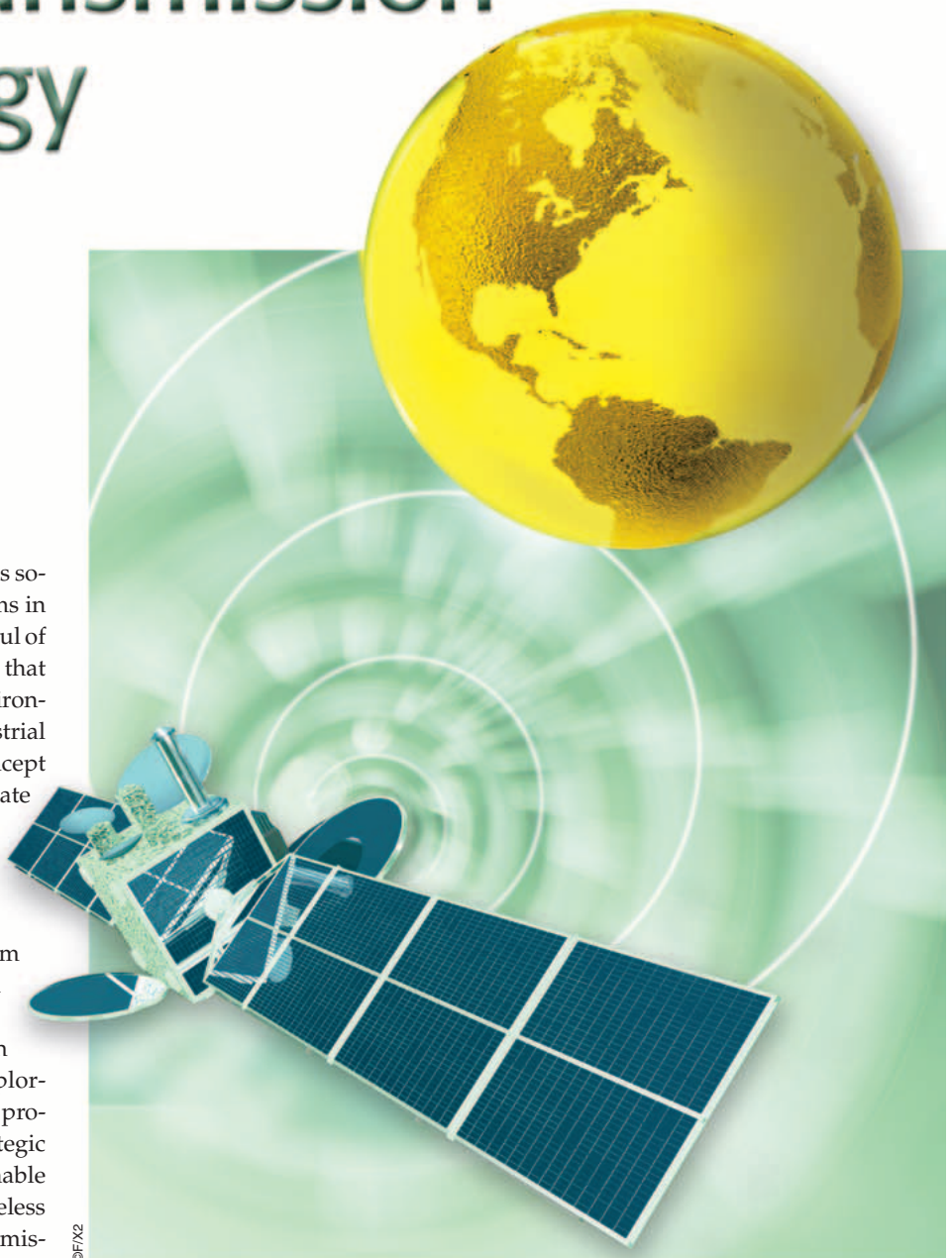


# Space Solar Power Programs and Microwave Wireless Power Transmission Technology

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**T**he concept of placing enormous solar power satellite (SPS) systems in space represents one of a handful of new technological options that might provide large-scale, environmentally clean base load power into terrestrial markets. In the United States, the SPS concept was examined extensively during the late 1970s by the U.S. Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA). More recently, the subject of space solar power (SSP) was re-examined by NASA from 1995-1997 in the "Fresh Look Study" and during 1998 in an SSP "Concept Definition Study." As a result of these efforts, in 1999-2000, NASA undertook the SSP Exploratory Research and Technology (SERT) program, which pursued preliminary strategic technology research and development to enable large, multimegawatt SSP systems and wireless power transmission (WPT) for government missions and commercial markets (in space and terrestrial). During 2001-2002, NASA has been pursuing an SSP Concept and Technology Maturation (SCTM) [1] program follow-up to the SERT, with special emphasis on identifying new,



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high-leverage technologies that might advance the feasibility of future SSP systems. In addition, in 2001, the U.S. National Research Council (NRC) released a major report providing the results of a peer review of NASA's SSP strategic research and technology (R&T) road maps.

One of the key technologies needed to enable the future feasibility of SSP/SPS is that of WPT. Advances in phased-array antennas and rectennas have provided the building blocks for a realizable WPT system. These key components include dc-RF converters in the transmitter, the retrodirective beam control system, and the receiving rectenna. Each subject is briefly covered, and results from the SERT program that studied a 5.8-GHz SPS system are presented.

This article presents a summary of results from NASA's SSP efforts, along with a summary of the status of microwave WPT technology development.

## Background

The concept of a large SPS that would be placed in geostationary Earth orbit (GEO) to collect sunlight, use it to generate an electromagnetic beam, and transmit the energy to the Earth was invented in 1968 by Peter Glaser of Arthur D. Little. In the United States, a major study of the SPS concept was conducted during 1976-1980 by the DOE with the support of NASA [2]. This effort was funded at a level of more than 55 million in fiscal year (FY) 2002 dollars and resulted in a wide range of useful research.

The DOE-NASA project in the 1970s is best remembered for the 1979 SPS Reference System. The central feature of this concept was the creation of a large-scale power infrastructure in space, consisting of about 60 SPS, each delivering 5 GW of base load power to the U.S. national grid (for a total delivered power of about 300 GW). However, connections to interim applications of SSP were tenuous, and the space infrastructure requirements were projected to be significant. The "cost-to-first-power" of the 1979 Reference System was expected to be more than 300 billion in FY 2002 dollars. As a result of the huge price tag, lack of evolutionary approach, and the subsiding energy crisis in 1980-1981, essentially all U.S. SPS efforts were terminated. In a 1980 report on SSP, the NRC recommended that the concept be re-assessed in about ten years, subsequent to additional technology development and maturation.

