# Solar Power Satellite by Wireless Power Transmission

Shuchi Shukla[1], Navin Kumar[2]

***Abstract***— *A immense anxiety has been voiced in latest years over the general use of energy, the partial supply of resources, and the pollution of the environment from the use of current energy conversion systems. Electrical power accounts for much of the energy consumed. Much of this power is wasted during transmission from power plant generators to the consumer. The resistance of the wire used in the electrical grid distribution system causes a loss of 26-30% of the energy generated. This loss implies that our current system of electrical distribution is only 70-74% efficient.*

*Nikola Tesla is greatest known for his remarkable statement concerning the wireless transmission of electrical power. His first efforts towards this end started in 1891 and were future to simply "disturb the electrical equilibrium in the nearby portions of the earth... to bring into operation in any way some instrument." In other words the entity of his experiments was simply to create effects locally and detect them at a distance.*

***Keywords— Power Transmission, Nikola Tesla, Electrical Power, Electrical Distribution.***

## I. INTRODUCTION

It is recognized that electromagnetic energy is linked with the propagation of electromagnetic waves. In theory, we can utilize all electromagnetic waves for a wireless power transmission (WPT). The distinction between the WPT and communication systems is only efficiency. Maxwell's Equations show that the electromagnetic field and its power diffuse to all directions. Though we transmit energy in a communication system, the transmitted energy is diffused to all directions. Though the conventional power is adequate for a transmission of information, the efficiency from the transmitter to receiver is quiet low. Therefore, we do not call it the WPT system.

WPT is a point-to-point power transmission. For the WPT, we had enhanced concentrate power to receiver. It was prove that the power transmission efficiency can approach close to 100%. We can added concentrate the transmitted microwave power to the receiver aperture areas with taper technique of the transmitting antenna power distribution. Renowned power tapers of the transmitting antenna are Gaussian taper, Taylor distribution, and Chepachet distribution. Such taper of the transmitting antenna is usually used for suppression of side lobes. It correspond to increase in the power transmission efficiency. Concerning the power transmission efficiency of the WPT, there are some good optical approaches in Russia.

Future appropriate and major application of the WPT via microwave is a Space Solar Power Satellite (SPS). The SPS is a gigantic satellite considered as an electric power plant orbiting the Geostationary Earth Orbit (GEO). It consists of mainly three segments; solar energy collector to convert the solar energy into DC (direct current) electricity, DC-to-microwave converter, and large antenna array to beam down the microwave power to the ground. The first solar collector can be moreover photovoltaic cells or else solar thermal turbine. The second DC-to-microwave converter of the SPS can be either microwave tube system and/or semiconductor system. It may be their combination. The third segment is a gigantic antenna array.

Table 1.1 shows some characteristic parameters of the transmitting antenna of the SPS. An amplitude taper on the transmitting antenna is adopt in order to amplify the beam collection efficiency and to reduce side lobe level in almost all SPS design. A characteristic amplitude taper is called 10 dB Gaussian in which the power density in the center of the transmitting antenna is ten times larger than that on the edge of the transmitting antenna.

The SPS is anticipated to be operational around 2030. Before understanding of the SPS, we can think about other applications of WPT. In recent years, mobile devices advanced considerably and have need of decreasing power consumption. It means that we can utilize the diffused weak microwave power as power source of the mobile devices with low power consumption such as RF-ID. The RF-ID is radio IC-tug with wireless power transmission and wireless information. This is a new WPT application like broadcasting.

