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LIST OF ABBREVIATIONS

1. SPS	Solar Power Satellite
2. DC	Direct Current
3. SSP	Space Solar Power
4. RF	Radio Frequency
5. WPT	Wireless Power Transmission
6 .MPT	Microwave Power Transmission

CHAPTER 1

INTRODUCTION

One of the major global issues we are facing today is the energy problem combined with a shortage of natural energy resources and increasing atmospheric concentrations of CO_2 . If we continue to rely only on nonrenewable resources , they will be completely consumed within 100– 150 years. Furthermore, large amounts of fossil fuel consumption increase the CO_2 concentrations in the atmosphere, which raises serious environmental concerns. The situation has become even more serious after the failure of the Fukushima nuclear plant in 2011, because it has been revealed that a low-carbon nuclear plant has substantial safety concerns. For these reasons, a clean, renewable, and safe energy system is urgently required in the near future.

One of the potential candidates for the required energy system, and probably the most realistic solution, is the SPS, which can be used to harvest solar energy in space and to transmit it to the ground. The sun's unlimited constant energy supply is available in space, where solar energy harvesting is unaffected by weather conditions and day/night cycles. The time average solar power available per unit area in space is five to ten times larger than that available on the ground.

The flight segment, which is called the solar power satellite, converts sunlight into direct current (dc) power using photovoltaic cells and then generates a micro- wave beam down to the ground segment. The conversion efficiency from dc to microwave energy is expected to be 80% in the near future.

One of the major concerns is the power cost of the SPS but many studies have shown that the SPS power price can be made competitive with that of the ground power plants . The CO_2 emissions from the SPS have been estimated to be about 20 g/kWh , which is com- parable to that of nuclear plants and much less than that of fossil fuel plants. Another important feature of the SPS is its capability to change the service area quickly on demand since the microwave power beam can be guided by a pilot signal from the receiving site on the ground.

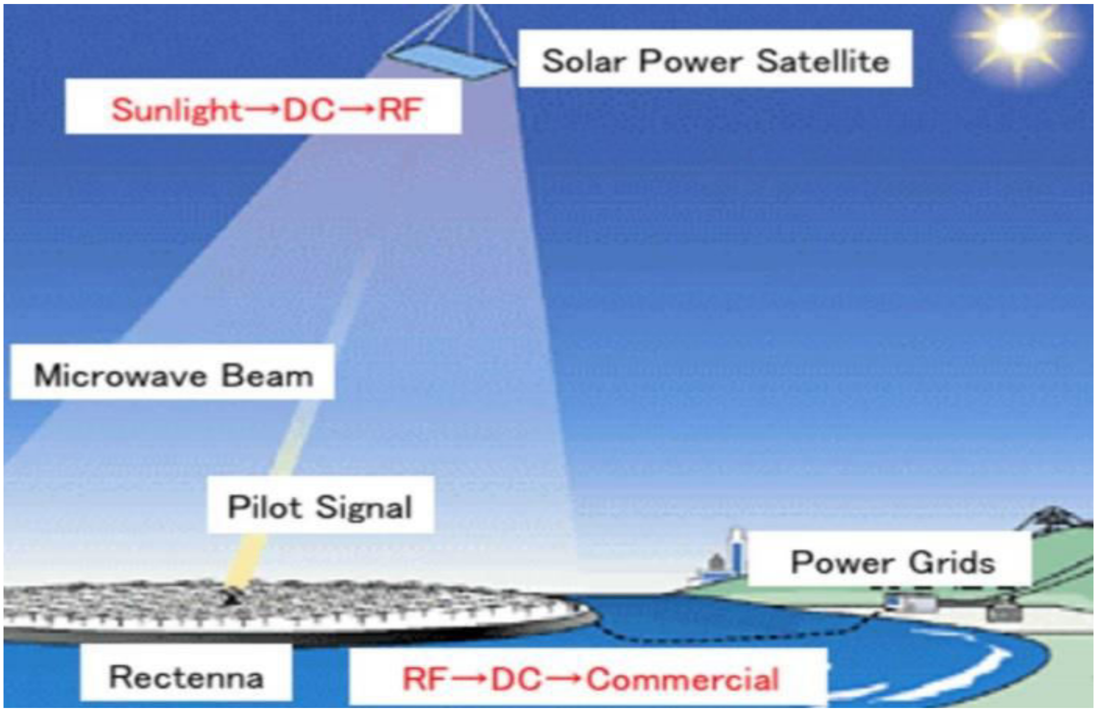

Fig.1.1 Configuration of the SPS System.