During the 1980s, technology development in a range of relevant areas continued—particularly in the area of solar power generation of broad applicability in commercial and scientific spacecraft. Also during the 1980s and early 1990s, low-level international interest in the SPS concept emerged, including WPT flight experiments in Japan and other activities in Europe and Canada. In the United States, activities were largely limited to generic research and modest systems studies of potential applications of SSP technology to space science and exploration missions.

## Recent NASA Efforts

### *Fresh Look Study*

In 1995, NASA undertook a reconsideration of the challenge of large-scale SSP systems [3], [4]. The goal of this effort—the Fresh Look Study—was to determine whether technology advances since the 1970s might enable new, viable SSP systems concepts. The Fresh Look Study examined about 30 SSP concepts, emphasizing systems and architectures for GW-class power in terrestrial markets.

## **SPS systems might provide large-scale, environmentally clean base load power into terrestrial markets.**

The general finding of this preliminary assessment was that there did appear to be a number of promising SSP systems concepts distinct from those of the 1970s that were enabled by recent or projected advances in relevant technologies [5]. The Fresh Look Study concluded that the prospects for power from space were more technically viable than they had been at the end of the 1980s, although still exceptionally challenging [5].

### *SSP Concept Definition Study*

During 1998, NASA conducted the SSP Concept Definition Study, following the suggestion of the House Science Committee. This study was a focused one-year effort that tested the results of the previous Fresh Look Study. The 1998 effort engaged a wide range of technologists from outside the agency as well as within. In addition, NASA funded an independent economic and market analysis study, led by Dr. Molly Macauley of the Washington, D.C.-based nonprofit, Resources for the Future. The 1998 SSP Concept Definition Study found that SSP did appear more viable than in the past—results that largely validated the findings of the Fresh Look Study—while invalidating some of the specific systems/architecture concepts that had emerged from the earlier effort. A principal product of the effort was the definition of a family of strategic R&T road maps for the possible development of SSP technologies.

### *Exploratory Research and Technology Program*

Beginning in Spring and continuing through Fall 2000, NASA conducted the SSP SERT Program. This program, completed in December 2000, further defined new systems concepts (including space applications), better defined the technical challenges involved in SSP, and initiated a wide range of competitively selected and in-house R&T activities to test the validity of SSP strategic research and technology road maps [6].

The SERT Program, led by the NASA Marshall Space Flight Center, involved technologists from across the United States. Participants included eight NASA Field Centers, as well as a number of external organizations

through a diverse family of some 31 individual, competitively procured projects created as a result of a 1999 NASA Research Announcement. Funded by NASA at a level of about US\$22 million (approximately US\$15 million in FY 1999 and US\$7 million in FY 2000), SERT Program participants included large and small companies, other agencies and laboratories, universities, and several international organizations. The SERT Program involved a focused portfolio of R&D investments, guided by systems studies with the maximum degree of leveraging of existing resources inside and outside NASA and comprised of three complementary elements:

- *Systems Studies and Analysis:* Analysis of SSP systems and architecture concepts (including space applications) with efforts including market/economic analyses to address the potential economic viability of SSP concepts, as well as environmental issue assessments, for various potential terrestrial and space markets
- *SSP Research and Technology:* Tightly focused exploratory research targeting “tall poles” and rapid analysis to identify promising systems concepts and establish technical viability to “first-order”
- *SSP Technology Demonstrations:* Initial, small-scale demonstrations of key SSP concepts/components using nearer-term technologies, with an emphasis on enabling multipurpose (space or terrestrial) applications of SSP and related systems/technologies.

### Current U.S. SSP Programs

During 2001-2002, NASA is continuing to advance key concepts and technologies for future SSP applications. In Winter 2002, NASA, the U.S. National Science Foundation (NSF), and the Electric Power Research Institute (EPRI) issued a joint broad-area announcement that is expected to yield a number of high-leverage, high-risk research studies targeting some of the key challenges facing future SSP systems. The solicitation seeks proposals for fundamental, high-risk research that has serious potential to have impact on the larger goals of SSP. The solicitation emphasized projects that would have an impact in one of four key areas:

- radical improvements in WPT, with primary emphasis on solid-state device issues central to solid-state transmission by microwaves
- more intelligent robotics, to allow the assembly of SSP structures in space with minimal use of humans in space
- improved power management, distribution, and control (PMAD), with a special emphasis on reducing system mass
- understanding of costs and opportunities and how to optimize them for the net impact on the environment, health, and safety, i.e., to the biosphere, the ionosphere, and to sustainable growth around the world.

NASA is also continuing other activities in support of SSP, including the definition of potential technology flight experiments and the refinement of new analytical modeling tools to enable more effective studies of technology alternatives and resulting economics [7].

### Microwave Power Transmission

Due in part to research programs, such as those funded by NASA's SERT program, and component improvements resulting from the wireless revolution, system components supporting microwave WPT have advanced significantly in the past 15 years. Three major WPT conferences held in the 1990s highlighted the applications, issues and concerns, environmental assessments, and the technology associated with beaming power via microwaves, as well as exposing international interest [8]-[10]. The purpose of this section is to status the key microwave components in a WPT system: the transmitter, beam control, and the receiving rectifying antenna (rectenna). Also, estimates of the end-to-end power transfer efficiency for a SPS, as developed in the SERT program, are discussed.

