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. Recent advances in power conversion technology and experimental results on overall efficiency of free-space power transmission are reviewed.

Summary

Electrical power is such a desirable form of energy that its demand is expected to increase five-fold 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 twenty years, however, three new technologies have been developed which can work together to provide nearly-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% duty cycle if the cell is placed in a synchronous, equatorial orbit. This arrangement removes the limitation of low duty cycle (typically 10%) 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%, becoming as great as 6% 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;[5] 2) the antenna technology of forming a narrow, efficient beam of microwaves and efficiently absorbing that beam on the Earth's surface;[6] 3) the conversion of the microwave power back into dc power at the Earth's surface.[7]

In studying the subject of adapting microwave techniques to a system (see Figure 1) which brings power from space, one finds that the system is so large and so different from any other existing system that the subject cannot be coherently discussed without a comprehensive preliminary study and the establishment of a preliminary base-line design for the system. This has already been accomplished by a four-company team comprised of personnel from Arthur D. Little, Inc., Raytheon Co., Grumman Aerospace Corp. and Textron, Inc.[8] In this discussion, the base-line design which they derived will be used, recognizing that it will be modified by subsequent study but that it has generally established many properties and characteristics of the system. This statement applies to the microwave power transmission portion of the system as well as to the system as a whole.

The first notable characteristics of the microwave system are that it must handle huge amounts of power in order to match the optimum economics of the overall system, but that it is made up of many relatively small components which in power rating are well below the existing state-of-the-art. Thus, the total power level of the free-space power transmission system may be 10,000 megawatts (our biggest conventional electrical power plants are about one-tenth this level), requiring one or two million microwave generators. While the construction of these generators is sophisticated, the material and labor requirements do not differ greatly from those required for a similar quantity of microwave generators currently being projected for a year's production of electronic ovens. The vacuum envelope around these generators, so necessary for a terrestrial environment, may be eliminated in space. The generators are so efficient that the small amount of waste heat can be passively radiated into space from relatively small cooling fins attached to the generators and operating at high temperature. Because of the highly efficient energy conversion (85-90%), elimination of the vacuum envelope, and the use of the new rare-earth cobalt permanent magnet materials, the specific weight of the converter can be held to less than one-half pound per killowatt of power output.

A second notable characteristic of the microwave system is the method by which the microwave energy is captured and rectified at the earth's surface. This is accomplished by means of the rectenna device which is made up of a huge array of elements each consisting of a half-wave dipole terminated in an efficient rectifier of one or more Schottky-barrier diodes. Such an arrangement allows the use of long-life diodes whose individual power handling capability is already adequate for the application. Even more important, this arrangement eliminates the high directivity characteristic of a conventional large antenna. The elimination of the high directivity eliminates concern about the phase and amplitude distributions within the incoming beam so that the adverse effects of severe meteorological disturbances are limited to a slight attenuation of the beam.

A third characteristic of the beam is its high gain - about 90 dB. Such a high gain cannot be achieved without the use of self-phasing principles which have been discussed in the literature.[9] The application of these principles to the large array in space is primarily an engineering problem, although a difficult one.

A fourth characteristic of the beam is the very high overall efficiency (see Figure 2) that can be achieved, including the energy conversion process at both the transmitting and receiving ends. The forecast of high efficiency is based in part upon overall efficiencies that have already been demonstrated[10] and in part upon additional improvements that can be realistically expected from additional device development. (See Table 1.) The efficiency of the beam to transfer microwave power is independent of distance if the aperture areas are increased in proportion to the distance of transmission;[6] consequently, scaled laboratory experiments are applicable. A beam efficiency of 94% from the rf output of the microwave generator to the receiving aperture has been achieved. The combined capture and rectification efficiency of the rectenna is currently 64%. An accurate efficiency measurement of 60.5% has been achieved in a laboratory experiment which included all portions of the transmission system with the exception of the conversion of dc power into microwave power. The latter efficiency has been independently established to be in the 85-90% region[5] for existing devices. From these considerations and the knowledge that the efficiency of the rectenna can be greatly increased, an overall efficiency of 65-70% is projected for the microwave-power transmission system in the satellite solar power station concept.

TABLE 1
MICROWAVE POWER TRANSMISSION EFFICIENCIES

	Efficiency Presently Demonstrated*	Efficiency Expected with Present Technology*	Efficiency Expected with Additional Development*
Microwave Power Generation Efficiency (η_g)	76.7***	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**	60.0	77.0

* Frequency of 2450 MHz (12.2 cm wavelength)

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

*** This efficiency was demonstrated at 3000 MHz and a power level of 300 kW cw

Several pieces of the laboratory equipment used in establishing some of the efficiencies listed in Table I are shown in Fig. 3. An off-the-shelf low-power magnetron is used to drive a large illuminating horn which utilizes the dual-mode principle to reduce side-lobe levels to negligible importance. The main lobe has an essentially gaussian distribution within a few feet of the horn mouth. The reflecting antenna is part of an ellipsoidal surface which is used to transform the divergent beam into a convergent beam which is focused onto the rectenna. The rectenna which is made up of many half-wave dipoles, each terminated in a bridge-type rectifier made from silicon Schottky barrier diodes, captures the microwave energy and converts it back into dc power. In the satellite solar power station an active phased array is used to launch the beam with close to 100% efficiency, and the beam travels directly to the rectenna on the earth.

Other important characteristics of the microwave power transfer system include a minimal use of strategic materials, longevity, and high reliability. A 20-30 year life time is projected for the system because of the use of long life semiconductors in the rectennas and the use of pure-metal, secondary-emitting (non-thermionic) cathodes in the microwave generators.