**TABLE 1**
**TYPICAL PARAMETERS OF TRANSMITTING ANTENNA OF THE SPS [7]**

| Model | Old JAXA model | JAXA1 model | JAXA2 Model | NASA/DOE model |
|---|---|---|---|---|
| Frequency | 5.8 GHz | 5.8 GHz | 5.8 GHz | 2.45 GHz |
| Diameter of transmitting antenna | 2.6 kmϕ | 1 kmϕ | 1.93 kmϕ | 1 kmϕ |
| Amplitude taper | 10 dB Gaussian | 10 dB Gaussian | 10 dB Gaussian | 10 dB Gaussian |
| Output power (beamed to earth) | 1.3 GW | 1.3 GW | 1.3 GW | 6.72 GW |
| Maximum power density at center | 63 mW/ $cm^2$ | 420 mW/$cm^2$ | 114 mW/$cm^2$ | 2.2 W/ $cm^2$ |
| Minimum power density at edge | 6.3 mW/ $cm^2$ | 42 mW/ $cm^2$ | 11.4 mW/$cm^2$ | 0.22 W/ $cm^2$ |
| Antenna spacing | 0.75 λ | 0.75 λ | 0.75 λ | 0.75 λ |
| Power per one antenna (Number of elements) | Max. 0.95 W (3.54 billion) | Max. 6.1W (540 million) | Max. 1.7 W (1,950 million) | Max. 185 W (97 million) |
| Rectenna Diameter | 2.0 kmϕ | 3.4 kmϕ | 2.45 kmϕ | 1 kmϕ |
| Maximum Power Density | 180 mW/$cm^2$ | 26 mW/$cm^2$ | 100 mW/cm2 | 23 mW/$cm^2$ |
| Collection Efficiency | 96.5 % | 86 % | 87 % | 89 % |

***JAXA: Japan Aerospace Exploration Agency, NASA: National Aeronautics and Space Administration, DOE: US Department of Energy***

## II. HISTORY OF WIRELESS POWER TRANSMISSION

In 1864, James C. Maxwell predict the survival of radio waves by means of mathematical model. In 1884, John H. Poynting realize that the Poynting vector would play an significant role in quantify the electromagnetic energy. In 1888, bolstered by Maxwell's theory, Heinrich Hertz succeed in performance new evidence of radio waves by his spark-gap radio transmitter. The forecast and evidence of the radio wave in the end of 19th century was initiate of the wireless power transmission.

During the identical period of Marchese G. Marconi and Reginald Fessenden who are pioneer of communication via radio waves, Nicola Tesla suggested an idea of the wireless power transmission and carried out the first WPT experiment in 1899[1][2]. He said “This energy will be composed all over the globe rather in small amounts, ranging from a fraction of one to a few horse-powers. One of its chief use will be the illumination of isolated homes”. He actually built a gigantic coil which was connected to a high mast of 200-ft with a 3 ft-diameter ball at its top. He fed 300 Kw power to the Tesla coil resonated at 150 kHz. The RF potential at the top sphere reach 100 MV.

Unfortunately, he abortive because the transmitted power was diffused to all directions with 150 kHz radio waves whose wave length was 21 km.

To deliberate the transmitted power and to enlarge transmission efficiency, we have to use higher frequency than that used by Tesla. In 1930s, much progress in generating high-power microwaves, namely 1-10 GHz radio waves, was achieved by invention of the magnetron and the klystron. After World War II, high power and high efficiency microwave tubes were advanced by expansion of radar technology. We can concentrate a power to receiver with microwaves. We call the wireless power transmission with microwaves as microwave power transmission (MPT). Based on the development of the microwave tubes during the World War II, W. C. Brown started the First MPT research and development in 1960.

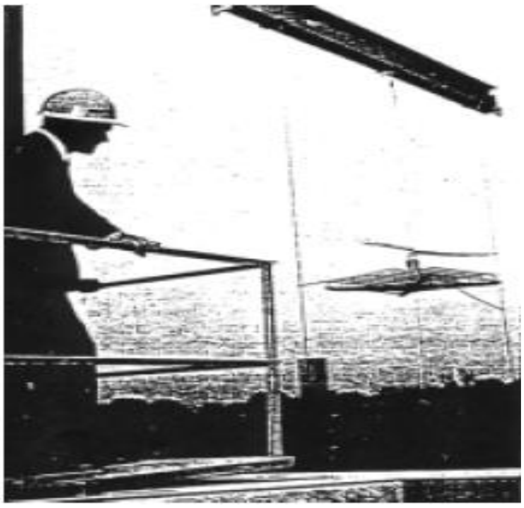


**FIGURE 1 MPT DEMONSTRATION WITH HELICOPTER BY W.C. .BROWN**

First of all, he made a retina, rectifying antenna which he named, for receiving and rectifying microwaves. The efficiency of the first rectenna developed in 1963 was 50 % at output 4WDC and 40% at output 7WDC, respectively [3].

