*, vol. 61, pp. 330–356, Mar. 1973.

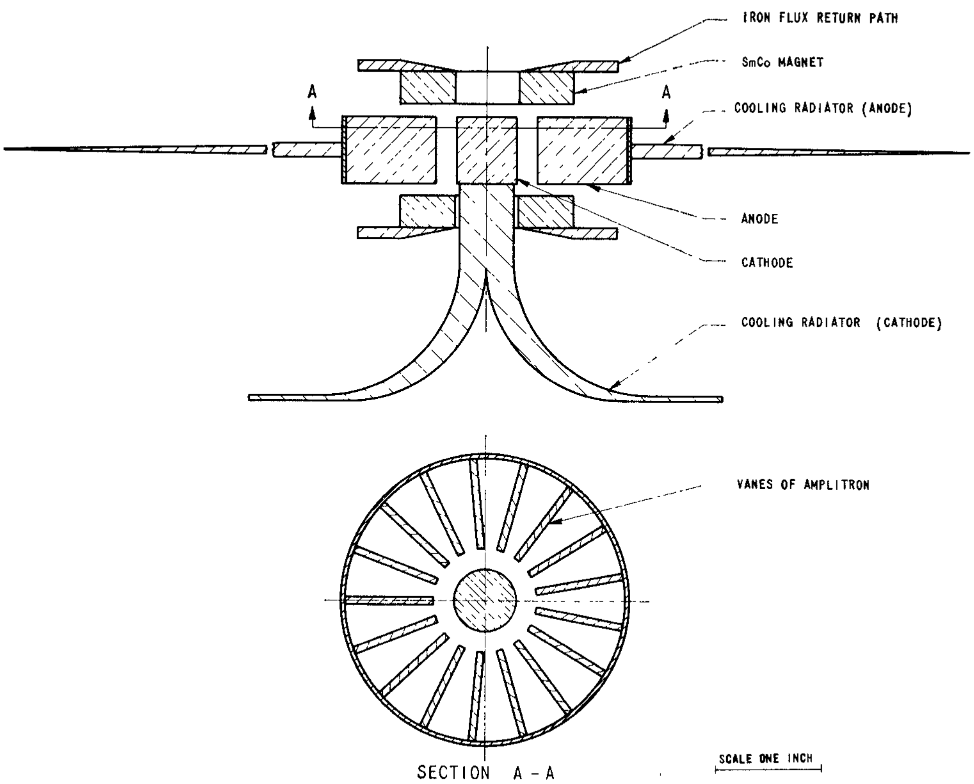

Fig. 13. Cross section of 17-vane Amplitron showing essential features of Amplitron from a heat flow and weight point of view. Other features such as input and output RF connections, strap transmission line, and insulating support structures for cathode and magnets have been omitted. Figure is drawn to scale. Design is for a tube operating at a wavelength of 15 cm, an anode voltage of 20 kV, a B/B_0 ratio of 10, and in the 180° circuit mode.

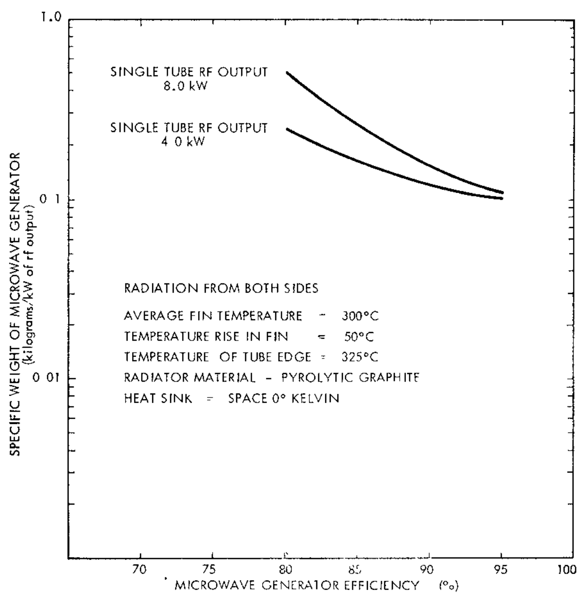

Fig. 14. Specific weight of microwave generator and associated magnet and cooling radiator as a function of generator efficiency and power rating of the tube.

size and efficiency has been made, and the results are shown in Fig. 14. A basic tube weight without input and output connections of about 0.13 kg/kW appears to be a realistic objective for a 5-kW tube.

