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Wireless Power Transfer from Space to Earth

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SUMMARY Microwaves have typically been used for communications and radar, but nowadays are given much attention to energy transfer applications. This paper describes microwave power transfer from a satellite to Earth that is visualized as a solar power satellite system (SPSS). After the system configuration is explained, unique engineering features are presented. Then, some contributions made by Japanese community are introduced, focusing on microwave and antenna engineering. As SPSS will handle high power levels at microwave frequency, and so components should be mass-produced to reduce the cost, then we need to shift our paradigm on the technology involved. Finally, the roadmap to a commercial SPSS is discussed.

key words: solar power satellite, high power microwave, beam control, mass-production, spacetenna, rectenna

1. Introduction

Humankind has consumed energy throughout their history, in order to improve their lives. Figure 1 shows human energy consumption from 6000 BC to 8000 AD [1]. At the time of slight ascent of the curve in the 13th century, our ancestors consumed only a small amount of energy. This is due to the small population of the earth, which was 400 million instead of 7 billion as of 2011. However, the more important point is the smaller energy consumption per capita. Most people lived like serfs even in the richest country at that time, China. They cultivated fields by their own power or with domestic animals, and burned wood in order to obtain a little heat. Europe was in a period of asceticism originated from medieval Christianity after the prosperous Roman Empire and before the glorious Renaissance.

After the Industrial Revolution in the early 1800s, humankind started to use machines in place of mills to grind grains to flour, or in place of domestic animals to carry things or to cultivate fields. The new energy source of the machines was coal. Coal production increased drastically so that the curve in Fig. 1 shows a sharp ascent. Through two world wars, much energy was extracted from oil for airplanes and ships. Now we are almost at the top of the consumption curve.

In the relatively near future, we are surely facing a shortage of energy from oil and natural gas. However, people will not tolerate poverty after richness, so we need to look for new energy sources. One strong candidate is a solar energy transferred from space to Earth via a solar power satellite system (SPSS). SPSS can supply an enormous quantity of energy to our society, but does not increase CO₂ like thermal power stations, nor contaminate our planet like atomic power stations when they fail [2]–[4]. Compared with terrestrial solar power generation, SPSS does not suffer from weather variability, and does not stop at night in the case of SPSS in GEO (the Geostationary Earth Orbit).

On the other hand, SPSS includes many new technical issues [5], [6]. For example, the way to control quite a narrow microwave beam, to generate and rectify multi-GW power at high frequencies, and to construct and control multi-km structures in space. This paper describes the outline of SPSS work mainly in USA and Japan, and extracts technical issues. Several research topics in microwave and antenna engineering will be introduced. More details will be given in relevance to antennas.

2. Configuration of a Solar Power Satellite System

The concept of SPSS proposed by P.E. Glaser in 1968 [7] is shown in Fig. 2 where we can see two parabolas. The upper-right one is a concentrator of solar light that comes from the upper-right direction. The lower left one is a microwave-transmitting antenna that sends beamed power to a receiving antenna on the earth. These two parabolas are connected by a superconducting network, which is an associated idea.

When the “oil shock” started in the early 1970s, the idea of SPSS was taken up by the Department of Energy and NASA of the USA, and was visualized as the so-called “Reference System” [8]. The system configuration with one
The satellite is shown in Fig. 3. The rectangular structure on the left side is a gigantic solar cell panel, which generates Direct Current (DC) power from sunlight. They planned to launch and allocate six satellites of this type in GEO.

The generated power is converted to a microwave, which is transmitted by an antenna on the upper side of the solar panel. The antenna seems relatively small but not in reality, and is called a “spacetenna” (i.e. a space-antenna). The spacetenna sends the power in the form of a beam to the receiving antenna on the earth, which is called a “rectenna” (i.e. a compound word of rectifier and antenna). The restored energy at DC is supplied to the commercial power grid using an interface device in the same way as other sustainable power sources [9].