The ability to accomplish the task of efficiently delivering electrical power wirelessly is dependent upon the component efficiencies used in the transmitting and receiving apertures and the ability to focus the electromagnetic beam onto the receiving rectenna. Microwave WPT is achieved by an unmodulated, continuous-wave signal with a bandwidth of 1 Hz. The historical frequency of choice for microwave WPT has been 2.45 GHz due to its low-cost power components; location in an industrial, scientific, and medical (ISM) band; and extremely low attenuation through the atmosphere. Alternatively, the next higher ISM band, centered at 5.8 GHz, has drawn WPT interest from the reduction of transmitting and receiving apertures. However, the penalty for increasing the beaming frequency is higher atmospheric attenuation in severe thunderstorms. The SPS configurations studied in the SERT program are based on a 5.8-GHz system. Other frequencies where power beaming demonstrations have been performed include 8.5 GHz [11], 10 GHz [12], and 35 GHz [13]. At the transmitting antenna, microwave power tubes, such as magnetrons and klystrons, have been extensively studied as primary RF power sources. However, at frequencies below 10 GHz, high-power solid-state devices have promise as a possible alternative. For beam safety and control, retrodirective arrays are applied in WPT systems due to their inherent self-phasing capability. The mobile communications industries have also shown interest in retrodirectivity to dynamically minimize interference and maximize intended signal reception. Whereas transmitter components and retrodirective phased-array antennas have direct applications in the communications industry, the rectenna is a component unique to WPT systems. The rectenna was conceived by Brown, of the Raytheon Company, in the early 1960s [14]. He eventually developed rectennas at 2.45 GHz with con-



version efficiencies greater than 90% [13]. Rectenna efficiency records have now been established at higher frequencies and continue to be broken in research labs across the world. The following sections describe the component performances used in transmitters, beam control systems, and rectennas.

### Transmitters

The key transmitter requirement is its ability to efficiently convert dc power to RF power and radiate the power in a controlled and low loss manner. The complexity of the transmitter is dependent on the WPT application. Transmitters in small-scale WPT applications could simply be a single high-power RF source feeding a mechanically steered reflecting antenna. Large-scale WPT applications, such as an SPS, would require a phased-array antenna to distribute the RF power sources across the aperture and electronically control the power beam. The transmitter's efficiency not only drives the end-to-end efficiency but also the thermal management system, which is particularly difficult in space. Any heat generated from inefficiencies in the dc-RF conversion or in the antenna feed system must be removed from the transmitter for long-life and reliable operation. Although operating at elevated temperatures takes advantage of the fourth power relationship between the quantity of heat radiated per unit area to the temperature, it also reduces the lifetime of the RF devices and control electronics. An efficient and reliable transmitter design is not a trivial matter, and many trades must be performed to meet overall system requirements. In space systems, multipactor [16] and passive intermodulation [17] concerns in high power transmitters are areas that deserve critical attention. The filtering of close-in phase noise and the suppression of harmonics will be required in most systems to meet regulatory requirements. However, filter implementation involves a trade in their cost, mass, temperature stability and in-band insertion loss to meet specified rejection requirements. For all of these reasons, the specific mass for a space-based transmitter requires an in-depth study.

In the SERT program, a 5.8-GHz, 500-m diameter phased-array transmitter was selected as the baseline aperture size for the GEO-based SPS. Common to the 2.45-GHz DOE/NASA Reference System study in the late 1970s, a 10-dB Gaussian amplitude tapered beam was used to efficiently couple the power from the transmitter to the Earth-based rectenna. The transmitter's RF output power is approximately 2 GW to deliver 1.2 GWe to the electric grid. Three dc-to-RF power converters were considered: klystron, magnetron, and solid-state amplifiers. Since these RF converters are the dominant heat-generating

component in the transmitter, efficiency and mass comparisons of the three approaches were developed.

Klystron and magnetron devices were extensively studied in the Reference System Study for a 2.45-GHz power beam [18] (Table 1). Although the klystron operated at a higher power level, the magnetron was preferred due to its efficiency, spectral purity, and reliability.

## Technologies and systems needed for SPS must support highly leveraged applicability to needs in space science and robotic and human exploration and development of space.

Much progress has been made in vacuum tubes since the Reference System, as was recently highlighted in this magazine [20]. Efficiency, reliability, and output power continue to increase at ever higher frequencies. Consistent with the Reference System trade, more powerful klystrons were compared to a slightly more efficient magnetron in the SERT program.

In the 5.8-GHz klystron transmitter, the output power of the most powerful tube located at the array center is 26 kW with an operating voltage and current of 28 kV and 1.12 A, respectively [22]. Although not validated by measured results, the high-efficiency 5.8-GHz klystron design is based on previously built units that have efficiencies over 70%. This modified design uses a multicavity configuration with one of the cavities tuned to the second harmonic and with five stages of depressed collectors. The tube body and solenoid operate at 300 °C, and the collectors operate at 500 °C. Preliminary design simulations revealed that the overall efficiency (i.e., combined electronic and circuit efficiencies) to be a conservative 76% without the depressed collectors. Including the collector recovery of 50%, the overall efficiency is 83%. Due to the 10-dB Gaussian amplitude taper, the approach taken with this transmitter design was to place the 26-kW klystrons in the array center and reduce the tube's output power to 2.6 kW at the array's edge in ten tapered steps. This transmitter

**Table 1. 2.45-GHz RF tube comparisons.**

Parameter	Klystron [19]	Magnetron [20]
Amplifier output power	50 W	4.39 kW
DC-RF power efficiency		87.5%
Overall efficiency	74%	81.7%
Carrier-to-noise ratio	120 dB @ 10 kHz	110 dB @ 10 kHz
	135 dB @ 1 MHz	137 dB @ 1 MHz
	140 dB @ 20 MHz	160 dB @ 20 MHz
	160 dB @ 100 MHz	196 dB @ 50 MHz
Lifetime	25 years*	50 years [18]
* Projected		

configuration is very similar to the Reference System design, albeit with a smaller power modules of 1 m<sup>2</sup> (Figure 1).

The second tube approach to the 5.8-GHz transmitter applies a phase-locked magnetron directional amplifier (MDA), whose proposed output power and efficiency are 5 kW and 85.5%, respectively [23]. The MDA operates at 6 kV and dissipates the waste heat at 350 °C with a pyrolytic graphite thermal radiator. The MDA is basically a phase-injection locked magnetron oscillator with an augmented magnetic bias coil on the

permanent magnet for controlling the output power and an output tuning slug for adjusting the frequency. Thus, the phase, amplitude, and frequency could all be independently varied. A detailed discussion of the MDA is given in [20] and [24]. Similar to the klystron transmitter, the MDA is married to a slotted waveguide antenna, whose subarray size is 4 × 4 m (Figure 2).