Increasing global energy demand is likely to continue for many decades. Renewable energy is a compelling approach – both philosophically and in engineering terms. However, many renewable energy sources are limited in their ability to affordably provide the base load power required for global industrial development and prosperity, because of inherent land and water requirements. The burning of fossil fuels resulted in an abrupt decrease in their availability. It also led to the green house effect and many other environmental problems. Nuclear power seems to be an answer for global warming, but concerns about terrorist attacks on Earth bound nuclear power plants have intensified environmentalist opposition to nuclear power.

Earth based solar panels receives only a part of the solar energy. So it is desirable to place the solar panel in the space itself, where, the solar energy is collected and converted in to electricity which is then converted to a highly directed microwave beam for transmission. This microwave beam, which can be directed to any desired location on Earth surface, can be collected and then converted back to electricity. This concept is more advantageous than conventional methods. Also the microwave energy, chosen for transmission, can pass unimpeded through clouds and precipitations.

CHAPTER 2

SOLAR POWER SATELLITE

The SPS was first proposed by Peter Glaser in 1968, followed by the National Aeronautics and Space Administration/Department of Energy (NASA/DOE) studies in the 1970s. After the early investigations in the United States, various types of SPSs have been proposed. They are categorized into five types on the basis of usage of the sunlight concentrating mirror and type of power collection/distribution. The beam pattern from the transmitting antenna is closely related to the type of power distribution. The ‘‘separated power’’ type, consisting of equivalent power generation/transmission panels (sandwich panels), can be highly modularized but the aperture amplitude distribution is uniform. On the other hand, the ‘‘bus power’’ type can produce a Gaussian distribution beam with low side lobes, although it requires long and heavy power cables to be installed. The NASA reference model, 5-GW class, is the oldest model but still the most well-known one in which sunlight is converted into electricity by a large solar panel, 5 km 10 km, and is supplied to a microwave power transmitter having a diameter of 1 km through a rotary joint. The SPS 2000 was the first Japanese model designed as a 10-MW class demonstrator early in the 1990s at the Institute of Space and Astronautical Science (ISAS, Kanagawa, Japan) . The SPS 2000 has the shape of a triangular prism with two solar panels as the upper panels and a microwave transmitter as the bottom panel.

The New Energy and Industrial Technology Development Organization (NEDO) grand design, studied by NEDO in 1992, is a 1-GW class model with a circular disc microwave transmitter between two rectangular solar panels. The basic-microwave-type model , the advanced-microwave-type model , and the laser-type model are 1-GW class operational models currently being studied in Japan. The basic-microwave-type model is the tethered SPS in which the power generation/ transmission panel is suspended by tether wires and stabilized by the gravity gradient force; this has been studied by the Institute for the Unmanned Space Experiment Free Flyer (USEF).

The advanced-microwave-type model is a combination of reflective mirrors with a power generation solar array and microwave transmitter. It utilizes the formation flight of reflective mirrors and power generation/ transmission complex, which has been studied by the Japan Aerospace Exploration Agency (JAXA, Kanagawa, Japan). The laser-type model is a combination of focusing mirrors, a crystal laser exciter, optics, and a heat radiator, and has been studied by JAXA. NASA Sun Tower , a 250-MW model, was selected as a promising model during the NASA fresh look study conducted in the mid-1990s. The structure is a treelike tower integrated by modular power generators with a circular transmitting antenna at the bottom. The NASA integrated symmetrical concentrator (ISC) , 1-GW class, was studied by NASA in 2001; it consists of two clamshell condenser mirrors, two power generators, and a power transmitter.

The NASDA 2001 model, a 1-GW class model studied by the National Space Development Agency in Japan in 2001, consists of two sets of reflective mirrors for sun pointing and one power generation/transmission panel. The International Academy of Astronautics (IAA) study model is the latest model, which has been studied by the IAA Space Solar Power (SSP) Study Group . Most of the models proposed thus far prefer microwave energy over laser energy for wireless power transmission, because the power efficiency both at the transmitter and the receiver is generally higher and attenuation through the atmosphere is lower for micro- waves as compared to those for lasers.

