Wireless Power Transmission for Solar Power Satellite (SPS)
(Second Draft by N. Shinohara)

1. Theoretical Background

It is known that electromagnetic energy also associated with the propagation of the electromagnetic waves. We can use theoretically all electromagnetic waves for a wireless power transmission (WPT). The difference between the WPT and communication systems is only efficiency. The Maxwell's Equations indicate that the electromagnetic field and its power diffuse to all directions. Although we transmit the energy in the communication system, the transmitted energy is diffused to all directions. Although the received power is enough for a transmission of information, the efficiency from the transmitter to receiver is quiet low. Therefore, we do not call it the WPT system.

Typical WPT is a point-to-point power transmission. For the WPT, we had better concentrate power to receiver. It was proved that the power transmission efficiency can approach close to 100%. We can more concentrate the transmitted microwave power to the receiver aperture areas with taper method of the transmitting antenna power distribution. Famous power tapers of the transmitting antenna are Gaussian taper, Taylor distribution, and Chebychev distribution. These taper of the transmitting antenna is commonly used for suppression of sidelobes. It corresponds to increase the power transmission efficiency. Concerning the power transmission efficiency of the WPT, there are some good optical approaches in Russia[5][6].

Future suitable and largest application of the WPT via microwave is a Space Solar Power Satellite (SPS). The SPS is a gigantic satellite designed as an electric power plant orbiting in 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 either photovoltaic cells or 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 typical parameters of the transmitting antenna of the SPS. An amplitude taper on the transmitting antenna is adopted in order to increase the beam collection efficiency and to decrease sidelobe level in almost all SPS design. A typical 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 expected to realize around 2030. Before the realization of the SPS, we can consider the other application of the WPT. In resent years, mobile devices advance quickly and require decreasing power consumption. It means that we can use the diffused weak microwave power as a power source of the mobile devices with low power consumption such as RF-ID. The RF-ID is a radio IC-tug with wireless power transmission and wireless information. This is a new WPT application like broadcasting.

Table 1.1 Typical parameters of the 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 : U.S. Department Of Energy

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2. History of Wireless Power Transmission

In 1864, James C. Maxwell predicted the existence of radio waves by means of mathematical model. In 1884, John H. Poynting realized that the Poynting Vector would play an important role in quantifying the electromagnetic energy. In 1888, bolstered by Maxwell's theory, Heinrich Hertz first succeeded in showing experimental evidence of radio waves by his spark-gap radio transmitter. The prediction and Evidence of the radio wave in the end of 19th century was start of the wireless power transmission.

At the same period of Marchese G. Marconi and Reginald Fessenden who are pioneers 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 collected all over the globe preferably in small amounts, ranging from a fraction of one to a few horse-power. One of its chief uses 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 reached 100 MV. Unfortunately, he failed because the transmitted power was diffused to all directions with 150 kHz radio waves whose wave length was 21 km.

To concentrate the transmitted power and to increase transmission efficiency, we have to use higher frequency than that used by Tesla. In 1930s, much progress in generating high-power microwaves, 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 development 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 1960s. First of all, he developed a rectenna, 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 succeeded in MPT experiments to wired helicopter in 1964 and to free-flied helicopter in 1968 (Fig.2.1). In 1970s, he tried to increase

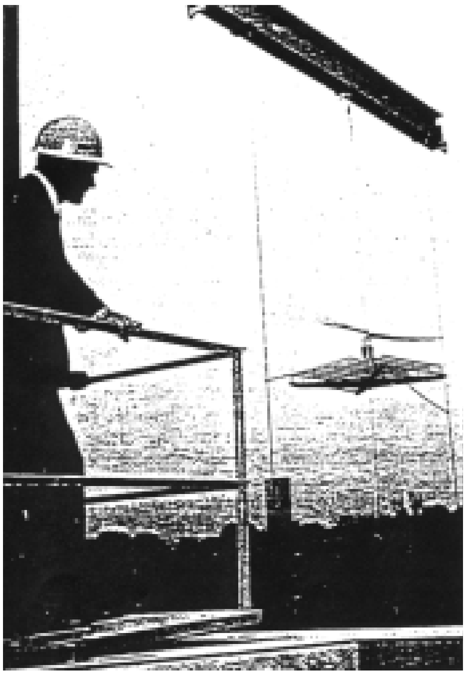

Fig. 2.1 MPT demonstration to helicopter with W. C. Brown

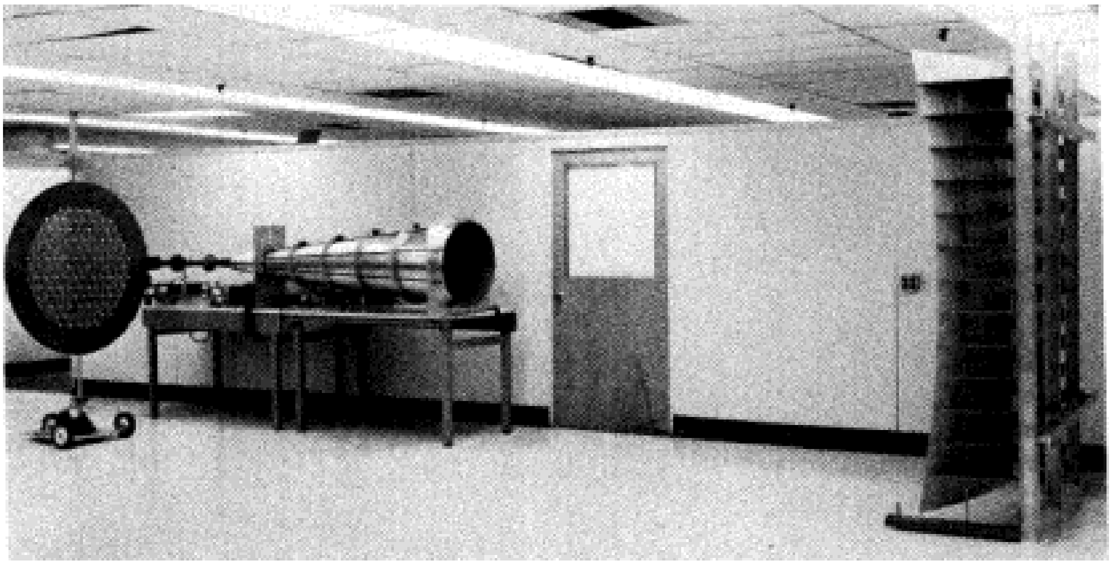

Fig.2.2 MPT Laboratory Experiment in 1975 by W. Brown [4]