The third type of transmitter studied in the SERT program uses solid-state devices [25] (Figure 3). Unlike the slotted waveguide array where a tube would feed many radiating slots, the solid-state transmitter places

a 5.8-GHz power amplifier and phase shifter behind every radiating element. Because a phase shifter is located at every element, the advantage of this approach over the tube transmitters is the elimination of grating lobes when electronically steering the beam. However, microwave filters are needed on each element to suppress both close-in carrier noise and harmonics generated by the power amplifier. Similar to the klystron approach, the 10-dB Gaussian taper is approximated by ten distinct power levels, where each of the center elements radiate 59 W, and the edge elements radiate 5.9 W. The operating voltage and junction temper-

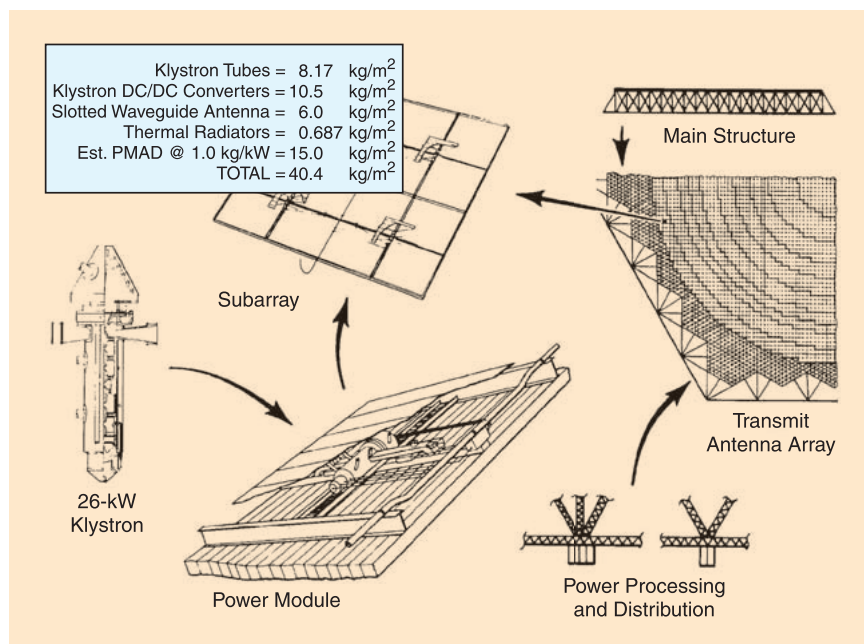


Figure 1. Klystron transmitter [22].

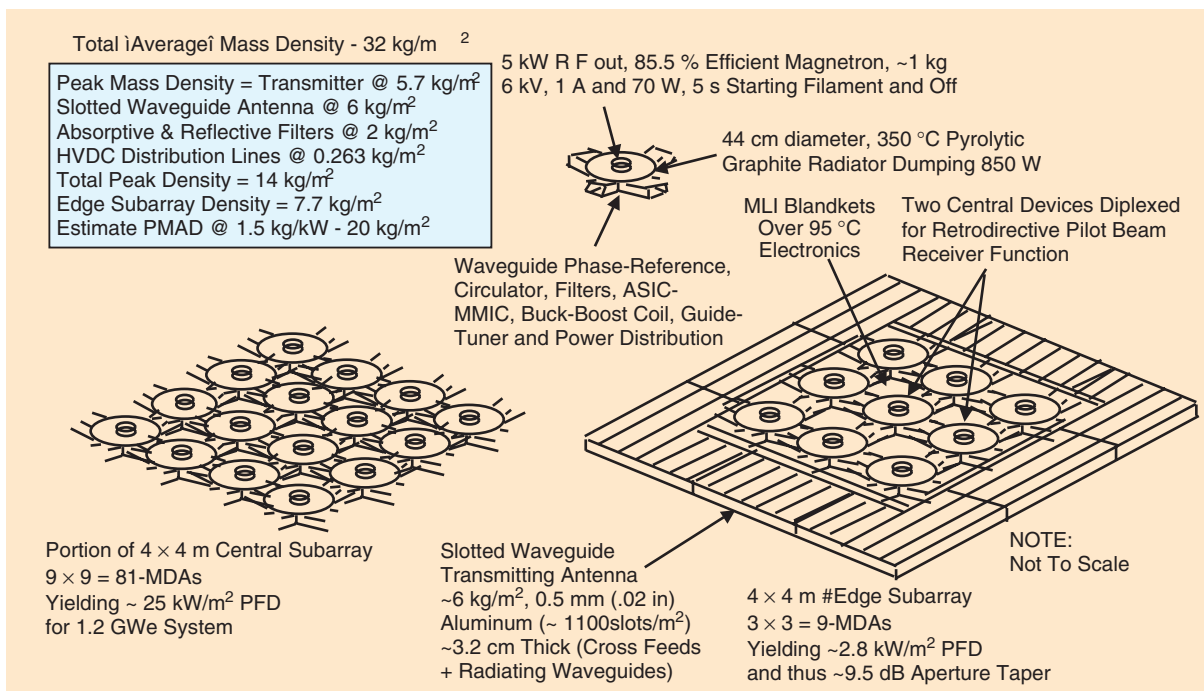


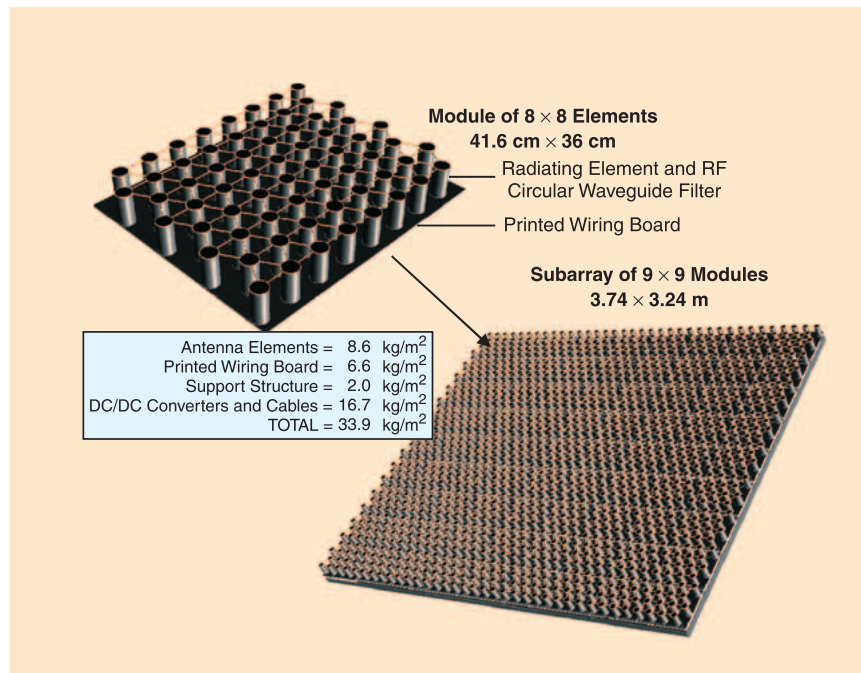
Figure 2. Magnetron directional amplifier transmitter [23].

atures for the power amplifiers are assumed to be 80 Vdc and 300 °C, respectively.