Each SPS would have been massive; measuring 10.5 km long and 5.3km wide or with an average area of 56 sq. km. The surface of each satellite Would have been covered with 400 million solar cells. The transmitting antenna on the satellite would have been about 1 km in diameter and the Receiving antenna on the Earth’s surface would have been about 10 km in diameter [5].In order to obtain a sufficiently concentrated beam; a great deal of power must be collected and fed into a large transmitter array. The power would be beamed to the Earth in the form of microwave at a frequency of 2.45 GHz. Microwaves have other features such as larger band width, smaller antenna size, sharp radiated beams and they propagate along straight lines. Microwave frequency in the range of 2-3 GHz are consider edoptimal for the transmission of power from SPS to the ground rectennas site .

Fig.2.1 Five types of SPS.

The efficiency difference between microwaves and lasers are summarized in Table 2.1.

	Microwave	Laser
Frequency (wave length)	5.8 GHz	1.06 μm
Atomospheric/ionospheric transmission (clear sky)	97 %	80 %
dc to RF (laser) conversion efficiency	80 % (expected)	60 % (expected)
RF (laser) to dc conversion efficiency	80 % (expected)	60 % (expected)

Table 2.1 Comparison of Microwave and Laser Power Transmission for SPS (Typical Statistics).

Primary technology	Existing level	Target level	Factor
Solar power generation	100 kW (space)	1 GW	10 000
Microwave power transmission	30 kW (ground)	1 GW	30 000
Large space structure	100 m (space)	1-2 km	10-20
Space transportation	5000 $/kg	100 $/kg	1/50

Table 2.2 SPS Technologies Compared With Existing Technologies.

Construction of the SPS requires the use of five major technologies, namely, power generation, wireless power transmission, heat rejection, large space structure, and space transportation, each on an extremely large scale. All technologies except wireless power transmission have al- ready been implemented on a certain scale. Wireless power transmission has been verified at the 30-kW level in the field experiment [15]. This situation is completely different from that in nuclear fusion, another revolutionary energy system, for which the principle technology ''break- even'' has not been verified as yet.

The main problem associated with the SPS is to apply the technologies to a larger system, which is at the giga watt level in terms of power, kilometer level in terms of size, and several tens of thousands of tons in weight. Further, it is desirable to make its power price competitive with that of existing power generation systems on the ground. Table 2 summarizes the existing technology level and the target level for the SPS primary technologies.

CHAPTER 3

MICROWAVE POWER TRANSMISSION FOR SPS

3.1 Microwave Frequency

The microwave frequency for the SPS is taken to be in the range of 1–6 GHz, by compromising between the antenna size and atmospheric attenuation. For higher frequencies, the scale of the transmitting/receiving antenna can be smaller and the ionospheric plasma interaction is less, but the rainy attenuation becomes larger. If we choose a frequency in the industrial, scientific, and medical (ISM) radio bands, then either 2.45 or 5.8 GHz would be a potential candidate. A frequency of 2.45 GHz was used in the early phase study, but considering the recent progress in the C-band RF technologies, 5.8 GHz is considered to be a more favorable frequency to use.

3.2 Research History

Fig 3.1 shows three major epoch-making events in the research on microwave power transmission. Nikola Tesla established the basis of wireless power transmission through his pioneering work in the late 19th and early 20th centuries . In the mid-1970s, W. C. Brown con- ducted a microwave power transmission experiment using the JPL Goldstone parabolic antenna . It has been the largest microwave power transmission experiment conducted thus far. For this experiment, 34 kW of power was harnessed by a rectenna array placed at a distance of 1.6 km from the transmitter. In 1983, the first microwave power transmission experiment in space was conducted in Japan using a sounding rocket . The nonlinear interaction be, tween the high-intensity microwave and ionospheric plasma was studied by operating an 800-W magnetron. Another space experiment was conducted in 1993 using a phased array antenna to transmit 1 kW of power into space . There are many researches of the rectenna elements. Famous research groups of the rectenna are Texas A&M University in USA, NICT(National Institute of Information and Communications Technology, past CRL) in Japan, and Kyoto University in Japan.