The cost of the dc–microwave power conversion is of critical importance. The quantity of one to two million tubes that would be needed for each SSPS station is large enough to warrant large-scale highly efficient mass production. Furthermore, there is comparable production experience on magnetrons, similar in many respects to the Amplitron device for the SSPS, from which some initial cost estimates can be made. These magnetrons, which supply the microwave power to microwave ovens, are being made in quantities of 250 000/year for less than 30 dollars each. It is reasonable to assume that the Amplitrons would cost no more than 125 dollars for a 5-kW tube, or 25 dollars/kW, after making allowance for the

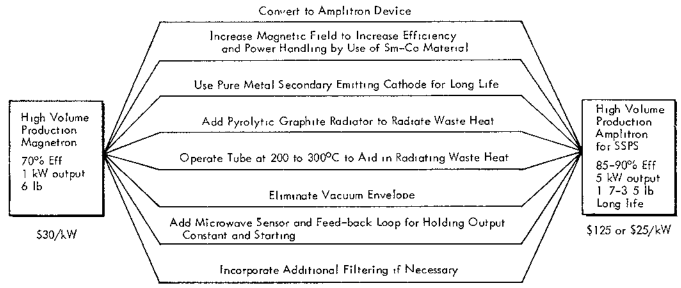

Fig. 15. Design resources used to convert a low-cost high-volume production magnetron to a low-cost high-volume production Amplitron for the SSPS.

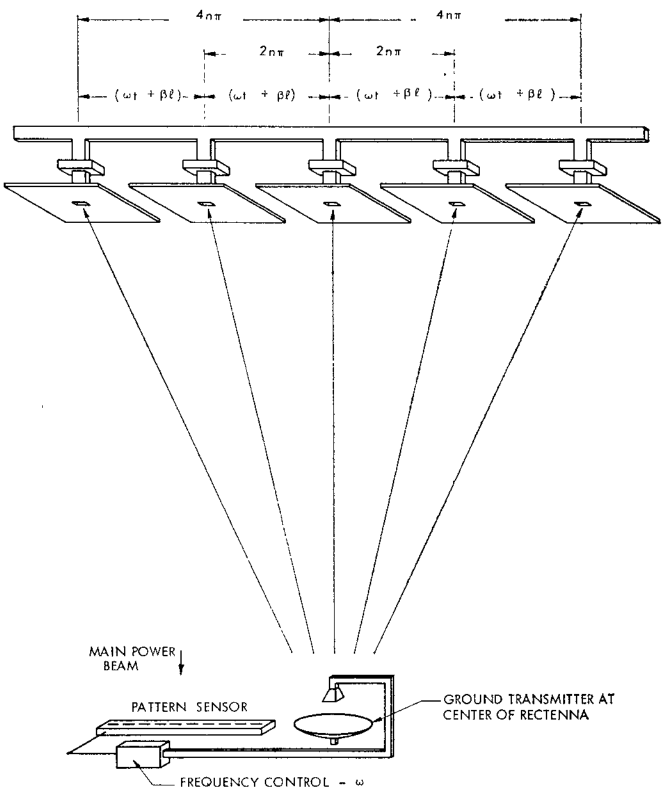

Fig. 16. Adaptive transmitter array—closed-loop mode.

higher material costs in their construction and their higher power rating.

The adaptation of microwave generator device technology and production experience to the SSPS may be summarized with the aid of Fig. 15, which shows various modifications made to an existing low-cost production magnetron to produce a low-cost Amplitron which is suitable for SSPS use.

The Use of Adaptive Array Techniques to Achieve Proper Beam Focusing and Pointing

The requirements for accurate beam forming and pointing in the SSPS system are severe. To hold the beam pointing to within 300 m of a fixed spot on the ground, an angular pointing accuracy of $\pm 1.7''$ is required. To minimize scattering loss due to random variations in the phase front of the transmitted beam, the random phase variation must be held to very low values, e.g., $\lambda/40$ for a 2-percent scatter loss.

The means for achieving the pointing accuracy may be divided into the mechanical pointing of the average mechanical surface of the transmitting antenna, and the additional accuracy provided electronically by the self-phasing feature of the retrodirective array.