The device most suited for the power amplification is a GaN-based alloy. This wide bandgap device allows high-voltage operation that lessens the impact of many low-voltage dc-dc converters that plagued earlier WPT studies based on GaAs devices. Its high breakdown voltage allows high power densities and high junction temperatures that are both desirable for a WPT transmitter. Additionally, predictions on efficiency indicate an ideal fit for this application. Figure 4 shows predicted power-added efficiency (PAE) comparisons of GaN to InGaAs and SiC with harmonic tuning [26].

Recently, Class E solid-state power amplifier designs have demonstrated excellent results in the microwave frequency range (Table 2). Class E amplifiers can theoretically achieve 100% efficiency. However, this class of operation is highly nonlinear, and unwanted harmonics generated by their switching action requires RF filtering in the transmitter. To achieve the efficiencies necessary for an SPS transmitter, the output of a GaN power amplifier would have to be combined with either a harmonically tuned circuit (i.e., Class F) or operate as a switch (Class E). A contract was awarded in the SERT program to study AlGaN heterojunction field effect transistors (HFETs) on SiC substrates operating in Class E [27]. Using existing AlGaN HFETs in a Class E circuit, simulations revealed that they are capable of achieving PAEs on the order of 70% at 5.8 GHz. The efficiency limitation is due to a fairly large knee voltage, where power is dissipated in part of the cycle (Figure 5). Reducing the source and drain contact resistances and reducing the channel access resistances will reduce the knee voltage where considerable improvement is possible. Ideally, these devices would operate at junction temperatures as high as possible (such as 300 °C), but the performance and reliability of AlGaN HFETs degrades with increasing temperature. In particular to performance, increasing the temperature decreases electron mobility and velocity and increases the knee voltage that ultimately reduces the efficiency.

Although GaN properties appear ideal for a WPT solid-state phased-array transmitter, ongoing research may take several years to fully develop its potential, as indicated in a recent wide bandgap workshop [32]. In addition to reducing the contact and channel resistances, other GaN limitations and defects include a lack of an inexpen-



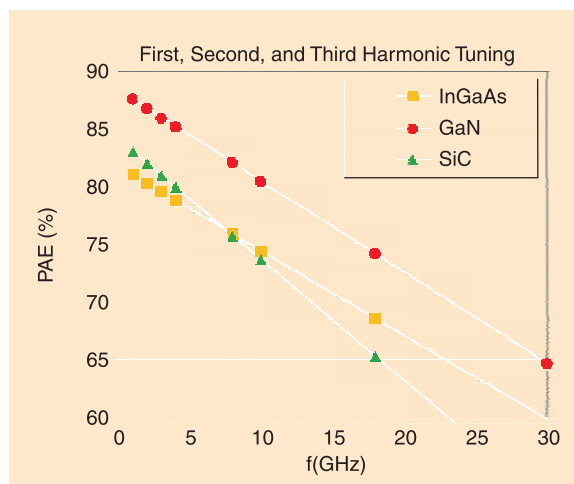
**Figure 3.** Solid-state transmitter [25].

sive substrate, surface traps, space charge effects, and interface effects. The goal of achieving a high-efficiency, high-power, and high-temperature GaN power amplifier should be reached in the upcoming years.

Finally, the design goals of the three transmitter types for a 5.8-GHz SPS are compared in Table 3. The key difference between the three approaches is the converter's RF output power that drives the quantities and operating voltage. However, the specific masses are relatively the same. The efficiency goals for each dc-RF converter type are ambitious but achievable with sound research and funding.

### Beam Control

A key system and safety aspect of WPT is its ability to control the power beam. Retrodirective beam control



**Figure 4.** Predicted solid-state device PAE performances [26].



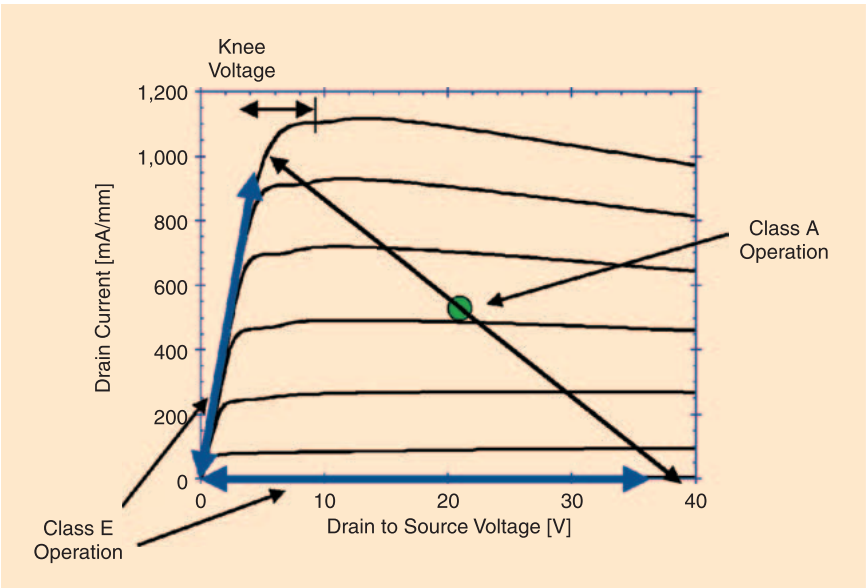
systems have been the preferred method of achieving accurate beam pointing. As depicted in Figure 6, a coded pilot signal is emitted from the rectenna towards the SPS's transmitter to provide a phase reference for forming and pointing the power beam. To form the power beam and point it back towards the rectenna, the phase of the pilot signal captured by receivers located at each subarray is compared to an onboard reference frequency distributed equally throughout the array. If a phase difference exists between the two signals, the received signal is phase conjugated and fed back to the phase control circuitry of each dc-RF converter. In the

absence of the pilot signal, the transmitter will automatically dephase its power beam, and the peak power density decreases by the ratio of the number of transmitter elements. This aspect of retrodirective beam control is an inherent safety feature of the system.