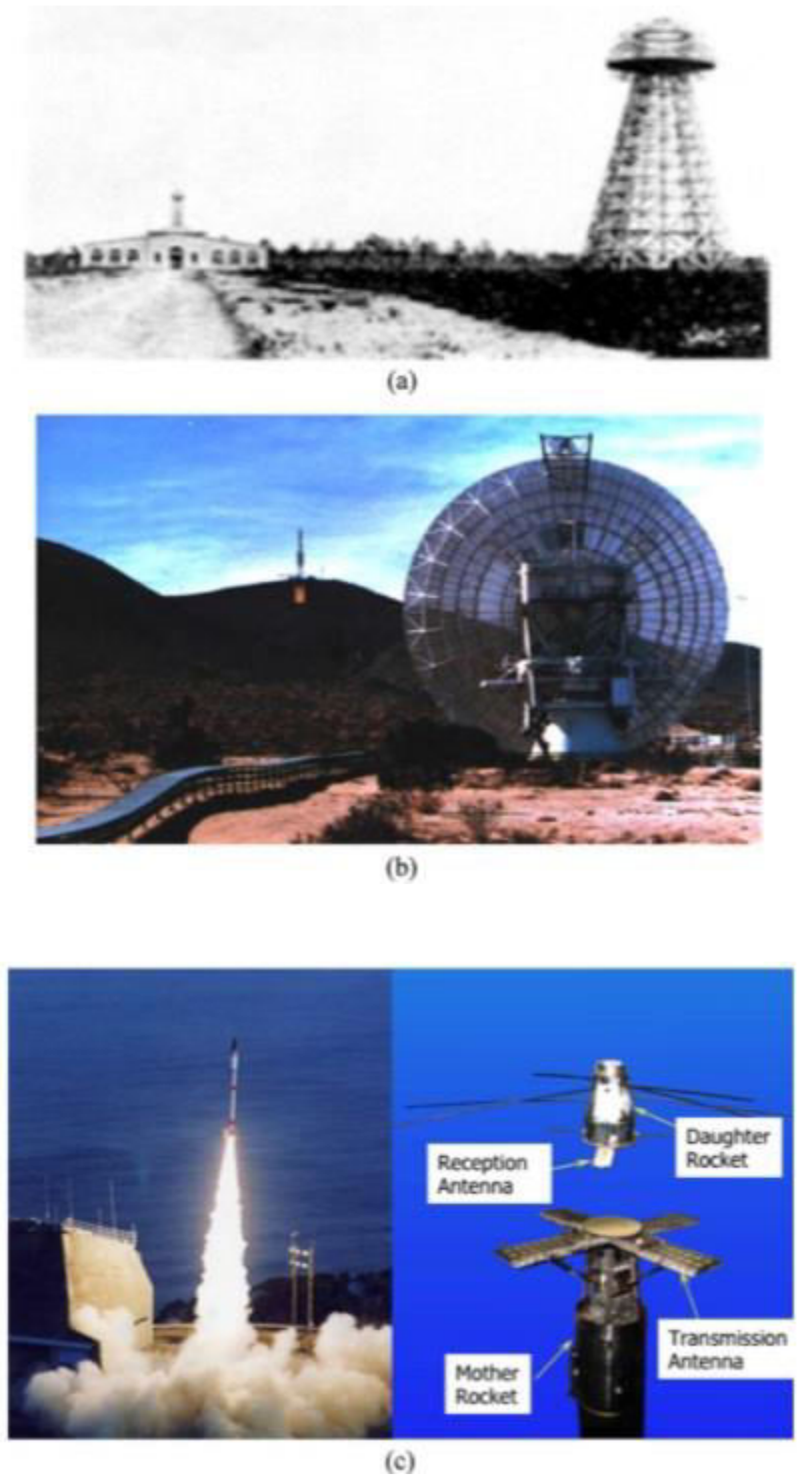

Fig.3.1 Historical milestones for microwave power transmission research for SPS: (a) Pioneering work by Nikola Tesla (early 20th century) ; (b) NASA JPL demonstration (1975) ; and (c) microwave power transmission experiment in space (1983, 1993) .

3.3 Microwave Technology

Transmission or distribution of 50 or 60 Hz electrical energy from the generation point to the consumer end without any physical wire has yet to mature as a familiar and viable technology. The 50 Hz ac power tapped from the grid lines is stepped down to a suitable voltage level for rectification into dc. This is supplied to an oscillator fed magnetron. The microwave power output of the magnetron is channeled into an array of parabolic reflector antennas for transmission to the receiving end antennas. To compensate for the large loss in free space propagation and boost at the receiving end the signal strength as well as the conversion Efficiency, the antennas are connected in arrays. A simple radio control feedback system operating in FM band provides an appropriate control signal to the magnetron for adjusting its output level with fluctuation in the consumers demand at the receiving side. The overall efficiency of the WPT system can be improved by-Increasing directivity of the antenna array. Using dc to ac inverters with higher conversion efficiency .Using schottky diode with higher ratings.