With the rectenna, he succeeds in MPT experiments to wired helicopter in 1964 and to free-flied helicopter in1968 (Fig. 1). In 1970s; he tried to increase DC-RF-transmission-RF-DC total efficiency with 2.45 GHz microwave. In 1970, overall DC-DC total efficiency was only 26.5 % at 39WDC in Marshall Space Flight Center.

In parallel, he and his team succeed in the major MPT demonstration in 1975 at the Venus Site of JPL Goldstone Facility (fig 2). Distance between a transmitting parabolic antennas, whose diameter was 26m, and a rectenna array, whose size was 3.4 m x 7.2 m, was 1 mile.

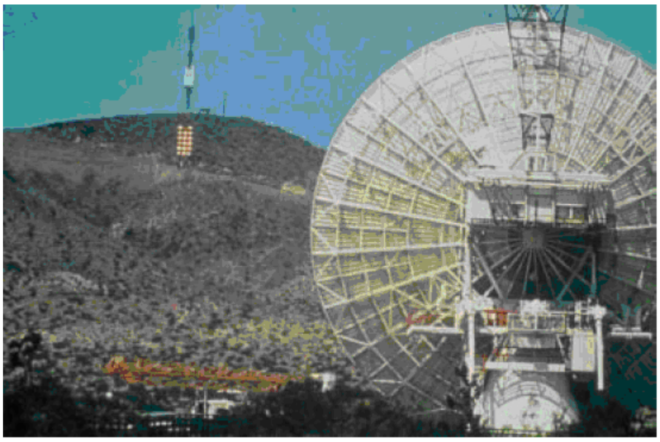


**FIG. 2: FIRST GROUND-TO-GROUND MPT EXPERIMENT IN 1975 AT THE VENUS SITE OF JPL GOLDSTONE FACILITY**

**FIG.3: STATIONARY HIGH ALTITUDE RELAY PLATFORM.**

After 1990s, many MPT laboratory and field experiments were carried out in the world. We often use 2.45 GHz or 5.8 GHz of the ISM band (ISM=Industry, Science, and Medical) for the MPT system. A Canadian group demonstrated fuel-free airplane flight experiment with MPT in 1987 which was called SHARP (Stationary High Altitude Relay Platform) with 2.45 GHz.

In USA, there were many MPT investigated and growth projects after W. C. Brown: for instance, retro directive microwave transmitters, rectenna, new devices and microwave circuit technologies.

In Japan, there were a lot of field MPT experiments such as fuel-free airplane flight experiment with MPT phased array with 2.411 GHz in 1992, ground-to-ground MPT experiment with Power Company and universities in 1994-95.

**FIG. 4 . GROUND-TO-GROUND MPT EXPERIMENT IN JAPAN IN 1994-95**

## III. RECENT TRENDS

*Antennas for Microwave Power Transmission:* All antennas can be practical for both the MPT system and communication systems, for example, Yagi-Uda antenna, horn antenna, parabolic antenna, micro strip antenna, phased array antenna or any extra type of antenna.

To predetermined target of the MPT system, we typically select a large parabolic antenna, for example, in MPT demonstration in 1975 at the Venus Site of JPL Goldstone Facility and in ground-to-ground MPT experiment in 1994-95 in Japan. In the fuel-free airship light experiment with MPT in 1995 in Japan, they changed a direction of the parabolic antenna to pursue the moving airship.

However, we have to employ a phased array antenna for the MPT from/to moving transmitter/receiver which comprise the SPS because we have to control a microwave beam direction exactly and quickly. The phased array is a directive antenna which generates a beam form whose shape and direction by the relative phases and amplitudes of the waves at the individual antenna elements.

It is likely to guide the direction of the microwave beam. The antenna elements might be dipoles [1], slot antennas, or any other type of antenna, even parabolic antennas [2, 3]. In some MPT experiments in Japan, the phased array antenna was adopted to steer a direction of the microwave beam (Fig.5).

All SPS is designed with the phased array antenna.

**FIG.5. PHASED ARRAY USED IN JAPANESE FIELD MPT EXPERIMENT**

*Recent Technologies for Transmitters:* The knowledge working for generation of microwave radiation is an vital topic for the MPT system. We require higher efficient generator/amplifier for the MPT system than that for the wireless communication system. For highly efficient beam collection on rectenna array, we require highly stabilized and precise phase and amplitude of microwaves for phased array system for the MPT.