Fig.2.3 First Ground-to-Ground MPT Experiment in 1975 at the Venus Site of JPL Goldstone Facility

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 1975, DC-DC total efficiency was finally 54 % at 495WDC with magnetron in Raytheon Laboratory (Fig.2.2). In parallel, He and his team succeeded in the largest MPT demonstration in 1975 at the Venus Site of JPL Goldstone Facility (Fig.2.3). Distance between a transmitting parabolic antenna, whose diameter was 26m, and a rectenna array, whose size was 3.4 m x 7.2 m, was 1 mile. The transmitted microwave of 2.388GHz was 450 kW from klystron and the achieved rectified DC power was 30 kWDC with 82.5% rectifying efficiency. Based on the Brown's work, P. E. Glaser proposed a Solar Power Satellite (SPS) in 1968[5].

Fig. 2.4 MINIX rocket experiment in 1983

In 1980s, Japanese scientists progressed the MPT technologies and research[6][7]. In 1983 and 1993, Hiroshi Matsumoto's team carried out the first MPT experiment in space. The rocket experiment were called MINIX (Microwave Ionosphere Nonlinear Interaction eXperiment) in 1983 (Fig.2.4) and ISY-METS (International Space Year - Microwave Energy Transmission in Space) in 1993, respectively. They focused nonlinear interaction between intense microwave and ionospheric plasmas. In the MINIX experiment, they used cooker-type 800W-2.45GHz magnetron for microwave transmitter. New wave-wave-particle interaction phenomenons were observed in the MINIX. Plasma theory and computer experiments supported the observations[8][9].

After 1990s, many MPT laboratory and field experiments were carried out in the world. We often uses 2.45 GHz or 5.8 GHz of the ISM band (ISM=Industry, Science, and Medical) for the MPT system. Canadian group succeeded fuel-free airplane flight experiment with MPT in 1987 which was

Fig. 2.5 SHARP flight experiment and 1/8 model in 1987 [11]

called SHARP (Stationary High Altitude Relay Platform) with 2.45 GHz (Fig.2.5)[10]. In USA, there are many MPT research and development after W. C. Brown, for instance, retrodirective microwave transmitters, rectennas, new devices and microwave circuit technologies[12]. In Japan, there were many field MPT experiments such as fuel-free airplane flight experiment with MPT phased array with 2.411 GHz in 1992 (Fig.2.6)[13], ground-to-ground MPT experiment with power

Fig. 2.5 MILAX Airplane Experiment and Model Airplane with Phased Array in 1992

Fig. 2.6 Ground-to-Ground MPT experiment in Japan in 1994-95

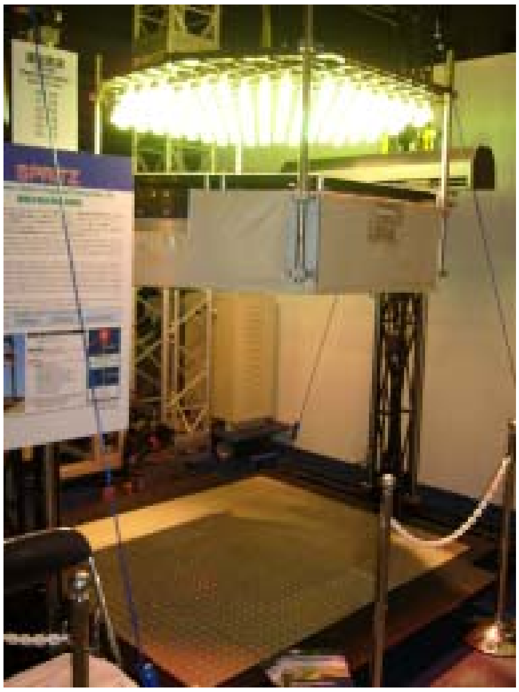

Fig.2.7 SPS Demonstrator “SPRITZ” with 5.8 GHz (Demonstration in IAC2005)

company and universities in 1994-95 (Fig.2.7)[14] with 2.45 GHz, fuel-free airship light experiment with MPT in 1995[15] with 2.45 GHz, development of SPS demonstrator with 5.8 GHz in 2000 (Fig.2.8)[7]. Some kinds of microwave transmitters, some kinds of retrodirective microwave transmitters, and many rectennas were also developed in Japan. In Europe, some unique technologies are developed. They plan ground-to-ground MPT experiment in Re-union Island (Fig.2.9)[16][17].

As described before, there is only quiet small difference between the WPT and wireless communications. We will show recent WPT technologies based on the wireless communications.

Figure 2.8 Grand Bassin, Reunion, France and Their Prototype Rectenna [17]

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3. Recent Technologies and Researches of Wireless Power Transmission – Antennas and Transmitters –

3.1 Antennas for Microwave Power Transmission

All antennas can be applied for both the MPT system and communication system, for example, Yagi-Uda antenna, horn antenna, parabolic antenna, microstrip antenna, phased array antenna or any other type of antenna. To fixed target of the MPT system, we usually 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 (See Fig.2.2 and Fig.2.6). In the fuel-free airship light experiment with MPT in 1995 in Japan, they changed a direction of the parabolic antenna to chase the moving airship.