The retrodirective array [15] is a well-established principle in which the transmitting aperture is divided into a number of subarrays. Each subarray radiates its power through slotted waveguides in the conjugate phase from that determined by a comparison of the phase of a signal reaching the subarray directly from a transmitter located at the middle of the receiving point (at the center of the rectenna on the earth in the SSPS) and a reference phase, which is identical for all of the subarrays, and which is transmitted to the subarrays by suitable means. In Fig. 16, a waveguide is shown as the transmission means. This principle, shown in Fig. 16, assures that the composite beam radiated by the subarrays is properly focused and pointed toward the pilot transmitter on the ground. The retrodirective array eliminates the need for a precise mechanical surface of the transmitting antenna, which would be very difficult, if not impossible, to construct and maintain. The beam

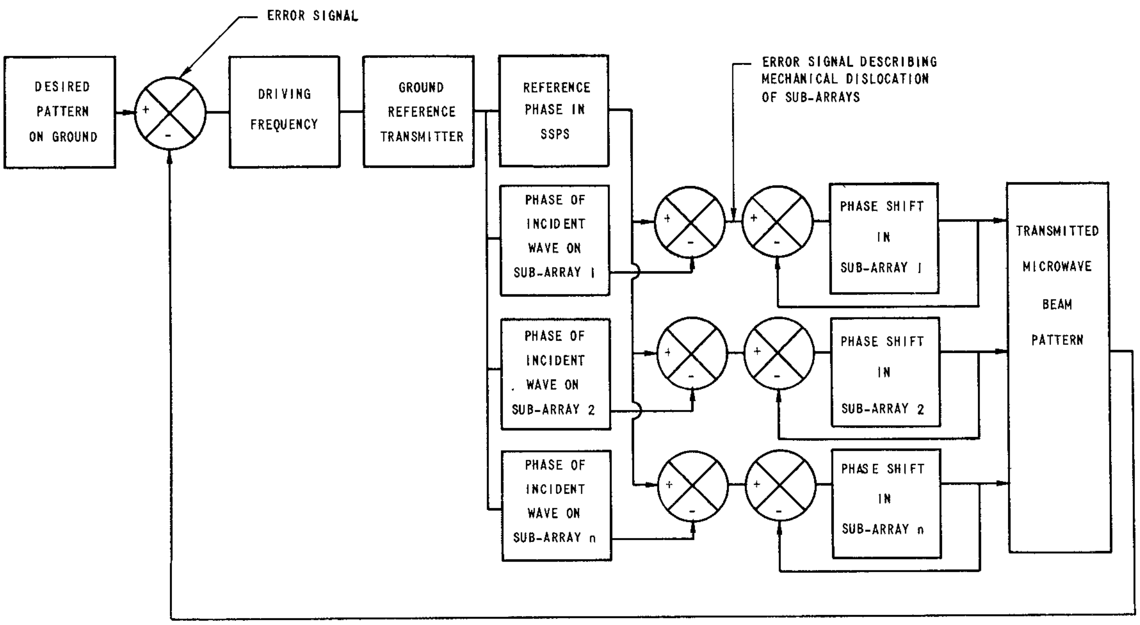

Fig. 17. Block diagram of control system for an adaptive transmitter array.

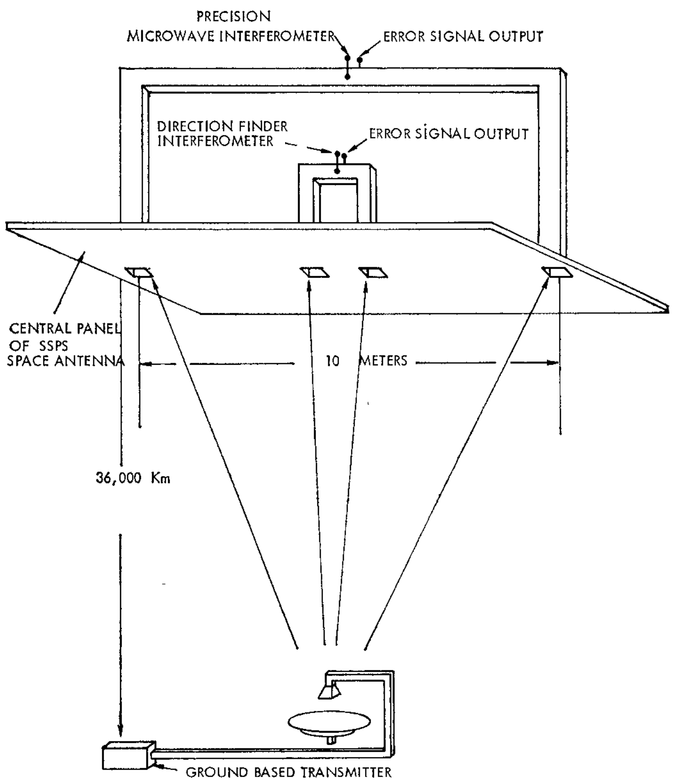

Fig. 18. System for accurate pointing of SSPS transmitting antenna.