There are two types of microwave generators/amplifiers. One is a microwave tube and the other is semiconductor amplifier.

***Magnetron:*** Magnetron is a cross field tube in which electrons emitted from the cathode take cyclical path to the anode. The magnetron is self-oscillatory device in which the anode contains a resonant RF structure. The magnetron has long history from invention by A. W. Hull in 1921.

The sensible and well-organized magnetron tube attracted worldwide attention only after K. Okabe proposed divided anode-type magnetron in 1928. Magnetron technologies received a boost during the World War II, especially with the Japanese Army. The magnetrons were also useful for microwave ovens. As a result, the magnetron of 500 – 1,000 W is widely in use for microwave ovens in 2.45 GHz, and is a relatively inexpensive oscillator (below $5). There is a net global capacity of 45.5GW/year for all magnetrons used in microwave ovens whose production is 50– 55 millions. It was W. C. Brown who invented a voltage controlled oscillator with a cooker-type magnetron in PLL.

***Semiconductor Amplifier:*** After 1980s, semiconductor devices became leading in microwave world in its place of the microwave tubes. This was driven by advances in mobile phone networks. The semiconductor device is expected to expand microwave applications, for example, phased array and active included antenna (AIA), because of its manageability and mass productivity. After 1990s, some MPT experiments were approved out in Japan with phased array of semiconductor amplifiers.

Typical semiconductor devices for microwave circuits are FET (Field Effect Transistor), HBT (Hetero junction Bipolar Transistor), and HEMT (High Electron Mobility Transistor). Present materials for the semiconductor devices are Si for lower frequency below a few GHz and GaAs for higher frequency.. It is simple to control phase and amplitude through the microwave circuits with semiconductor devices, for example, amplifiers, phase shifters, modulators, and so on.

At present, new materials are underneath development to allow semiconductor devices yield increased output power and efficiency.

***Transmitter Issues and Answers for Space Use:*** Largest MPT application is a SPS in which over GW microwave will be transmitted from space to ground at distance of 36,000km. In the SPS, we will use microwave transmitters in space. For space use, the microwave transmitter will be required lightness to reduce launch cost and higher efficiency to reduce heat problem.

A weight of the microwave tube is lighter than that of the semiconductor amplifier when we compare the weight by power-weight ratio (kg/kW). The microwave tube can generate/amplify higher power microwave than that by the semiconductor amplifier. Kyoto University's groups have developed a light weight phase controlled magnetron called COMET, Compact Microwave Energy Transmitter with a power-weight ratio below 25g/W (fig.6.)

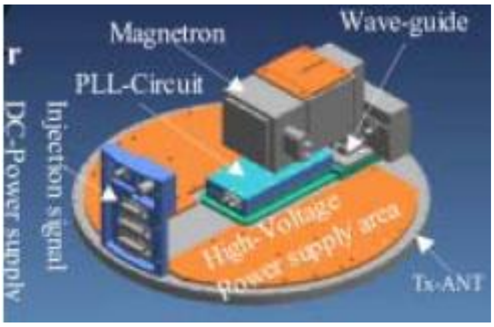



**FIG. 6 COMPACT MICROWAVE ENERGY TRANSMITTER WITH THE PCM (COMET)**

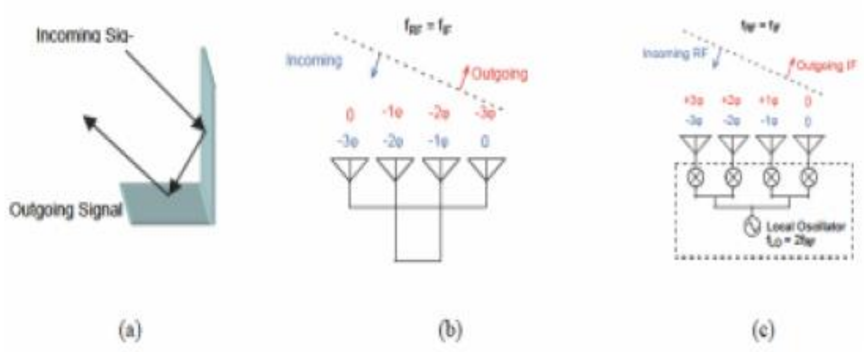
The COMET includes DC/Converters, a control circuit of the phase controlled magnetron with 5.8 GHz, a heat radiation circuit, a wave guide, and an antenna [4]. The power-weight ratio of the COMET is lightest weight in all microwave generators and amplifiers. TWTA for satellite use has lighter power weight ratio: 220Wat 2.45GHz at 2.65 kg (the TWTA weighs 1.5kg, the power supply weighs 1.15kg). 130W at 5.8 GHz at 2.15 kg (the TWTA weighs 0.8kg, the power supply weighs 1.35kg). Hence, they can deliver12g/W and 16.5g/W, respectively. They do not include a heat radiation circuit, a wave guide, and an antenna.