However, we have to use a phased array antenna for the MPT from/to moving transmitter/receiver which include the SPS because we have to control a microwave beam direction accurately and speedy. The phased array is a directive antenna which generate a beam form whose shape and direction by the relative phases and amplitudes of the waves at the individual antenna elements. It is possible to steer 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]. In some MPT experiments in Japan, the phased array antenna was adopted to steer a direction of the microwave beam (Fig.3.1). All SPS is designed with the phased array antenna. We consider the phased array antenna for all following MPT system.

Fig.3.1 Phased Array Used in Japanese Field MPT Experiment (Left : for MILAX in 1992, Right : for SPRITZ in 2000)

3.2 Recent Technologies for Transmitters

The technology employed for the generation of microwave radiation is an extremely important 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.

There are two types of microwave generators/amplifiers. One is a microwave tube and the other is a semiconductor amplifier. Trew reviewed microwave generators/amplifiers, frequency vs. averaged power as shown in Fig.3.1[2]. 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.

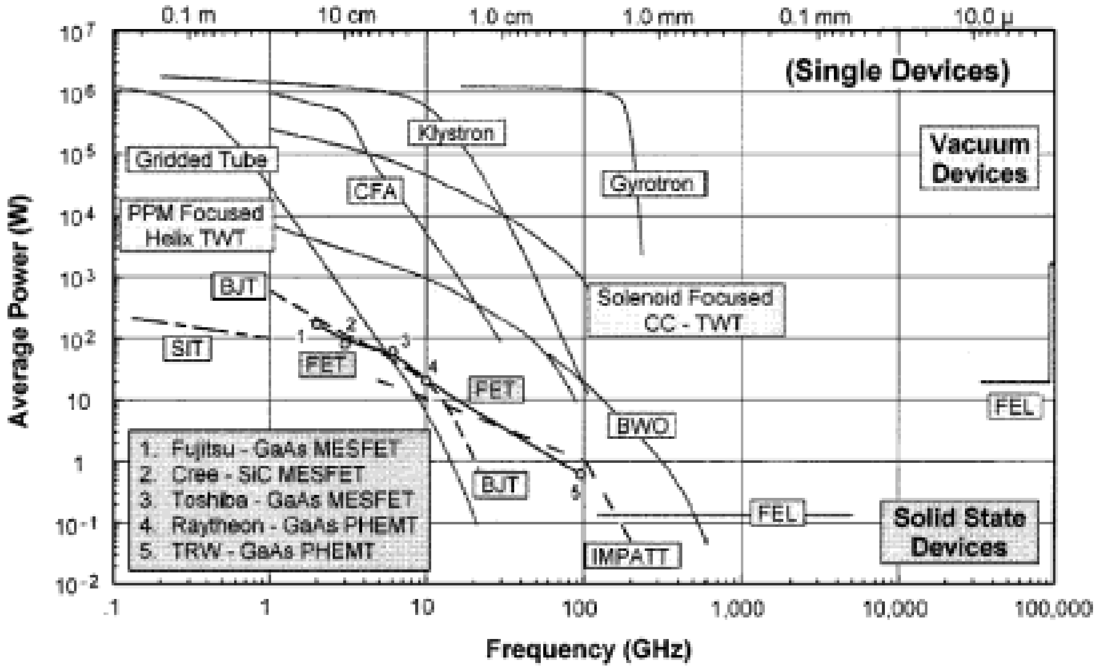

Fig. 3.1 Average RF output power versus frequency for various electronic devices[4] and semiconductors[2]

3.2.1 Magnetron

Magnetron is a crossed field tube in which $\vec{E} \times \vec{B}$ forces electrons emitted from the cathode to take cyclonical 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 practical and efficient magnetron tube gathered world interest only after K. Okabe proposed the divided anode-type magnetron in 1928. Magnetron technologies were advanced during the World War II, especially in Japanese Army. The magnetrons main were advanced and manufactured for the microwave ovens. As a result, the magnetron of 500 – 1,000 W is widely used in 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. A history of the magnetron is a history of a microwave oven. The first microwave oven with a magnetron sold shortly in U. S. A. after the World War II ended for more than $2,000, the equivalent of about $20,000 today. In 1960's, Japan played a important role to reduce the cost of the microwave oven. Compared that American tube's cost was $300 and they planned to sell for $500 in 1960's, Japanese tube cost was less than $25. In 1970, U.S. manufacturers sold 40,000 ovens at $300 to $400 apiece, but by 1971 the Japanese had begun exporting low-cost models priced $100 to $200 less. Sales increased rapidly over the next 15 years, rising to a million by 1975 and 10 million by 1985, nearly all of them Japanese[5]. But history repeats itself. Instead of Japanese microwave oven, Korean and Chinese more reduce the cost of the microwave oven now.

Therefore, the magnetron is suitable device for the MPT because of high efficiency and low cost and unsuitable device because of its unstable frequency and uncontrollable phase. If we do not make a phased array to control beam direction electrically, the magnetron can be applied for the MPT system. However, the cooker-type magnetron itself cannot be applied for the phased array-type MPT because it is only a generator and we cannot control/stabilize the phase and the amplitude. The cooker-type magnetron was considered as noisy device. It is however confirmed that spurious emissions from the cooker-type magnetron with a stable DC power supply is low enough and this can be applied to the MPT system[6]. Peak levels of higher harmonics are below -60 dBc and other spurious is below -100 dBc.