The microwave transmission system have three aspects :

1. The conversion of direct power from the photovoltaic cells, to microwave power on the satellites on geosynchronous orbit above the Earth.
2. The formation and control of microwave beam aimed precisely at fixed locations on the Earth's surface.
3. The collection of the microwave energy and its conversion into electrical energy at the earth's surface.

Element	Parts	Efficiency/ Loss	Power level	Tasks required for SPS application
Microwave generator/ amplifier	Electronic tube (Magnetron, TWT, Klystron)	Efficiency 70-80%	Several hundreds W~ Several MW	Phase control Weight (g/w) reduction
	Semiconductor	Efficiency 60-70%	Less than 100 W	Efficiency improvement Weight (g/w) reduction Cost reduction
Microwave beam controller	Phase shifter	Loss -1dB/bit	Less than 10 W	Loss reduction Life improvement (MEMS)

Table 3.1 Current Performance of SPS Microwave Elements.

CHAPTER 4

TRANSMITTER

The technology employed for the generation of microwave radiation is an extremely important Phased Array Used in Japanese Field MPT Experiment (Left : for MILAX in 1992,Right : for SPRITZ in 2000)subject for the MPT system. We need higher efficient generator/amplifier for the MPT system than that for the wireless communication system. For highly efficient beam collection on rectenna array, we need higher stabilized and accurate phase and amplitude of microwave when we use phased array system for the MPT.

The key requirement of a transmitter is its ability to convert dc power to RF power efficiently and radiate the power to a controlled manner with low loss. The transmitter's efficiency drives the end-to-end efficiency as well as thermal management system .The main components of a transmitter include dc-to-RF converter and transmitting antenna. Power distribution at the transmitting antenna=$(1- r^2)$, where r is the radius of antenna .There are mainly three dc-to-RF power converters: magnetrons, klystrons and solid state amplifiers.

These have electric characteristics contrary to each other. The microwave tube, such as a cooker-type magnetron, can generate and amplify high power microwave(over kW) with a high voltage (over kV) imposed. Especially, magnetron is very economical. The semiconductor amplifier generate low power microwave (below 100W) with a low voltage (below fifteen volt) imposed. It is still expensive currently. Although there are some discussion concerning generation/amplifier efficiency, the microwave tube has higher efficiency (over 70%) and the semiconductor has lower efficiency (below 50%) in general. We have to choose tube/semiconductor case by case for the MPT system.

4.1 Klystron

Fig.4.1 shows the schematic diagram of a klystron amplifier . Here a high velocity electron beam is formed, focused and send down a glass tube to a collector electrode which is at high positive potential with respect to the cathode. As the electron beam having constant velocity approaches gap A, they are velocity modulated by the RF voltage existing across this gap. Thus as the beam progress further down the drift tube, bunching of electrons takes place. This variation in current enables the klystron to have significant gain. Thus the catcher cavity is excited into oscillations at its resonant frequency and a large output is obtained. The overall efficiency is 83%. The microwave power density at the transmitting array will be 1 kW/m² for a typical 1 GW SPS with a transmitting antenna aperture of 1 km diameter. If we use 2.45 GHz for MPT, the number of antenna elements per square meter is on the order of 100.