can also be aimed more quickly and with greater precision than it could be by mechanical means alone.

The difficult aspect of the application of this principle to the SSPS is the maintenance of a signal of identical phase at each of the subarrays under conditions of large temperature changes which may occur throughout the structure, particularly when the satellite is eclipsed by the earth. If the reference signal is transmitted to the subarrays through transmission lines, and the temperature changes are uniform throughout the structure, then the identical phase can be preserved by changing the frequency of the system, as suggested by Fig. 16. In fact, with suitable sensors distributed throughout the rectenna area, it would be possible to have a closed-loop control system, as shown in Fig. 17, which would keep the frequency at the optimum value. Additional means of coping with the problem caused by the expansion of the transmitting antenna are available. The dimensional changes can be measured directly by laser interferometers, and this information can be

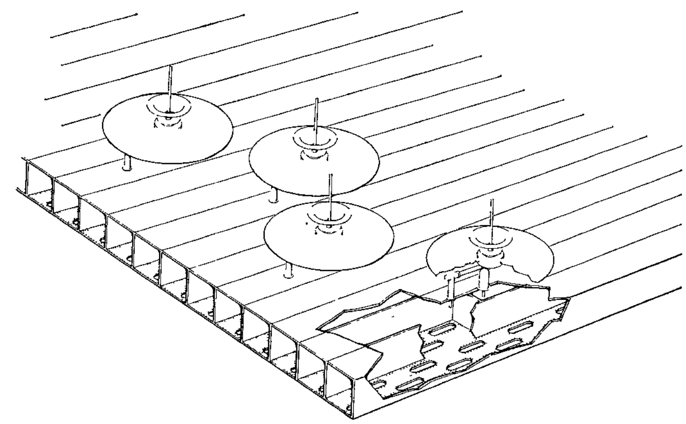

Fig. 19. Illustration showing mechanical and electrical interface between Amplitron and the slotted waveguide array in a subarray of the SSPS.

SSPS REQUIREMENTS / DESIGN RESOURCES	HIGH EFFECIENCY 68% SATELLITE	HIGH EFFECIENCY 68% BEAM	HIGH EFFECIENCY 68% GROUND	PASSIVE RADIATION OF WASTE HEAT SAT	PASSIVE RADIATION OF WASTE HEAT GND	HIGH POWER 5 X 10^3 KW SAT.	HIGH POWER 5 X 10^3 KW GND	LOW WEIGHT IN ORBIT	LOW COST SAT	LOW COST GND.	LONG LIFE (20 YR)	HIGH RELIABILITY	EASE OF SYSTEM STARTUP	LOW RFI	HIGH POINTING ACCURACY	ALL WEATHER CAPABILITY
ACTIVE PHASED ARRAY PRINCIPLE	●			●		●		●	●		•	●	•			
ADAPTIVE ARRAY PRINCIPLE		●						●	●			●	•	•	●	
RECTENNA PRINCIPLE			●		●		●			●	●	●				●
SELECTION OF WAVELENGTH	•		•	•	•	•	•	•	•	•	•	●		•		●
AMPLITRON PRINCIPLE	●			●		●		●	●		●	●	•			
HIGH MAGNETIC FIELD	●			•		•		•	•							
Sm-Co MAGNET MATERIAL	●			•		•		●	•							
OUTPUT POWER SENSING VARIABLE MAGNETIC FIELD		●						▲	▲			●	●	•	●	
PURE METAL SECONDARY EMITTING CATHODE	▲							●	●		●	●	●			
PYPOLYTIC GRAPHITE RADIATOR				●		●		●	•		•	•				
HIGH OPERATING TEMPERATURE	▲			●		●		●	●		▲	▲				
SMALL INDIVIDUAL TUBE SIZE				●		●		●	●			•				
GaAs SCHOTTKY-BARRIER DIODE			●		●		●			●	●	●	●			
MICROWAVE INTERFEROMETER PRINC													●		●	
AUXILIARY FILTERS	▲		▲	▲	▲	•	•	▲	▲	▲				●		
SUBARRAY PRINCIPLE						●		●	●							
LASER BEAM															●	
LIGHTWEIGHT, HIGH STRENGTH MATERIALS								●	▲						•	