It was W. C. Brown who invented a voltage controlled oscillator with a cooker-type magnetron in a phase locked loop[7]. He could control and stabilize a phase of microwave emitted from cooker-type magnetron. In present, some research groups try and succeed to develop new magnetron

Fig.3.2 Phased Array with 2.45GHz Phase Controlled Magnetrons Developed in Kyoto University

system which we can control and stabilize a phase of microwave emitted from cooker-type magnetron[8]-[13]. In their developed magnetrons, an injection locking and PLL feedback are adopted as same as that adopted in Brown's work. The difference between the methods proposed in these papers is how to control a phase of the magnetron. The Kyoto University's system is most stabilized. As an advanced method, a phase and amplitude controlled magnetron (PACM) has been developed at Kyoto University, Japan[14]. They realized that the frequency stability and an error in phase and amplitude of the PACM are below 10^{-6}, within 1 degree, and within 1 %, respectively. The technology of the PACM is effective to realize the economical MPT system with light weight and high DC-RF conversion efficiency. They have also succeeded to control beam directions with phased arrays with phase controlled magnetrons operated in 2.45 GHz and 5.8 GHz (Fig.3.2)[15].

3.2.2 Traveling Wave Tube Amplifier (TWTA)

Traveling Wave Tube (TWT) was invented by R. Kompfner in the World War II and was advanced theoretically and improved by J. R. Pierce and L. M. Field in 1945. The TWT is a linear beam tube with helix structure. The helix slow wave structure (SWS) slows the RF waves down to just below the velocity of the electron beam. In the TWT, the interaction between the RF waves and the electron beam is continuous along the length of the SWS. The TWT can be used for amplifier and we call it TWT amplifier (TWTA). The longer the tube, the higher gain. Applied frequency of the TWTA is very wide, from 1GHz-band to 60 GHz-band. Typical output power of the TWT is a few hundreds watts.

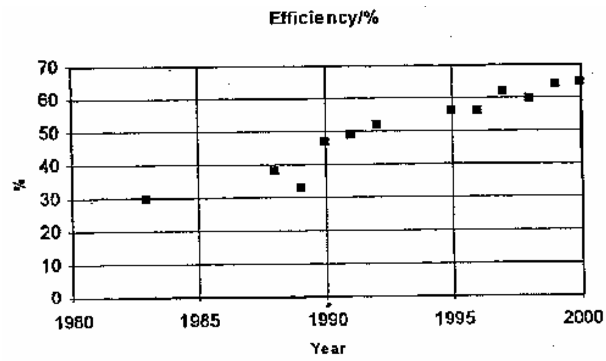

Fig.3.3 Trend of DC-RF Conversion Efficiency of TWTA [17]

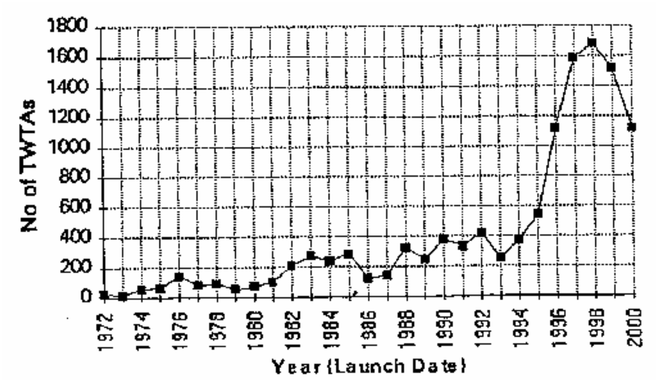

Fig.3.4 Estimated TWTA World Market [17]

The TWTA is widely used in television broadcasting satellites and communication satellites. The TWTA has a proven track record in space. Before 1980s, the efficiency of the TWTA is very low, around 30%. It is not enough to use for the MPT system. There was no MPT system design and experiment with

TWTA. However, in recent years, a TWTA uses techniques called velocity tapering energy recovery [16]. In this way, the net conversion rate has risen to around 70 %[17] (Fig.3.3). Market of the TWTA grows from 1972 and the price of

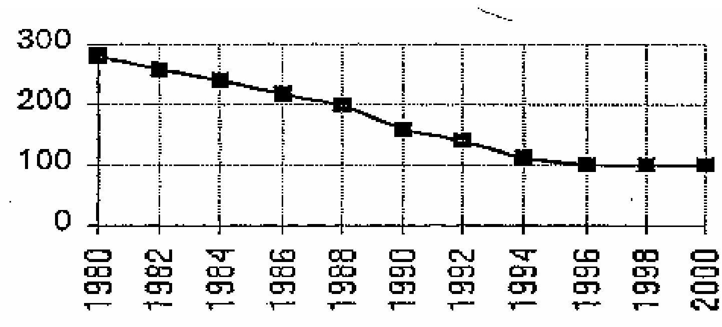

Fig.3.5 Trend of Price of TWTA (% ; 1996=100%) [17]

the TWTA decreases (Fig.3.4, Fig.3.5)[17]. The paper [17] describes that main reasons for this price decrease are (1) development time and effort could be reduced due to the standardization of the product, (2) parts cost could be reduced due to buying higher number of parts and holding them on stock, (3) manufacturing cost could be reduced by manufacturing larger number of TWTAs in a certain time frame and by more automatization in the manufacturing process, and (4) test time and effort has been reduced due to the higher credibility of the product.

Trends of development of the TWT are MPM (Microwave Power Module) and phased array TWT. The MPM combines the best aspects of TWT, semiconductor amplifiers, and state-of-the-art power supply technology into one package. This makes MPM into a good candidate for space application because it has high conversion efficiency, small size and low weight. In near future, we may consider the MPT system with TWTA.