The satellite of the Reference System is designed to be located in GEO that is 36000 km above the equator. As the diameter of the transmitted beam on the earth is determined by the diffraction angle from the spacetenna and the distance between the satellite and the rectenna, the beam size is about 5 km in diameter.

In order to reduce the size of the spacetenna and rectenna, another type of SPSS with a satellite in a Low Earth Orbit was proposed in Japan, which is called the “SPS 2000 System” [10]. The satellite is of a triangular prism shape as shown in Fig. 4, of which one side faces the ground through the whole orbital revolution. The important point of this system is that the look angle of the satellite from the rectenna changes, in the worst case from −90 to +90 degrees in elevation. Therefore, the rectenna should have wide tracking capability, and the spacetenna should have beam scanning capability in addition to precise beam control.

3. Engineering Features of the System

As being a novel system, an SPSS includes many innovations in terms of engineering [2]. I will explain each feature and consider its quantitative significance in the proposed SPSSs.

(1) Generation of direct current power and its distribution

The solar cell panel in Fig. 3 is required to generate DC power of 8 GW, which corresponds to about one-fourth of the total production of solar cells in the world as of 2011 [11]. The total area of 5 km × 10 km in sides is needed for this purpose. The solar cells are connected in a combination of parallel and series connections to isolate failures of opening and shorting, respectively, among cells.

The constitution of the panel and the way of construction are to be studied. As the size of the panel is enormous, the distribution of the DC power should be well designed to reduce ohmic losses. A compromise must be made between the weight and ohmic loss of the buss-bars including the distributing voltage.

The solar cells should be efficient in generating DC power in order to reduce the total area. The first influential factor is the material to be used. Crystalline silicon is more efficient than amorphous silicon though more difficult to manufacture and assemble. Compound semiconductors may be a good solution despite the disadvantages of weight, cost, difficulty in assembling, and scarcity as a resource. The second factor is the configuration of the cells. Excellent energy absorption has been achieved by using multiple junction layers to cover a wide range of wavelength of solar
(2) Generation of microwave power and its feeding

DC power of 8 GW is converted to the power at a microwave frequency either by high power oscillators of vacuum tubes [12] or high power amplifiers of transistors [13]. The latter method may be more convenient and promising as semiconductor technology is growing fast. In the Reference System, the power of 5 GW is generated at 2.45 GHz. This value is beyond engineering “common sense”. The power level of a microwave cooker is about 1 kW, and that of the Deep Space Network of the USA is 400 kW at 2 GHz-band [14].

In conventional radio systems such as communications and radar, many linear amplifiers of class A to C are used. Instead, in SPSS the power conversion efficiency is important to reduce the number of amplifiers and to prevent excessive heat generation. Therefore, non-linear amplifiers of class E or F are used, as the efficiency is much higher than the above-mentioned classes. For that purpose, the cutoff frequency should cover several harmonics of the fundamental frequency.

The performance of high power amplifiers is expressed by two kinds of metrics: drain efficiency (DE) and power added efficiency (PAE). Eventually, the final stage of a high power amplifier (HPA) has to handle large power with low gain, so that PAE is more convenient to express actual operation.

In order to handle high power, a heat resistive material with a wide energy band gap and good heat conductivity is preferred to fabricate transistors. Therefore, the compound semiconductors of GaN or SiC are more attractive than Si.

(3) Transmission and reception of microwave beam

The most important requirement of this part of the SPSS is to exactly fill the rectenna aperture with the beam, as explained by Fig. 5(a) [15]. On the other hand, the beam in a conventional radio system is expanded much wider than the aperture of the receiving antenna, as shown in Fig. 5(b). We have no experience of controlling a beam as in Fig. 5(a) so that much attention should be paid to study the performance.

The size of the spacetenna is determined to give an appropriate diffraction angle for the beam width, and is 1 km in diameter in the Reference System. This size is much larger than conventional onboard antennas: the largest one is the deployable parabola antenna aboard Kiku 8 satellite of Japan of which diameter is 13 m.