A cost analysis to produce the microwave power transmission system inclusive of fabrication of the space transmitter and ground rectenna, but exclusive of transportation into orbit and development costs has been made. Because of the relatively small amount of material used, the relatively small number of different parts, and the high automation made possible by long production runs of identical parts, the cost for the 10,000 megawatt microwave power transmission system can be produced for less than $200.00/KW

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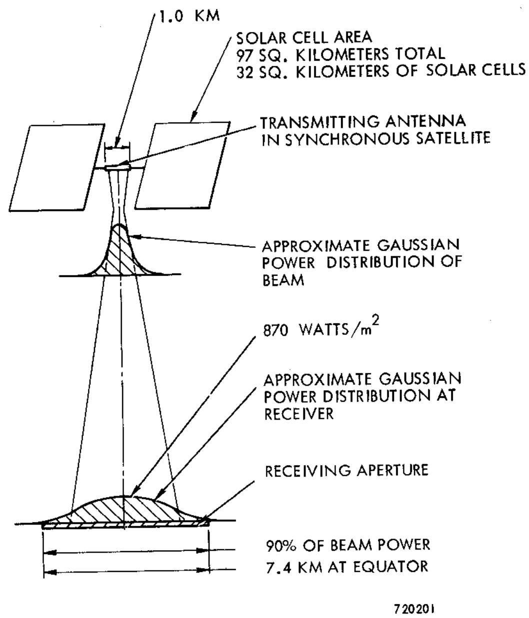

FIG. 1 Dimensions and essential physical features of the SSPS for a system using a 10 cmwavelength and a power level of 10, 000 megawatts.

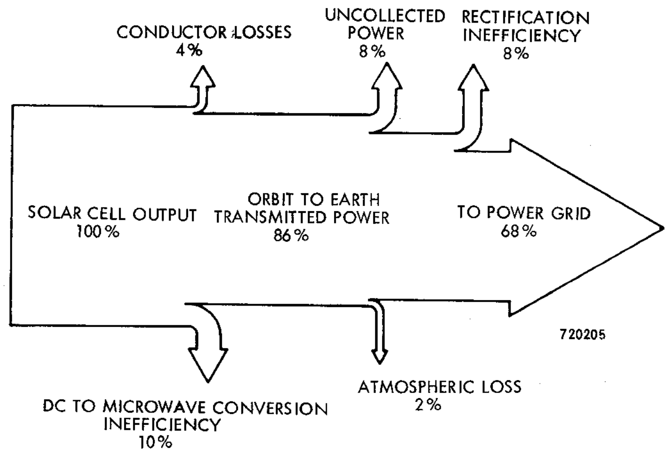

FIG. 2 Proposed energy balance for a 22, 300 mile synchronous-orbit to earth microwave power transmission system.

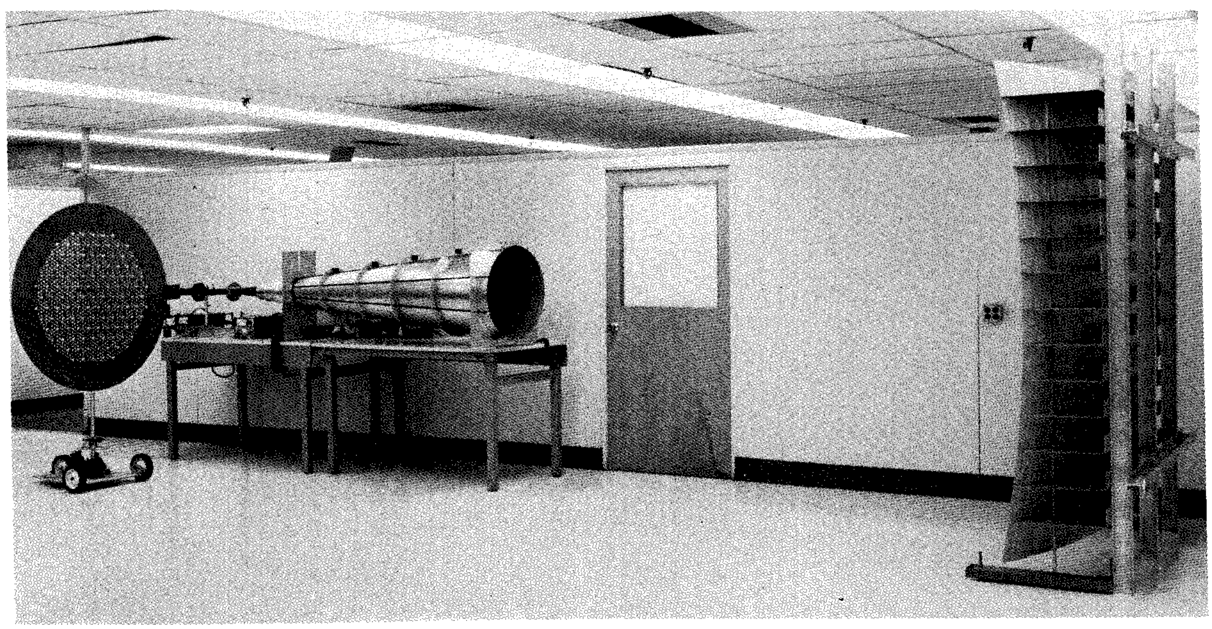

FIG. 3 Laboratory set-up for demonstrating free-space microwave power transmission consists of microwave generator, dual-mode horn for launching the beam, ellipsoidal reflector for changing the divergent beam to a convergent beam, and a rectenna for intercepting the beam and converting the microwave power into dc power. In the set-up as shown an efficiency from the output of the magnetron to the dc output of the rectenna is limited to 50. 5%, principally because the microwave beam is larger in diameter than the rectenna at the point of intersection. An efficiency of 60. 2% was measured with the rectenna placed a few feet in front of the horn where 94% of the energy measured at the horn input was intercepted.