3.2.3 Klystron

The klystron was invented by the Varian brothers in the late 1930s. The klystron is also a linear beam tube with cavities. Electrons are emitted from the cathode and electron beam passes through the cavities. When RF inputs from input cavity, the electron beam is modulated and RF is amplified in last. The klystron is high power amplifier from tens of kilowatts to a few megawatts with high efficiency, over 70%. It requires a ponderous power supply and also a heavy magnet. The klystrons are used for broadcast applications in 400-850 MHz-band. The klystron is also used for uplinks (earth stations beaming to orbital satellites). The other application of the klystron is fusion.

The klystron was used in MPT demonstration in 1975 at the Venus Site of JPL Goldstone Facility. One klystron transmitted microwave of 450 kW and 2.388 GHz. The klystron is suitable for large MPT system such as SPS. The SPS designed by NASA/DOE in 1980 was designed with phased array of the klystrons. However, there has not been klystron phased array system yet.

Detail general theory of the microwave tubes is described in reference [18].

3.2.4 Semiconductor Amplifier

After 1980s, semiconductor device plays the lead in microwave world instead of the microwave tubes. It causes by advance of mobile phone network. The semiconductor device is expected to expand microwave applications, for instance, phased array and Active integrated antenna (AIA), because of its manageability and mass productivity. After 1990s, some MPT experiments were carried out in Japan with phased array of semiconductor amplifiers[19].

Typical semiconductor device for microwave circuits are FET (Field Effect Transistor), HBT (Heterojunction Bipolar Transistor), and HEMT (High Electron Mobility Transistor). Present materials for the semiconductor device are Si for lower frequency below a few GHz and GaAs for higher frequency. We design microwave circuits with these semiconductor devices. It is easy to control a phase and amplitude through the microwave circuits with semiconductor devices, for example, amplifiers, phase shifters, modulators, and so on. For the microwave amplifiers, circuit design theoretically determines efficiency and gain. A, B, C class amplifiers are classified in bias voltage in device. These classes are also applied in kHz systems. In D, E, F class amplifiers for microwave frequency, higher harmonics are used effectively to increase efficiency, theoretically 100%. Especially F class amplifier is expected as high efficient amplifier for the MPT system.

We always have to consider the efficiency. Some reports noted that it is possible to realize a PAE (power added efficiency = $(P_{out}-P_{in})/P_{DC}$) of 54%, efficiency of about 60%, at 5.8GHz. These are champion data in laboratory. To develop the high efficient amplifier, we need strict adjustment in contrary of mass productivity. It causes that the semiconductor amplifiers keep expensive cost for the MPT system. It potentially has low price capability by the mass production. An efficiency of a driver stage is also taken into consideration if the gain of the final stage is not enough.

The other requirement from MPT use to the semiconductor amplifier is linearity of amplifier because power level of the MPT is much higher than that for wireless communication system and we have to suppress unexpected spurious radiation to reduce interference. The maximum efficiency usually is realized at saturated bias voltage. It does not guarantee the linearity between input and output microwaves and non-linearity causes high spurious which must be suppressed in the MPT. Therefore, dissolution of tortuous relationship between efficiency and linearity is expected by the MPT.

There are unique development items for the SPS from the microwave point of view distinguished from the ordinary use of the microwave technology such as telecommunications. These three points may be described as 1) pureness in spectrum, 2) high power and high efficient power generation and high efficient detector in a small and light fashion, and 3) precise beam control for a large phased array antenna combining with a huge number of sub-arrays.

To cope with the second requirement for the microwave technology, the large plate model by a layered configuration in a sandwich fashion was proposed. The point of this configuration is the effective integration with DC power generation, microwave circuit operation and radiation, and their control. As one of the promising microwave technologies, the “the Active Integrated Antenna (AIA)” technique is considered. The AIA is defined as the single entity consisting of an integrated circuit and a planar antenna. The AIA has many features applicable to the SPS. Due to the nature of small-size, thinness, lightness and multi-functions in AIA, a power transmission part of the spacetenna (space antenna) can be realized in thin structure. Prof. Kawasaki’s group have developed some AIA system for the MPT application[20].

In present, new materials are developed fore the semiconductor device to increased output power and efficiency. They are called wide-bandgap devices such as SiC and GaN. The wide-bandgap devices can make over hundreds watt amplifier with one chip. In recent days, there are some development of microwave amplifiers with SiC MESFET[21][22] or GaN HEMT[23][24]. The other trend is development of MMIC (Microwave Monolithic Integrated Circuit) to reduce space and weight, especially for mobile applications. Lighter transmitters can be realized with the MMIC devices. The MMIC devices still have heat-release problems, poor efficiency, and low power output. However, it is expected that the technical problems will be solved by efforts of many engineers.

3.3 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 group have developed a light weight phase controlled magnetron called COMET, Compact Microwave Energy Transmitter with a power-weight ratio below 25g/W (fig.3.6)[25]. The COMET includes a DC/DC

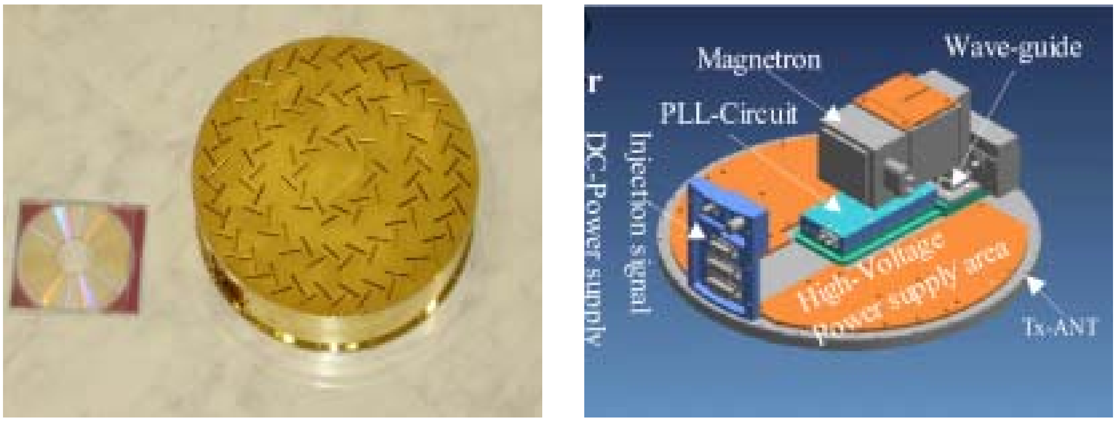

Fig.3.6 Compact Microwave Energy Transmitter with the PCM (COMET)