We can conceive three ways to manufacture such a large antenna, as shown in Fig. 6 [15]. The antenna with a single parabola in figure (c) is not practical but only referential. The Reference System assumes a large array antenna with several hundred billion dipoles, as shown in figure (a). In order to reduce the element number, we proposed an array of parabolas that fills the aperture area most densely, as shown in figure (b) [16]. In this case, the periphery of each parabola should be hexagonal, so that its primary radiator should have a beam with a hexagonal cross-section [17].

At present, an array antenna with small elements of half-wavelength size as shown in figure (a) is considered most promising due to its beam steering capability. However, the element number is tremendous so that mass-production is inevitable for the antenna elements as well as associated components. And the feed network must be simplified as much as possible.

A larger element in Fig. 6 must radiate a larger power. Accordingly, the connection of an element and a microwave source has variations as shown in Fig. 7. A constituent unit of the Reference System corresponds to Fig. 7(a), though the SPS 2000 System to Fig. 7(c).

The actual way of installation and connection depends on the types of antennas and circuit components. A dipole, for example, is suitable for feeding by a balanced line so that
a component with a balanced output can be placed on the substrate surface, and directly connected to the dipole. On the other hand, a patch is easily fed at one point by a probe. Consequently, a component with an unbalanced output can be placed on the backside of the substrate, and one of the lines is connected to the patch through a hole.

The beam propagates along a path through the atmosphere with thermal coupling, or through the ionosphere with non-linear coupling [18]–[20]. The resultant irregular distribution of dielectric constant in space may cause the deformation and migration of the beam profile, as is expected considering the propagation of a laser beam in the atmosphere. Therefore, the effects should be studied with much care.

(4) Rectification of microwave power and connection to a commercial power grid

The rectenna is 5 km in diameter in the Reference System. This size exceeds the “common sense” of current antenna technology. The largest antenna on the ground is the fixed parabola with 300 m diameter at Arecibo in Puerto Rico, or the fully steerable parabola with 100 m diameter at Effelsberg in Germany [14].

On the other hand, the rectenna may be constructed as an assembly of smaller elements such as apertures or half-wavelength elements. In this configuration, each element or several elements are followed by a rectifying circuit, and the DC output is combined with the others. The fact that each power component loses the phase information may be beneficial for manufacturing the antenna with less accuracy.

The diode number in a rectenna is given by the total RF input divided by the power handling level of each diode. Therefore, a diode should handle a large power at microwave frequency in order to reduce the diode number and eventually to lower the output impedance of the rectenna. Moreover, the energy conversion efficiency should be high.

On the other hand, there are already two related devices: a high power rectifying diode of several kW at 50 or 60 Hz, and a microwave detector with a power of several mW. Comparing the characteristics of these diodes, the requirements of SPSS diodes are not easy to fulfill.

An SPSS satellite in GEO does not suffer from power interruption due to solar eclipse or thick clouds. A satellite in LEO appears above a rectenna only intermittently, but the time is predetermined. Accordingly, the connection of SPSS to the power grid is much easier than terrestrial solar power generation systems with strong weather dependence [4].

(5) Control of microwave beam

The radiated beam from a spacetenna should be kept within the aperture of a rectenna. However, the beam may migrate due to many disturbances: mechanical fluctuation of the satellite, thermal deformation of the spacetenna, and turbulence of the propagation media. Therefore, precise beam control is inevitably required in SPSS.

One method is so-called retro-directive control where the spacetenna automatically adjusts the beam direction according to the uplink signal [21]. Quick response is an advantage of this scheme. However, the frequency relation to the high power downlink, and the constitution of the receiving antenna onboard are issues in consideration of the obtainable S/N ratio and the pattern degradation of the downlink beam.

The other method is a conventional feedback loop system. Sensors on the ground sense the downlink footprint and eventually the deviation of the beam. The deviation information and control signal are transmitted to the satellite via the up-link. Then, the downlink beam is adjusted according to the control signal. This scheme has much flexibility for the system design, and secure operation. However, the response may be slower than the retro-directive control.