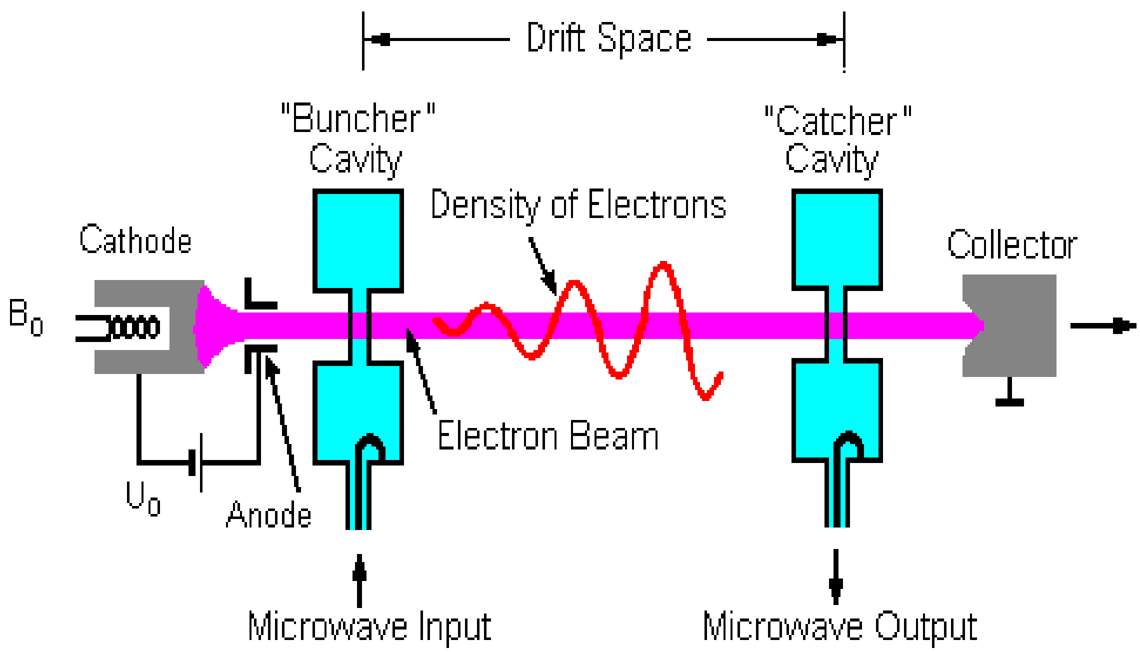

Fig.4.1 Klystron amplifier schematic diagram.

CHAPTER 5

RECEIVER

The main part of the receiver side is an array of dipole antennas known as Rectennas.

5.1 RECTENNA

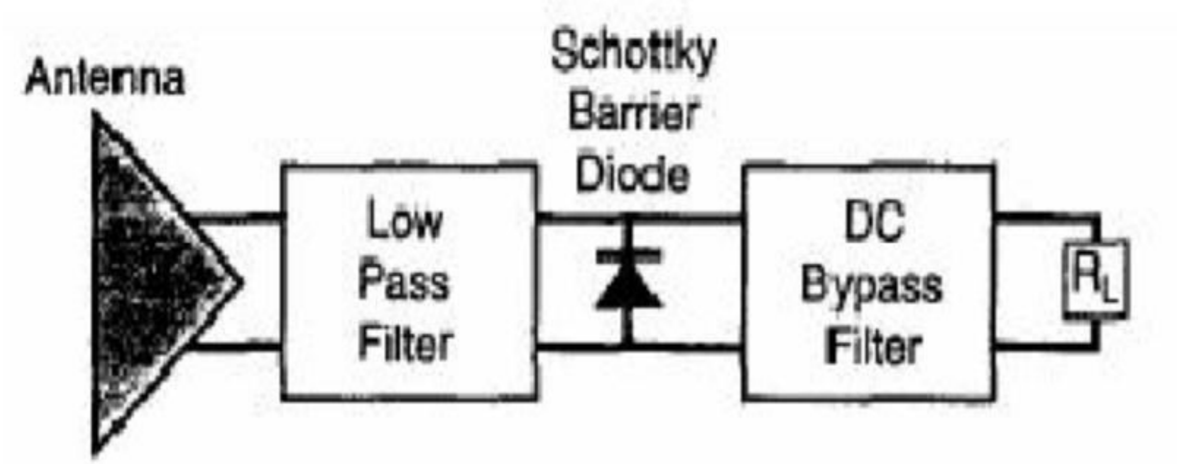

Fig.5.1 Block diagram of Rectenna.

Brown was the pioneer in developing the first 2.45GHz rectenna . Rectenna is the microwave to dc converting device and is mainly composed of a receiving antenna and a rectifying circuit. Fig 5.1 shows the schematic of rectenna circuit . It consists of a receiving antenna, an input low pass filter, a rectifying circuit and an output smoothing filter. The input filter is needed to suppress radiation of high harmonics that are generated by the non linear characteristics of rectifying circuit. Because it is a highly non linear circuit, harmonic power levels must be suppressed.

For rectifying Schottky barrier diodes utilizing silicon and gallium arsenide are employed. Diode selection is dependent on the input power levels. The breakdown voltage limits the power handling capacity and is directly related to series resistance and junction capacitance through the intrinsic properties of diode junction and material .For efficient rectification the diode cut off frequency should be approximately ten times the operating frequency. Diode cut off frequency is given by f=1/ [2_RsCj], where f is the cut off frequency, Rs is the diode series resistance, Cj is the zero-bias junction capacitance.