converter, a control circuit of the phase controlled magnetron with 5.8 GHz, a heat radiation circuit, a wave guide, and an antenna. 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: 220W at 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 deliver 12g/W and 16.5g/W, respectively[26]. They do not include a heat radiation circuit, a wave guide, and an antenna. The semiconductor amplifier is not light remarkably. Examples of characteristics of various transmitters for space use are shown in Table 3.1. Although it may seem that semiconductor amplifiers are light in weight, they have heavy power-weight ratio because output microwave power is very small.

Table 3.1 Characteristics of Semiconductor Amplifier for Space Use (most are arranged from a reference [27])

Satellite	ETS-6	TDRSS	NSTAR	INT-7	JCSAT-3
Efficiency	31%	32%	36%	29%	40%
Output	14W	24W	40W	30W	34W
Weight	1.2kg = 85g/W	3.4kg =121g/W	2.5kg =63g/W	1.7kg =57g/W	1.9kg =56g/W
Frequency	2.5GHz	2GHz	2.5GHz	4GHz	4GHz

Heat reduction is most important problem in space. All lost power converts to heat. We need special heat reduction system in space. If we use high efficient microwave transmitters, we can reduce weight of heat reduction system. We should aim for over 80 % efficiency for the microwave transmitter, which must include all loss in phase shifters, isolators, antennas, power circuits. Especially, the SPS is a power station in space, therefore, heat reduction will be a serious problem[28].

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4. Recent Technologies and Researches of Wireless Power Transmission – Beam Control , Target Detection, Propagation –

4.1 Recent Technologies of Retrodirective 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. Retrodirective system is always used for SPS.

A corner reflector is most basic retrodirective system[1]. The corner reflectors consist of perpendicular metal sheets, which meet at an apex (Fig.4.1(a)). 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 retrodirective system[2]. This array is made up of pairs of antennas spaced equidistant from the center of the array, and connected with equal length transmission lines (Fig.4.1(b)). 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 retrodirectivity. Usual retrodirective system have phase conjugate circuits in each receiving/transmitting antenna, (Fig.4.1(c)) which play a same role as pairs of antennas spaced equidistant from the center of the array in Van Atta array. A signal transmitted from the target is received and re-radiated through the phase conjugate circuit to the direction of the target. The signal is called a pilot signal. We do not need any phase shifters for beam forming. The retrodirective system is usually used for satellite communication, wireless LAN, military, etc. There are many researches of the retrodirective system for these applications (Fig.4.2)[3]-[11]. They use the almost same frequency for the pilot signal and returned signal with a local oscillator (LO) signal at a frequency twice as high as the pilot signal frequency in the typical retrodirective systems (Fig.4.1(c)). Accuracy depends on stability of the frequency of the pilot signal and the LO signal. Prof. Itoh's group proposed the pilot signal instead of the LO signal[12].

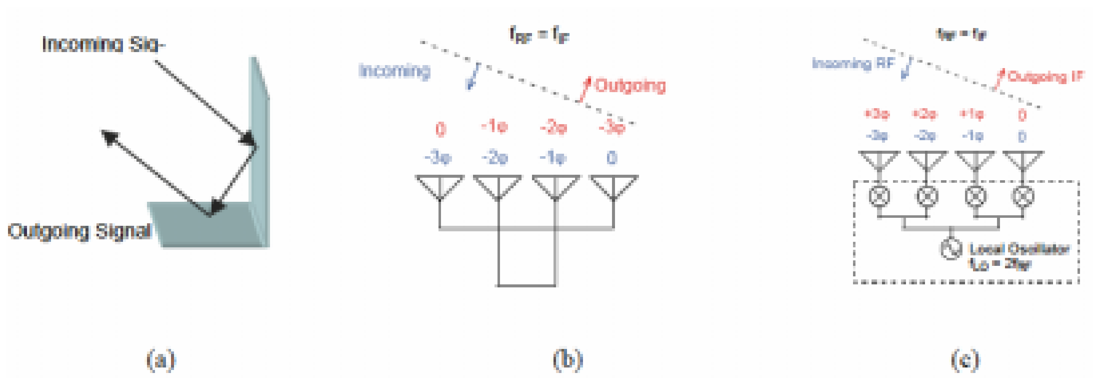

Fig. 4.1 (a) two-sided corner reflector, (b) Van Atta Array, (c) retrodirective array with phase conjugate circuits. (Sung et al., http://hcac.hawaii.edu/tcwct03/papers/s16p03.pdf)[1]

There are other kinds of the phase conjugate circuits for the MPT applications. Kyoto University's group have developed a retrodirective system with asymmetric two pilot signals, $\omega_t+\Delta\omega$ and $\omega_t+2\Delta\omega$, and the LO signal of $2\omega_t$[13]. ω_t indicate a frequency of a transmitter. They have also developed the