● STRONG POSITIVE CORRELATION • WEAK POSITIVE CORRELATION ▲ WEAK NEGATIVE CORRELATION

Fig. 20. Interaction between the requirements placed on the microwave power transmission system in the SSPS and various design resources.

used to actuate phase shifters which will make the necessary corrections in the phase. There seem to be enough design resources available to cope with this problem.

The phase front established by the ground transmitter at the synchronous satellite can also be used as an attitude position reference in roll and pitch, and can be sensed by means of interferometers mounted on a small stiffened area with a precision surface left at the center of the array, as shown in Fig. 18. This general principle has been successfully used in a number of different applications. The pointing accuracy achieved by this approach in the ATS-F satellite is 10^{-4} rad, which is adequate resolution for the mechanical pointing of the SSPS [26].

The size of the subarrays in the baseline design is 5×5 m. Each subarray contains a means of comparing the arrival phase of the pilot beam from the earth with a reference phase and establishing a low-level resultant signal with the appropriate phase. The power level of this signal must then be amplified by suitable means to a level appropriate for driving the first Amplitron, which then drives several other Amplitrons, which in turn drive several strings of cascaded Amplitrons. The phase of the microwave power in the slotted waveguides is monitored throughout the subarray, and corrections to the phase are made by phase-shifting devices if necessary. An artist's concept of one of the subarrays is shown in Fig. 19.

Summary

The SSPS has placed many unusual requirements on the microwave power transmission portion of the system. However, there have been many design resources in the form of materials, devices, and systems concepts to meet these requirements. The interrelationship between the requirements and the large number of different design resources is best summarized by means of Fig. 20.

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Military Applications of Fiber Optics and Integrated Optics

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Invited Paper

***Abstract*—A general discussion of military applications of integrated optics and fiber optics is presented. Specific applications discussed are: 1) a multiterminal multiplexed data highway for aircraft and shipboard use; 2) optical fibers as tethers; 3) a 10.6-μm heterodyne detector; and 4) integrated optical phased arrays.**

I. Introduction

THE VIRTUES and potential of fiber optics and integrated optics are well known and have been discussed in other papers in this section. This area of optical technology is receiving a lot of attention at the present time from industry and the military. From the military point of view there are a fairly large number of application areas where this technology can possibly offer unique solutions to critical problems. In the remainder of this paper a few possible application areas will be discussed ranging from near-term to long-range possibilities.

Fiber optics is receiving a lot of attention at present due primarily to its potential for the telecommunications industry. Fibers with extremely low losses have been reported and the prospect of ultrahigh bandwidth optical transmission lines with multikilometer repeater spacing is a very real possibility. However, the large-scale use of fibers for telecommunications is probably at least ten years away. The military, on the other hand, has very real problems that can be solved with fibers of shorter length and more modest bandwidth. For example, optical information transfer (OIT) on board aircraft involves fiber lengths of less than 30 m, and bandwidths less than 100 MHz. Since higher losses can be tolerated, these applications can proceed without a large amount of fiber development.

The realization of the full military potential of OIT, and in particular fiber optic systems, will be aided by the development of integrated microoptical circuits [1]. In general, this technology will eliminate many problems inherent in bulk optical devices. The optical processing of information with integrated microoptical circuits will minimize the number of optics–electronics interfaces in OIT systems.

The potential advantages of OIT systems are well understood qualitatively. Generally, the use of fiber optics instead of conventional transmission lines in military hardware should cause the following impact.

1) Reduce, by up to a factor of 5, transmission-line system size and weight for conventional information bandwidths. This will make redundant control systems attractive which will increase reliability and battlefield survivability. As the individual fibers in a fiber bundle break, optical systems are expected to experience a gradual degradation in contrast to the catastrophic failure caused by shorts with conventional technology.

2) Eliminate the problems caused by electromagnetic crosstalk and interference which will allow close spacing of transmission lines and operation near radar transmitters.

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