There are many researches of the rectenna elements. Famous research groups of the rectenna are Texas A&M University in USA, NICT(National Institute of Information and Communications Technology, past CRL) in Japan, and Kyoto University in Japan. The antenna of rectenna can be any type such as dipole, Yagi-Uda antenna[, microstrip antenna, monopole, loop antenna, coplanar patch, spiral antenna, or even parabolic antenna.

The rectenna can also take any type of rectifying circuit such as single shunt full-wave rectifier, full-wave bridge rectifier, or other hybrid rectifiers. The circuit, especially diode, mainly determines the RF-DC conversion efficiency. Silicon Schottky barrier diodes were usually used for the previous rectennas. New diode devices like SiC and GaN are expected to increase the efficiency. The rectennas with FET[or HEMT appear in recent years. The rectenna using the active devices is not passive element. The single shunt full-wave rectifier is always used for the rectenna. It consists of a diode inserted to the circuit in parallel, a λ/4 distributed line, and a capacitor inserted in parallel. In an ideal situation, 100% of the received microwave power should be converted into DC power. Its operation can be explained theoretically by the same way of a F-class microwave amplifier. The λ/4distributed line and the capacitor allow only even harmonics to flow to the load. As a result, the wave form on the λ/4 distributed line has a π cycle, which means the wave form is a full- wave rectified sine form. The RF-DC conversion efficiency of the rectenna with a diode depends on the microwave power input intensity and the connected load. It has the optimum microwave power input intensity and the optimum load to achieve maximum efficiency. When the power or load is not matched the optimum, the efficiency becomes quite low.

The characteristic is determined by the characteristic of the diode. The diode has its own junction voltage and breakdown voltage. If the input voltage to the diode is lower than the junction voltage or is higher than the breakdown voltage, the diode does not show a rectifying characteristic. As a result, the RF-DC conversion efficiency drops with a lower or higher input than the optimum.

CHAPTER 6

DEMONSTRATION PROJECTS

6.1 SPS 2000

The prize for most ambitious wireless power transmission demonstration proposed since Tesla's Long Island tower experiment before World War I goes to the Japanese SPS 2000 project . The purpose is to demonstrate a functioning solar power satellite system including the wireless transmission link and develop the ground infrastructure in several locations to provide the basis for a space solar power market.

The design calls for a gravity stabilized satellite capable of delivering 10 MW of electricity from a spherical 1100 km east-to-west equatorial orbit. The phased array antenna will be capable of steering ±30° along the orbital path (E-W) and ±16.7° perpendicular to the orbital path (N-S). This will limit the possible rectenna sites to close to the equator. In addition to being limited to an equatorial band, the receiving sites must be at least 1200 km apart to maximize the length of time for power transmission to each individual site. Because power can only be received intermittently at any ground site (about 4 minutes out of the 108 minute orbit for a beam scan angle of 30°) energy storage is an important component of any ground site. Further limitations are placed on the power available to any site by the diurnal rotation of the Earth, since the satellite is incapable of delivering energy while in eclipse over a site during the night. With an average daily coverage of less than 30 minutes per site, 4 to 4.5 MWh of energy could be available to a site from the SPS 2000 satellite.

The satellite is in the form of a long prism. The base of the satellite is always earth facing and mounts the transmitting array. The "roof" faces of the satellite are paneled with photovoltaic cells. The phased array transmitting array is based on a dense array of low energy solid state antenna elements (the design assumes an efficiency of 60%, which has not yet been achieved, the MILAX/METS antenna solid state elements achieved 42% efficiency). To assure target acquisition and tracking, a retro directive beam at 245 MHz transmitted from each rectenna site is used. The satellite would be launched in sections and assembled on orbit.

Initial designs studies have been completed and a scale model mock-up of the satellite has been made. Several potential receiving sites, from Pacific Islands to South American Andes locations have been visited by the SPS 2000 team, with a generally enthusiastic reception.