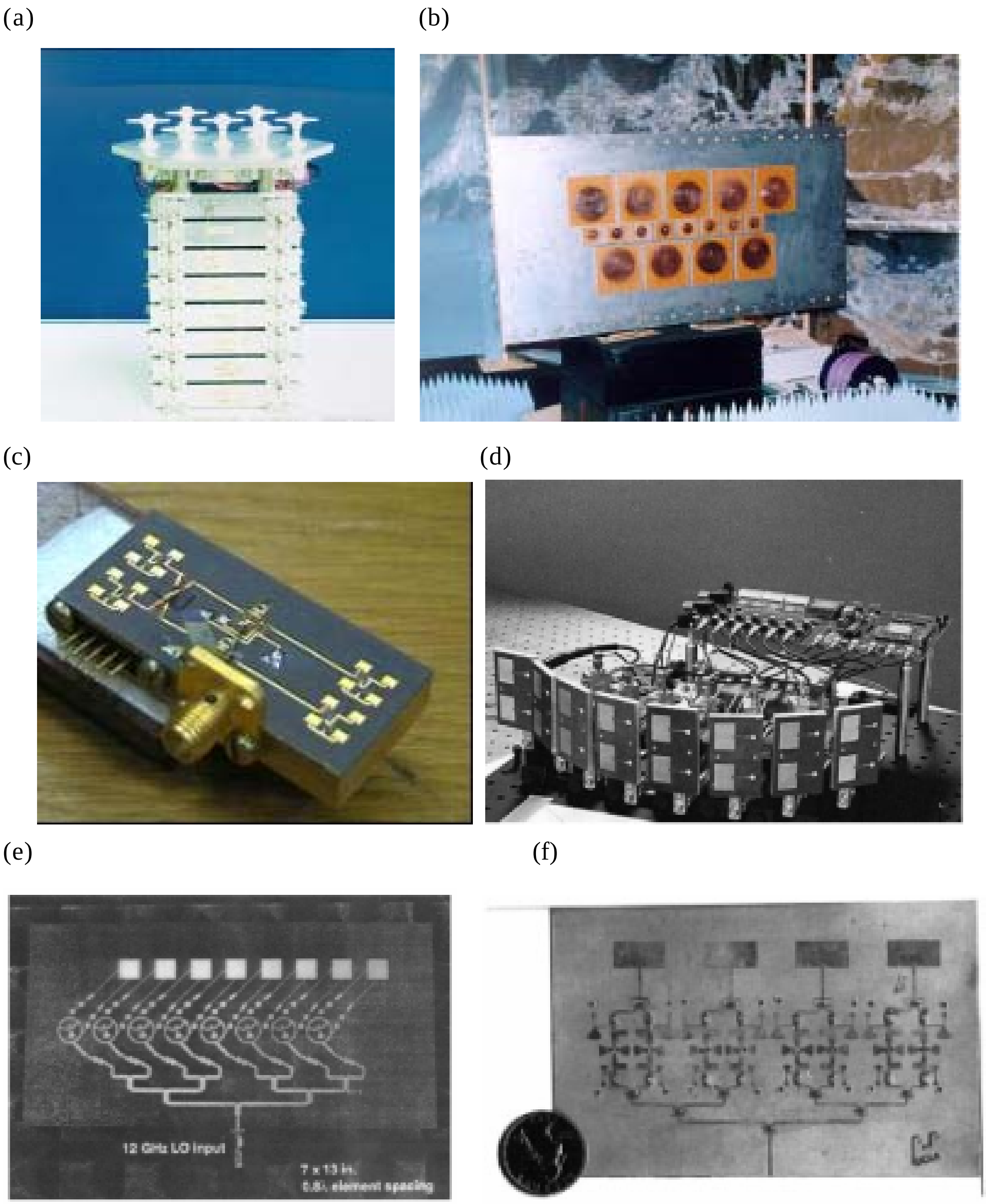

Fig.4.2 Various Retrodirective Array with Phase Conjugate Circuits Developed in (a) Kyoto University and Kobe University in 1987 (2.45GHz)[13], (b) Kyoto University in 1996 (2.45GHz)[13], (c) Queen's University (62-66GHz)[8], (d) Jet Propulsion Laboratory and University of Michigan in 2001 (5.9GHz)[11], (e) UCLA in 1995 (6GHz)[5], (f) UCLA in 2000 (6GHz)[3]

other retrodirective system with 1/3 ω_t pilot signal and without LO signal. The LO signal is generated from the pilot signals. The latter system solve a fluctuation problem of the LO and the pilot signal which cause phase errors because the fluctuations of the LO and the pilot signals are synchronous. They have used 2.45 GHz for ω_t. Mitsubishi Electric Corporation in Japan have developed PLL-heterodyne type retrodirective system in which different frequencies for the pilot signal and the microwave power beam, 3.85 GHz and 5.77 GHz, respectively, have been used[14].

The retrodirective system unifies target detection with beam forming by the phase conjugate circuits. There are some methods for target detecting with pilot signal which is separated to beam forming. We call the method “software retrodirective”. Computer is usually used for the software rectodirective with the phase data from a pilot signal and for the beam forming with calculation of the optimum phase and amplitude distribution on the array. In the software rectodirective, we can form microwave beam freely, for example, multi-beams. On contrary, we need phase shifters in all antennas.

After the target detection, we need accurate beam forming. For the optimum beam forming, there are some algorism, for instance, neural network, genetic algorithm, and multi-objective optimization learning. The “optimum” has multi-meanings, to suppress sidelobe level, to increase beam collection efficiency, and to make multiple power beams. We can select object of optimum and algorism freely with consideration of time of calculation.

Kyoto University in Japan and Texas A&M University in USA have developed the software retrodirective system independently[16][17]. Kyoto University’s group use a pilot signal modulated by spread spectrum in order to use the same frequency band of microwave power beam and the pilot signal and also in order to use two or more pilot signals for multi-target MPT[16].