In case of emergency, the beam should be controlled to avoid hazard extension. The response should be quick, and the associated change of system architecture should as small as possible.

(6) Thermal control

In the case of the Reference System, DC power of 8 GW is generated, and RF power of 5 GW is output to space. As a result, the difference of 3 GW has to be dissipated as heat, which should be well disposed of without damaging the internal components.

In space, heat is transferred between a satellite and the surrounding space only by radiation. Convection makes no contribution. Accordingly, devices with high efficiency are important, as well as excellent thermal control design.

(7) Interference with conventional radio wave systems

Though an SPSS will probably use an ISM frequency, other systems operate in the same frequency band: Bluetooth and wireless LANs in 2 GHz-band, and ETC (Electronic Toll Collection) systems in 5 GHz-band. Moreover, an SPSS may generate harmonics due to the non-linearity of internal devices. It is necessary to study the interference and to reduce its effect as much as possible, before we proceed to the development stage of an actual SPSS [3].

(8) Effects on living things

Microwave systems are criticized for having ill-effects on living things through heating and non-heating effects [22]. The power limit is specified in the IEEE document to be less than 1.0 mW/cm² for non-professional person [23]. We have to at least keep within the power density regulation.
(9) Space structure

An SPSS is a huge system, as described above. The weight of the Reference System is twenty kilo-tons that is 50 times heavier than the International Space Station (ISS). Therefore, the architecture and the way of construction should be studied.

People cannot stay in space for the total construction period. Consequently, automatic assembly is inevitable. For example, a spacetenna could be carried to orbit as modules. Each module is fixed in the target position and deployed automatically.

(10) Transportation to orbits

The Reference System is to be located in GEO so that each module should be launched first to LEO using a chemical fuel launcher, then to GEO using slow but efficient propulsion such as electrical propulsion. On the other hand, in an SPSS in LEO, a module can be transported to orbit by one flight.

In either system, each module is so large that launching to orbit is critical. If we use H-IIB rocket of Japan for the transportation of the Reference System only to LEO, the flight should be more than 1105 times so that the launch cost is a key to commercialize SPS. In the USA, companies are developing new types of launcher to drastically reduce the launch cost. Falcon 9 is for logistics to ISS, and Space Ship 2 for space tourism [24]. If the launch cost is reduced to 1/40 from the current value, the study result showed that SPSS could be competitive with conventional power generation, such as thermal or atomic power generation.

In concluding this section, we have seen that the amplifiers, rectifiers and passive components in SPSS must handle large power levels at several GHz, which is comparable with a conventional power system at AC frequency. Moreover, the number of elements is beyond current experience. For example, the antenna elements in the Reference System exceed $2 \times 10^8$ in number. Accordingly, our old paradigm of microwave and antenna engineering should be shifted: (i) from low power to high power, and (ii) from a-la-carte production to mass-production.

4. Current Research Results in the Relevant Microwave and Antenna Engineering

4.1 Microwave Amplifier and Phase Shifter

The most efficient HPA at present was developed at 5.65 GHz using GaN HEMT technology in Japan [25]. The cut-off frequency is approximately 29 GHz, which covers the fourth harmonics of 5.65 GHz. Therefore, class F operation is possible. The response of the HPA is shown in Fig. 8. The power added efficiency (PAE) was as good as 79%, and the drain efficiency reached 90%. The output level was 2.2 W.

The phase shifter should have sufficient accuracy and precision in addition to large power handling capability to realize precise beam control. A phase shifter of MEMS technology is being developed in Japan. The MEMS switch is not of a conventional torsion-bar type, but of a cantilever type that is suitable for dual-pole operation and ohmic loss reduction [26].

4.2 Constitution of a Transmitting Antenna (Spacetenna) For the mass-production of antennas, the followings are important.