6.2 Grand-Bassin Project

This project, planned for La Réunion will supply electricity to the remote village of Grand-Bassin . During its implementation, the French led Grand-Bassin project will accomplish several goals. Most important of these is to provide an actual demonstration of point-to-point power beaming. Grand-Bassin is a small isolated mountain village on La Réunion. Set in the scenic environment of a river valley surrounded by steep cliffs, access is limited to trail or helicopter. Several tourist lodges have been established in Grand-Bassin to accommodate sightseers. Further development of the tourist potential of Grand-Bassin is hampered by the lack of electricity in the village to supply refrigeration for food and laundry for overnight guests. Several options were investigated for providing up to 10 kW of electricity to Grand-Bassin. For primarily aesthetic reasons, a microwave wireless power transmission link from the existing terminus of an electric power line was chosen.

The primary constraint imposed on the system was cost. In order to compete with photovoltaic conversion and keep overall energy costs low, the end-to-end electrical conversion and transmission system efficiency had to be at least 20%. Although the aesthetic desire was to use as small a transmitter and rectenna as possible, concern for the perceived safety of the human inhabitants and other biota argues for low energy density (maximum of 5 mW/cm2) in the beam, with an attendant loss of efficiency. An “H” dipole design is used for the rectenna. The transmitter will consist of injection locked phase and amplitude controlled magnetrons feeding a multi-focus parabolic reflector. This design consists of several parabolic reflector sectors with a common focus, a microwave analogue to the Fresnel lens. The distance of the wireless link is 700 m. The design system will utilize a rectenna aperture diameter of 17 m, with a 6 m transmitter diameter to give 95% collection efficiency. Overall ac-to-ac conversion efficiency is calculated to be 57%.

A prototype system demonstration will consist of four multi-focus parabolic reflectors fed by 1 kW magnetrons transmitting over a distance of 150 m to a 180 m2 H dipole rectenna to deliver 2 kW output power.

6.3 SPS End-to-End Terrestrial Demonstration

A test project to demonstrate all the major elements of a solar power satellite on the ground has been proposed . In this demonstration concept, the DC output of a photovoltaic array is used to power a transmitting array at the hundreds of kW power level. The receiving rectenna, located at a distance of 1 to 5 km from the transmitter, would convert the RF power to DC for a utility grid. The objective is to verify practical wireless power transmission and to establish the reliability of components operated over time. In addition to operation data, environmental studies could be performed to ensure the safety of the beam. Finally, it would be possible to test the concept of beam splitting (targeting multiple receivers) from the transmitting antenna.

CHAPTER 7

Construction of SPS from Non Terrestrial Materials: Feasibility and Economics

SPS, as mentioned before is massive and because of their size they should have been constructed in space . The aluminum and silicon can be refined to produce solar arrays . Among them are the shallow gravity wells of the Moon and asteroids; the presence of an abundance of glass, metals and oxygen in the Apollo lunar samples; the low cost transport of those materials to a higher earth orbit by means of a solar- powered electric motor; the availability of continuous solar energy for transport, processing and living . One major new development for transportation is required: the mass driver .The mass driver is a long and narrow machine which converts electrical energy into kinetic energy by accelerating 0.001 to 10 kg slugs to higher velocities. The mass driver conversion efficiency from electrical to kinetic energy is close to 100 percent.

7.1 Microwaves-Environmental Issues

The price of implementing a SPS includes the acceptance of microwave beams as the link of that energy between space and earth. Because of their large size, SPS would appear as a very bright star in the relatively dark night sky. SPS possess many environmental questions such as microwave exposure, optical pollution that could hinder astronomers, the health and safety of space workers in a heavy-radiation (ionizing) environment, the potential disturbance of the ionosphere etc. The atmospheric studies indicate that these problems are not significant, at least for the chosen microwave frequency . On the earth, each rectenna for a full-power SPS would be about 10 km in diameter. This significant area possesses classical environmental issues. These could be overcome by sitting rectenna in environmentally insensitive locations, such as in the desert, over water etc. However, the issues related to microwaves continue to be the most pressing environmental issues.

CHAPTER 8

CONCLUSION

The SPS will be a central attraction of space and energy technology in coming decades. However, large scale retro directive power transmission has not yet been proven and needs further development. Another important area of technological development will be the reduction of the size and weight of individual elements in the space section of SPS. Large-scale transportation and robotics for the construction of large-scale structures in space include the other major fields of technologies requiring further developments. The electromagnetic energy is a tool to improve the quality of life for mankind. It is not a pollutant but more aptly, a man made extension of the naturally generated electromagnetic spectrum that provides heat and light for our sustenance. From this view point, the SPS is merely a down frequency converter from the visible spectrum to microwaves.

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