## IV. RECENT TECHNOLOGICAL TRENDS

***Retro directive Beam Control:*** A microwave power transmission is suitable for a power transmission from/to moving transmitters/targets. Therefore, accurate target detection and high efficient beam forming are important. Retro directive system is always used for SPS.

A corner reflector is most basic retro directive system. The corner reflectors consist of perpendicular metal sheets, which meet at an apex. Incoming signals are reflected back in the direction of arrival through multiple reflections off the wall of the reflector. Van Atta array is also a basic technique of the retro directive system. This array is made up of pairs of antennas spaced equidistant from the center of the array, and connected with equal length transmission lines. The signal received by an antenna is re-radiated by its pair, thus the order of re-radiating elements are inverted with respect to the center of the array, achieving the proper phasing for retro directivity.

Usual retro directive system have phase conjugate circuits in each receiving/transmitting antenna, which play same role as pairs of antennas spaced equidistant from the center of the array in Van Atta array. The signal is called a pilot signal. We do not need any phase shifters for beam forming. The retro-directive system is usually used for satellite communication, wireless LAN, military, and so on.




**(A) TWO-SIDED CORNER REFLECTOR, (B) VAN ATTA ARRAY, (C) RETRODIRECTIVE ARRAY WITH PHASE CONJUGATE CIRCUITS.**

***Environmental Issues:*** One of the characteristics of the MPT is to use more intense microwave than that in wireless communication systems. Therefore, we have to consider MPT safety for humans.

***Interaction with Atmosphere:*** In general, effect of atmosphere on microwaves is quite small. There are absorption and scatter by air, rain, and irregularity of air refraction ratio. In 2.45 GHz and 5.8 GHz, the absorption by water vapor and oxygen dominate the effect in the air. Especially, it is enough to consider only absorption by the oxygen in the microwave frequency. It is approximately 0.007 dB/km. In the SPS case, the amount of total absorption through the air from space is approximately 0.035 dB.

***Interaction with Space Plasmas:*** When microwaves from SPS propagate through ionospheric plasmas, some interaction between microwaves and the ionospheric plasmas occurs. It is well known that refraction, Faraday rotation, scintillation, and absorption occur between weak microwave used for satellite communication and the plasmas. However, influence on the MPT system is negligible. It is nonlinear interaction between intense microwave and the space plasmas that we have to investigate before the commercial SPS. We theoretically predict that the following may occur: heating of the plasmas, plasma hall effect, thermal self-focusing effect of the microwave beam, and three-wave interactions and excitation of electrostatic waves in MHz bands. These interactions don't not occur in existent satellite communication systems because microwave power is very weak.

## V. RECENT TRENDS: WIRELESS POWER TRANSMISSION–RECEIVERS AND RECTIFIERS

Point-to-point MPT system needs a large receiving area with a rectenna array because one rectenna element receives and creates only a few W. Especially for the SPS, we need a huge rectenna site and a power network connected to the existing power networks on the ground. On contrary, there are some MPT applications with one small rectenna element such as RF-ID.

***Recent Technologies of Rectenna:*** The word "rectenna" is composed of "rectifying circuit" and "antenna". The rectenna can receive and rectify a microwave power to DC. The rectenna is passive element with a rectifying diode, operated without any power source. The circuit, especially diode, mainly determines the RF-DC conversion efficiency. Silicon Schottky barrier diodes were usually used for earlier rectenna. New devices like SiC and GaN are expected to increase the efficiency. The rectenna with FET or HEMT appear ed recently. The single shunt full-wave rectifier is always used for the rectenna. It consists of a diode inserted in 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.