Today's wireless service industries are continually discovering methods to expand their networks and capacity to accommodate greater volumes of voice and data traffic. To handle the increased demand, smart antenna technology is being deployed globally to reduce signal interference. Retrodirective beam control is one such technique the wireless industry could use to track a mobile phone user [33].

**Table 2. State-of-the-art microwave Class E power added efficiencies.**

Frequency (GHz)	Output RF Power (W)	Drain Efficiency/PAE
2.45 [28]	1.27	- /72%
5 [29]	0.61	81%/72%
8.35 [30]	1.41	64%/48%
10 [31]	0.10	74%/62%



**Figure 5.** Class E and Class A comparison on an AlGaIn HFET IV plot [27].

### State-of-the-Art Rectennas

Since the early 1960s, rectennas have been researched and developed at varying levels of intensity. Brown was a pioneer in developing the first 2.45-GHz rectennas that included the basic circuit components still evident in today's rectenna designs (Figure 7). Measured in 1977, Brown's aluminum "bar-type" rectenna still holds the highest recorded efficiency of any rectenna in the microwave frequency range at 91.4% [15].

Figure 8 shows the highest measured conversion efficiencies for 2.45- [15], 5.8- [34], and 35-GHz [13] rectennas as a function of input microwave power density. Also shown are the performance curves for the 2.45-GHz rectenna scaled to 5.8 and 35 GHz for comparison. Due to the substantial amount of research performed at 2.45 GHz over the last 40 years, efficiency at this fre-

**Table 3. 5.8 GHz, 2 GW transmitter comparisons.**

Transmitter Type	Klystron [22]	Magnetron [23]	Solid-State [25]
Maximum converter $P_{out}$ (W CW)	26,000	5,000	59
Converter operating voltage ( $V_{dc}$ )	28,000	6,000	80
Converter dc-RF efficiency (%)	83	85.5	90
Converter mass (kg)	14.15	1	0.001
Operating temperatures	300 °C on tube body 500 °C on collectors	350 °C on radiator	300 °C at junction
No. of converters in 500-m diameter antenna	209,863	~400,000	84,001,536
Transmitter specific mass (kg/m <sup>2</sup> )	40.4	32	33.9

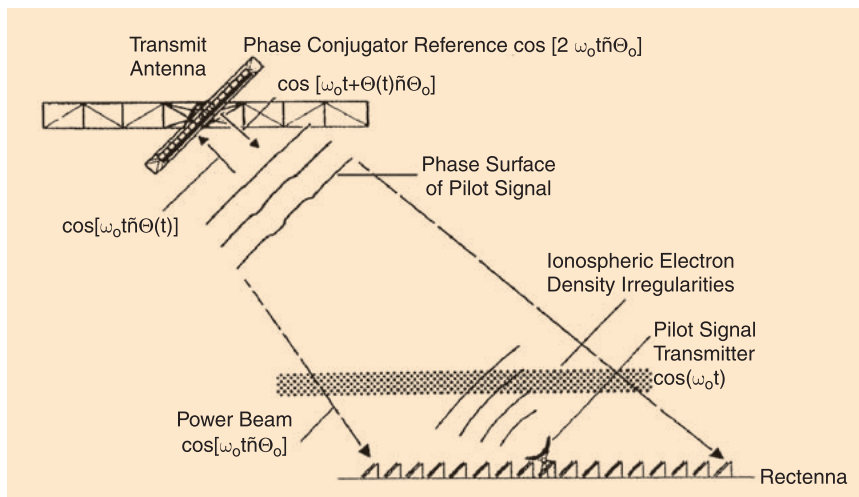
quency is used as a standard for estimating the highest conversion efficiencies attainable at the higher frequencies. This efficiency comparison is made possible by keeping the gain of the 2.45-GHz rectenna (6.4 dBi) constant and scaling in frequency the effective areas of rectennas at 5.8 and 35 GHz. With an effective area of 52 cm<sup>2</sup> for the 2.45-GHz rectenna, the effective areas for the hypothetical 5.8- and 35-GHz rectennas are 8.92 and 0.245 cm<sup>2</sup>, respectively.

Since the middle-to-late 1980s, interest in rectenna development has shifted to higher frequencies, dual and circular polarization, and printed-circuit formats. Emphasis has been placed on thin, lightweight, low-cost approaches to make power beaming to high-altitude communication platforms more feasible. Table 4 lists some of these printed rectennas and their performances.

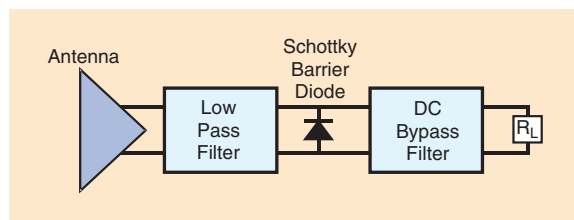
In the SERT program, a high gain and circular polarized printed rectenna array was developed with over 78% efficiency at Texas A&M University (Figure 9) [38]. Similar to dual polarization, circular polarization adds the flexibility to WPT systems that are mobile, such as beaming power to a high-altitude communications platform. Because the antenna is a dual rhombic, the element gain was measured to be 11 dBi. High gain allows the rectenna elements to be arrayed with wider separations in the effort to lower the number of diodes in a large rectenna array. The rectenna used in the SERT 5.8-GHz system was sized to be 7.5-km in diameter, requiring millions of diodes. Also developed at Texas A&M during the same time was a dual-frequency rectenna with efficiencies greater than 80% at both 2.45 and 5.8 GHz (Figure 10).