(1) Simple radiating element

In the Reference System, a half-wavelength dipole that is located a quarter wavelengths above a reflector is adopted as a radiating element. Such a high profile radiator is not convenient to fold the antenna panels in the launch phase. An Ultra-Low Profile Dipole was proposed to realize the antenna by laying a coaxial cable on the reflector, as shown in Fig. 9 [27]. ULPD has a simple structure and wide frequency characteristics in virtue of a built-in balun.

However, in order to mass-produce radiators, a printed antenna on a substrate is most suitable. A patch antenna and a printed dipole with a built-in balun are those candidates [28].
Fig. 10 Effectiveness of partial drive technique in a four-element array [29].

Fig. 11 Two types of partial drive technique.

(2) Reduction of driven elements and feed network

The complexity of a feed network can be relaxed to less than half by a novel technique of partial drive, which is shown in Fig. 10. Four radiating elements in free space are drawn in figure (a), and only two of them are really driven through transmission lines. The remaining two are parasitic, and are just metallic rods. The parasitic elements are excited by the radiated wave from the driven elements, as shown in Fig. 11(a). By optimizing the arrangement, the gain of the partially driven array is almost the same as that of the equivalent array whose elements are all driven, as shown in figure (b) [29].

An actual antenna for practical application is often backed with a reflector. In this case, the reflected wave must be taken account in addition to the direct wave for coupling estimation, as shown in Fig. 11(b). An array antenna with four driven and six parasitic elements were optimized in the arrangement to show the validity of partial drive technique [30].

In a partially driven array antenna, grating lobes tend to appear due to a slight difference of amplitude between adjacent driven and parasitic elements. A novel algorithm to arrange two kinds of elements was proposed to suppress the grating lobes, as shown in Fig. 12 [31].

In order to reduce the number of phase shifters and HPAs, a large array antenna is divided into sub-arrays, each of which is attached with a phase shifter. In this scheme, the elements in each sub-array are in phase, and the beam is steered according to the phase difference between the sub-arrays. As the antenna characteristics tend to be degraded, the radiation patterns were analyzed and formulated. The result is shown in Fig. 13 in the case of a one-dimensional array with 2 sub-arrays and 3 elements in each sub-array [32]. Consequently, the size of a sub-array can be compromised to reduce the gain decrease, grating-lobe appearance, and the deviation of the beam direction.

(3) Deployable Antenna Structure

Radiating elements are installed on a substrate panel, and many panels are folded for launch on a rocket. Consequently, the division of the total antenna and the folding structure affect the folding efficiency. Multiple-folding structure of antenna panels is proposed as a basic structure of an antenna, as shown in Fig. 14 [33]. In this case, the elements on adjacent panels have a phase bias due to a panel step so that the phase of each element should be adjusted according to the desired direction.
4.3 Beam Control

A retro-directive system using spread-spectrum signals on the uplink has been proposed. The direction of wave arrival is computed onboard, and the control signal is generated by software [34]. The advantages are: (i) The uplink frequency can be independent from the downlink frequency, in contrast to a hardware retro-directive system. (ii) The system is robust against interference. (iii) Multiple rectennas can be managed due to the discrimination capability of the signal.

As a countermeasure against an emergency, the system shown in Fig. 15 was proposed [35]. The transmitted beam is expanded instantaneously by rearranging the phases of all radiating elements following a proposed algorithm. As a result, the radiated fields are not summed to cause spontaneous side lobes probabilistically, and the radiated power is not concentrated on a small number of components.

4.4 Constitution of Receiving Antenna (Rectenna)

In 1977, a large GaAs power diode was developed at 2.4 GHz. The conversion efficiency from RF to DC power came up to 91.4% at 7 W input, though the details of the experiment are not clear [36]. In Japan, efficiency of 76% at 5.8 GHz, without reflection loss, was obtained using a GaAs diode [37]. The power level was 3 W.