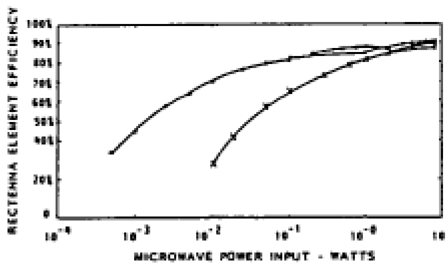
***Recent Technologies of Rectenna Array:*** The rectenna will be used as an array for high power MPT because one rectenna element rectifies a few W only. For usual phased array antenna, mutual coupling and phase distribution are problems to solve. For the rectenna array, problem is different from that of the array antenna because the rectenna array is connected not in microwave phase but in DC phase.

When we connect two rectenna in series or in parallel, they will not operate at their optimum power output and their combined power output will be less than that if operated independently. This is theoretical prediction.

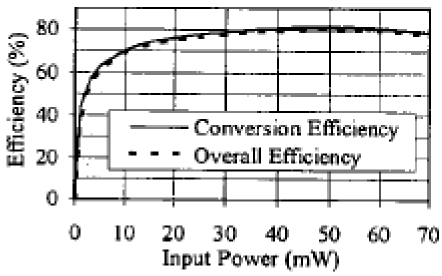
## VI. EFFICIENCY

We classify the MPT efficiency roughly into three stages; DC-RF conversion efficiency which includes losses caused by beam forming, beam collection efficiency which means ratio of all radiated power to collected power on a receiving antenna, and RF-DC conversion efficiency.

***RF-DC Conversion Efficiency:*** The RF-DC conversion efficiency of the rectenna or the CWC is over 80 % of experimental results as shown. Decline of the efficiency is caused by array connection loss, change of optimum operation point of the rectenna array caused by change of connected load, trouble of the rectenna, and any losses on the systems, for example, DC/AC conversion, cables, etc. [6] However, it is easier to realize higher efficiency than that on the other two stages.




**(A)EFFECIENCY OF 2.45 GHZ RECTENNA**




**(B)EFFECIENCY OF 5.8 GHZ RECTENNA[2]**

**FIG. 7 EFFICIENCY OF RECTENNA ELEMENT**

***Beam Collection Efficiency:*** The beam collection efficiency depends on the transmitter and receiver aperture areas, the wavelength, and the separation distance between the two antennas.

## VII. CONCLUSION

Electrical energy can be reasonably transmitted without wires to any terrestrial distance. The monetary transmission of power without wires is of vital importance to man.

This knowledge opened up the possibility of constructing power stations on the moon. These power stations will be able of transmitting power to earth using microwave energy. Such microwave energy would then be changed into electricity using a huge array of rectenna receivers on the earth.

However with all the challenge that face wide-scale consumption of this new technology wireless power transmission for solar power satellite is still measured as a next-generation power transmission system.

## REFERENCES

[1] Tesla, N., "The transmission of electric energy without wires", *Electrical World*, March 5, 1904

[2] Brown, W. C., "Beamed microwave power transmission and its application to space", *IEEE Trans. Microwave Theory Tech.*, vol. 40, no. 6, 1992, pp.1239-1250

[3] Kaya, N., S. Ida, Y. Fujino, and M. Fujita, "Transmitting antenna system for airship demonstration of Space Energy and Transportation" *IEEE* Vol.1, No.4, 1996, pp.237-245

[4] Fujiwara, E., Y. Takahashi, N. Tanaka, K. Saga, "Compact Microwave Energy Transmitter (COMET)", Proc. of Japan-US Joint Workshop on SSPS (JUSPS), 2003, pp.183-185.

[5] Hatsuda, T., K. Ueno, M. Inoue, "Solar power satellite interference assessment", *IEEE*, Vol. 3, No. 4, Dec. 2002, pp.65-70

[6] McSpadden, J. O., L. Fun, and K. Chang, "A High Conversion Efficiency 5.8 GHz Rectenna", *IEEE MTT-S Digest*, 1997, pp.547-550