In well-matched rectenna arrays, the diode is the most critical component to achieve high efficiencies because it is the main source of loss. Schottky barrier diodes utilizing Si and GaAs have been employed with rectification efficiencies greater than 80%. Although the electron mobility of GaAs is over six times greater over Si for high efficiency, Si has a higher thermal conductivity for better reli-

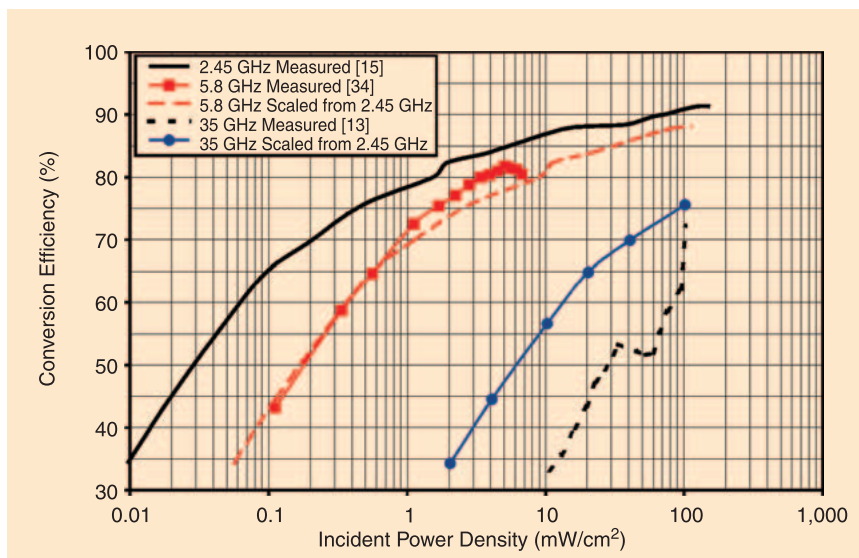
ability. Proper diode selection for a WPT application is dependent on input power levels, and the diode parameters should be chosen carefully for an efficient rectifier at a specified operating frequency. The breakdown voltage ( $V_{br}$ ) limits the diode's power handling capability and is directly related to the series resistance and junction capacitance through the intrinsic properties of the diode's material and structure. For instance, increasing the breakdown voltage increases either the series resistance or junction capacitance. Decreasing the series resistance will decrease the power dissipated in the diode; however, the breakdown voltage will decrease or the



**Figure 6.** Retrodirective beam control concept with an SPS.



**Figure 7.** Schematic of rectenna circuit.



**Figure 8.** State-of-the-art rectenna efficiencies.



**Table 4. Printed rectenna performances.**

Rectenna Type	Operating Frequency (GHz)	Measured Peak Conversion Efficiency	Peak Output Power per Element (W dc)	Polarization	Mass to DC Output Power Ratio (W/kg)	Specific Mass (kg/m <sup>2</sup> )
Printed dipole [35]	2.45	85%	5	Linear	4,000	0.25
Circular patch [36]	2.45	81%	5	Dual	263	2.5
Printed dipole [37]	2.45	70%	1	Dual	-	-
Printed dual rhombic [38]	5.61	78%	0.084	Circular	-	-
Circular patch [39]	5.8	76%	3	Linear	-	-
Printed dipoles [40]	2.45 5.8	84.4 82.7	0.094 0.052	Linear Linear	-	-
Square patch [13]	8.51	66%	0.065	Dual	-	-

junction capacitance will increase. Increasing the junction capacitance will lower its cutoff frequency. These parameters must be traded in selecting the proper diode for high- power applications.

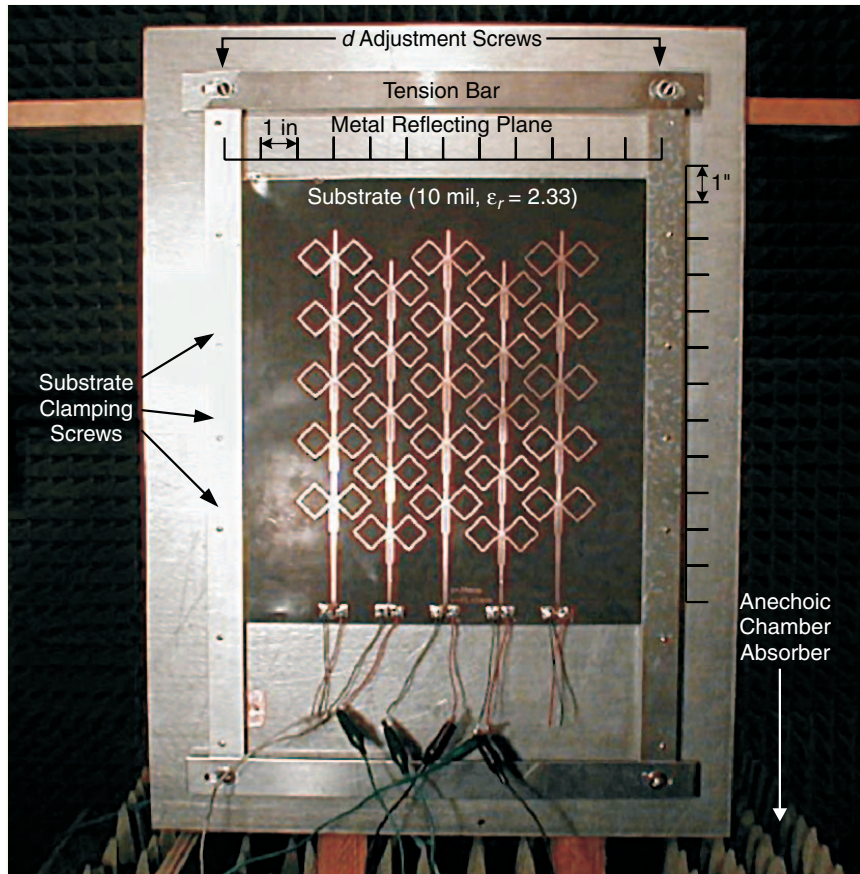
Fortunately, a database of experiments now exists to guide in the diode selection. Table 5 provides a short list of diode parameters (Figure 11) and their measured conversion efficiency. The diode theoretical conversion efficiency is also shown using the closed-form equations in [35]. Operation of rectennas higher than 35 GHz is tech-

nically possible. Schottky barrier diodes have been produced with cutoff frequencies up to several terahertz, where the cutoff frequency needs to be approximately ten times the operating frequency for efficient rectification [42]. Diode cutoff frequency is given by [43]

$$f_c = \frac{1}{2\pi R_s C_{j0}}$$

where  $R_s$  is the diode's series resistance, and  $C_{j0}$  is the zero-bias junction capacitance.