As stated before, GaN has many attractive features for a high-power diode. A novel diode with a ten finger electrode and its relevant rectifier were developed at 2.45 GHz [38]. The main parameters are as follows: On-resistance 2.0Ω, Zero V-capacitance 0.36pF, Breakdown voltage 90 V, Size 890μm × 1900μm for a chip. A rectifying circuit using the above-mentioned diode was developed. The characteristics of conversion efficiency and reflection ratio are shown in Fig. 16. The maximum efficiency is 75% at the optimum power level of 5 W.

In a practical application in a large power system, the diodes should be connected in serial and/or parallel. An experiment to generate 29 W was performed using 97 diodes [39]. The diodes were classified in three serial blocks, each of which was composed of diodes in parallel. Before the system experiment, they tested each rectifier to show no breakdown at the specified power level of 300 mW per rectifier. However, in actual operation, seven diodes in the central region of the array were broken through insulation breakdown. The cause of the failure is now under study.

5. Strategy for the Realization of a System

There have already been several R&D study groups on SPSS, even only in Japan. This situation is understandable, as SPSS is a novel and unprecedented system. We have to discuss the most appropriate scheme before starting the development phase that will need much money.

An R&D schedule following the author’s personal idea is shown in Fig. 17, based on the author’s experience in a research and development division [40]. This schedule includes some basic principles that may be applicable to large-scale R&D planning in general.

As a first step, we have to focus on solving critical problems using a limited amount of money. In order to accomplish this, most appropriate research themes should be selected.

As the second step, we have to demonstrate the feasibility of the system on the smallest scale, including the launch of a satellite to orbit. The scale of the satellite is an important issue to be discussed. If we want to show the power transferred from the satellite, the power level should be sufficient to satisfy people. Instead, if we confirm the most critical issue in orbit, which may be sending a beam to a rectenna aperture, the size of the spacetenna is a more important parameter than the power level.

Before starting the commercial phase, we have to demonstrate the system availability with sufficient power level to attract investors. The minimum power level depends on the group in question, and may be around 10 kW with sufficient capability of the beam.

In the final stage of R&D, a commercial satellite will be realized with a sufficient amount of fund, which may be 2 trillion yen. The amount of generated power should result in superior cost competitiveness against conventional power
generation. It can be considered advantageous that SPSS needs almost no operational cost for providing fuel, different from thermal or atomic power generation.

At the time of judgment in the figure, the results of the former step are evaluated objectively, and their adequacy for the next step should be approved. Through the whole R&D process, the schedule should be consulted or managed by commercial interests who are responsible for the final investment. Otherwise, decisions in the process may be distorted by political considerations.

6. Conclusions

In this paper, the outline of SPSS was explained to show its novelty and unusualness. The technical details show the difficult target for each device, and encourage R&D activity with indications of achievement. There are many R&D topics including components, subsystems, and the total system that range from electrical engineering, mechanical engineering, and architecture to materials.

In relation to microwave and antenna engineering, it was shown that components in SPSS must handle high power levels. Accordingly, microwave engineering should be innovated to become High Power Microwave Engineering rather than conventional microwave engineering for communications and radar.

Moreover, special designs suitable for mass-production are needed for radiating elements, feed networks and the associated active and passive components. At this stage, an antenna and components should be combined and designed as a whole. Consequently, we have to exploit a new field of microwave and antenna engineering to be called Mass-production Microwave and Antenna Engineering.

Along these new paradigms, many contributions and proposals have been made in Japan, as introduced above. Some of them are to enhance the component characteristics at high frequency and high power level, and the others are to promote mass-production of devices.

The process to realize the final SPSS includes overcoming several difficulties. As shown in the author’s idea of the long R&D schedule, it is critically important to have close contact with final investors, and to show fundamental and timely demonstrations.

Note: ISM

This word stands for Industry, Science and Medical. The ISM frequencies were used mostly as energy sources, but nowadays a part of the frequency band is co-used with communications. For example, 2.45 GHz-band is with Bluetooth and wireless LAN, and 5.8 GHz-band is with ETC (Electronic Toll Collection) system.

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References


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