One of the main concerns about rectennas is the radiation of harmonics generated by the diode. Because it is a highly nonlinear circuit, harmonic power levels are significant and must be suppressed. Harmonic radiation patterns from bar-type rectennas have been measured as a single element and in an array at 2.45 GHz [44]. Although the second harmonic peak power level from a single element was 25 dB down from the fundamental, an array of 42 elements revealed a peak of -11 dBc in the resistively loaded pattern measurements. One method of suppressing harmonics is by placing a frequency selective surface in front of the rectenna that passes the operating frequency and attenuates the second and third harmonics [45], [46]. Experiments have shown 10-15 dB suppression of the second harmonic using this



**Figure 9.** 5.61-GHz circular polarized printed rectenna with over 78% efficiency [38].

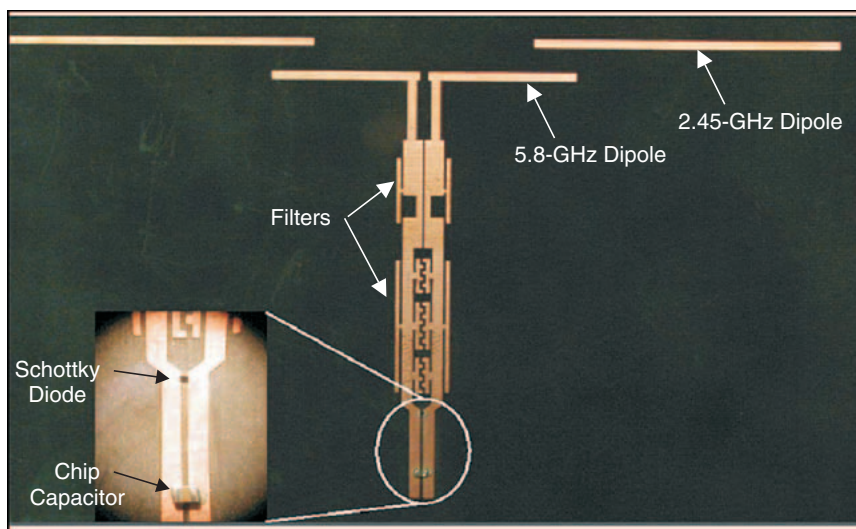
technique. A more powerful technique to suppressing harmonics is locating the rectifying diode and filtering circuits behind the antenna ground plane. A reduction of the second, third, and fourth harmonics by greater than  $-47$  dB from the fundamental has been achieved using this rectenna implementation [39], [47]. In addition to the filter rejection, a circular patch antenna also serves as a harmonic filter due to its noninteger resonance.

### End-to-End Power Efficiency

Finally, the entire SPS system is linked together to provide an approximation to the dc-to-dc WPT efficiency (Table 6). Due to the enormous size of the transmit and receive apertures of 500-m and 7.5-km diameter, the power transfer efficiency over 36,000 km is approximately 45%. Although the collection efficiency from the two apertures is sized to be 92%, the cumulative system losses have a large effect on the overall link efficiency.

### The National Research Council

The NRC Aeronautics and Space Engineering Board (ASEB) conducted an independent assessment of the SSP strategic research and technology road maps during 2000-2001 [48]. The general findings of this review were quite positive, although a number of important areas for improvement were also identified. The key findings included the following. NASA's current SSP technology program is directed at technical areas that have important commercial, civil, and military applications for the United States. Also, NASA has defined a potentially valuable program, but one that will require significantly higher funding and programmatic stability to attain the aggressive performance, mass, and cost goals that are required. The NRC also recommended that NASA's SSP efforts should substantially leverage work ongoing in other agencies in the United States, as well as internationally.



**Figure 10.** Dual-frequency rectenna operating at 2.45 and 5.8 GHz [40].

### Conclusions

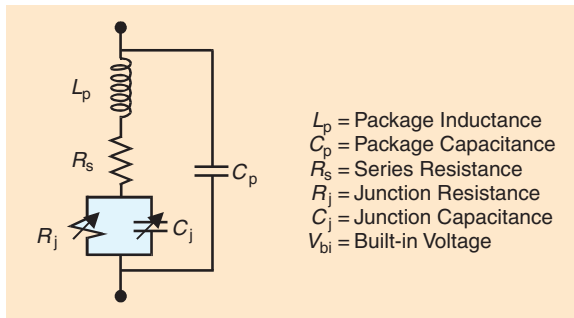
Future large-scale SSPs will form a very complex integrated system of systems requiring numerous significant advances in current technology and capabilities. Ongoing technology developments have narrowed many of the gaps, but major technical, regulatory, and conceptual hurdles remain. Continuing systems concept studies and analyses will be critical to success, as will following a clear strategic R&T road map. This road map must assure both an incremental and evolutionary approach to developing needed technologies and systems is followed, with significant and broadly applicable advances with each increment. In particular, the technologies and systems needed for SPS must support highly leveraged applicability to needs in space science, robotic and human exploration, and the development of space.

Considerable progress has been made in the critical area of microwave power transmission. At 5.8 GHz, dc-RF converters with efficiencies over 80% are achievable today. Rectennas developed at 5.8 GHz have also been measured with efficiencies greater than 80%. With optimized components in both the transmitter and rectenna, an SPS system has the potential of a dc-to-dc efficiency of 45%. Although not considered to be a significant technology barrier, the beam control system

**Table 5. Diode parameters and their measured and calculated rectenna efficiencies.**

Frequency (GHz)	Schottky Diode	$C_{jo}$ (pF)	$R_s$ ( $\Omega$ )	$V_{bi}$ (V)	$V_{br}$ (V)	RF $P_{in}$ (W)	$R_L$ ( $\Omega$ )	Measured Efficiency (%)	Calculated Efficiency (%)
2.45 [15]	GaAs-W	3.7	0.66	0.6	60	7.0	160	92.5	90.5
5.8 [36]*	Si	0.12	8	0.4	8.8	0.05	327	82	78.3
8.51 [13]*	GaAs	0.26	11.2	0.714	9.5	0.10	250	62.5	66.2
35 [43]*	GaAs	0.03	3	0.8	12	0.025	213	60 **	63.6

\* Efficiency measured in a rectenna element. \*\* Reflected power not subtracted.



**Figure 11.** Schottky barrier diode circuit model.

based on retrodirectivity needs to be demonstrated in a large scale WPT system.

The decades-long time frame for SPS technology development is consistent with the time frame during which new space transportation systems, commercial space markets, etc., could advance. The question of ultimate large-scale SPS economic viability remains open. However, ongoing studies suggest that economic targets may be achievable in the far term, but only if key investments in technology development and infrastructure can be justified on the basis of non-SPS space applications.

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