A standard of the phase/frequency is very important to steer microwave power beam to a desired direction Both for beam forming with the software retrodirective and for retrodirective with the phase conjugate circuit. If the standard of the phase/frequency like the LO signal is different on one array, we cannot form the microwave beam to the desired direction. Although the best way is to use only one oscillator for the standard of the phase/frequency for one phased array of larger than km in size with more than billion elements, it is quite difficult. A better way is use of some oscillators on some group of sub-phased array and the oscillators are synchronous with each other. Some trials have been carried out. One is wireless synchronization of separated units. The present accuracy of wireless synchronization is below 0.6 ppm of the frequency and below 3.5 degree of phase error[18]. The other is self-synchronization with some data sent from the target[19]. In this method, a phase of a part of arrays is changed and a resultant change of the microwave beam intensity is measured in the rectenna site. The change gives us information on phase corrections.

4.2 Environmental Issues

4.2.1 Interferences to Existent Wireless System

Most MPT system adopted 2.45 GHz or 5.8 GHz band which are allocated in the ITU-R Radio Regulations to a number of radio services and are also designated for ISM (Industry, Science and Medical) applications. Conversely speaking, there is no allowed frequency band for the MPT, therefore, we used the ISM band. The bandwidth of the microwave for the MPT do not need wide band and it is enough quite narrow since an essentially monochromatic wave is used without modulation because we use only carrier of the microwave as energy. Power density for the MPT is a few orders higher than that for the wireless communication. We have to consider and dissolve interferences between the MPT to the wireless communication systems.

One calculation of the interferences between the MPT of the SPS, mainly 2.45 GHz, to the wireless communication systems was done in Japan[20]. If the harmonics of the MPT frequencies are, however, regulated by the ITU (International Telecommunication Union) power flux density (PFD) limits, some modulation might be necessary. Carrier noises, harmonics, and spurious emissions of the MPT signal should be quite small to avoid interference to other radio services in operation around the world. Grating lobes and sidelobes of the MPT beam should be low enough in order to make the affected region as small as possible. Also, grating lobes should be mitigated because they are a direct loss of transmitter power.

The other interference assessment on 2.45 GHz and 5.8 GHz MPT of the SPS was published in Japan[21]. They discussed mainly Japanese case. They discussed four main existent systems, terrestrial radio relay links on 5GHz (5G-150M) system and 11GHz (11G-50M) system, radars called ARSR (air route surveillance radar, 1.3-1.35 GHz), ASR (airport surveillance radar, 2.7-2.9GHz) and MR (meteorological radar, 5.25 - 5.35GHz), Space-to-Earth communications on 11-12 GHz-band, and applications in the ISM bands, wireless LAN and DSRC (Dedicated Short Range Communication).

JAXA (Japanese Aerospace Exploration Agency) estimated the interference and submitted "Proposal of the extension regarding the termination year of Question ITU-R 210/1 to 2010 from 2005"to ITU in 2004[22], and will submit in 2005. Responses to Question ITU-R 210/1 (1997) had been submitted to the ITU-R WP1A meetings by USA. Since the response (Document 1A/18-E, which was incorporated into Document 1A/32-E Annex8) in October 2000 [23], no response has been submitted. As the studies for this Question had not been completed by 2002, the date has been extended by three years. They submit the above document from JAXA in response to Question 210/1 which would otherwise terminate this year, to extend the Question.

4.2.2 Safety on Ground

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 human. In recent years there have been considerable discussions and concerns about the possible effect for human health by RF and MW radiation. Especially, there have been many research and discussions about effects at 50/60 Hz and over GHz (microwave). These two effects are different.

There is long history concerning the safety of the microwave[24]. Contemporary RF/microwave standards are based on the results of critical evaluations and interpretations of the relevant scientific literature. The SAR (specific absorption rate) threshold for the most sensitive effect considered potentially harmful to humans, regardless of the nature of the interaction mechanism, is used as the basis of the standard. The SAR is only heating problem. The scientific research results have indicated that the microwave effect to human health is only heating problem. This is different from the EMF research. Famous guideline, the ICNIRP (International Commission on Non-Ionizing Radiation Protection) guidelines, are 50 or 10 W/m^2 for occupationally exposed vs. the general public, at either frequency[25]. The corresponding limits for IEEE standards for maximum permissible human exposure to microwave radiation, at 2.45 or 5.8 GHz, are 81.6 or 100 W/m^2 as averaged over six min, and 16.3 or 38.7 W/m^2 as averaged over 30 min, respectively, for controlled and uncontrolled environments[26]. The controlled and uncontrolled situations are distinguished by whether the exposure takes place with or without knowledge of the exposed individual, and is normally interpreted to mean individuals who are occupationally exposed to the microwave radiation, as contrasted with the general public. In future MPT system, we have to keep the safety guideline outside of a rectenna site. Inside the rectenna site, there remains discussion concerning the keep out area, controlled or uncontrolled area.

4.2.3 Interaction with Atmosphere

In general, effect of atmosphere to microwave 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[27]. In the SPS case, the amount of total absorption through the air from space is approximately 0.035 dB[28]. When elevation is 47 degree in the middle latitude, for example, in Japan, the total absorption is approximately 0.05 dB. Attenuation factor by rain is shown in Fig.4.3[29]. The attenuation factor by rain whose intensity is 50 mm/h and 150 mm/h is 0.01 dB/km and 0.03 dB/km in 2.45 GHz and 0.3 dB/km and 1.2 dB/km in 5.8 GHz, respectively. In assumption that rain cell size is 5km at 50 mm/h and 3km at 150 mm/h, respectively, and that the elevation is 47 degree in the Japanese SPS case, we calculate the rain attenuation as follows; When rain intensity is 50 mm/h and 150 mm/h, the attenuation is 0.01 (dB/km) x 5 (km) x sec 47 (degree) = 0.07 (dB), 0.13 (dB) in 2.45 GHz, and 1.3 (dB) and 5.2 (dB) in 5.8 GHz, respectively. Scatter by irregularity of air refraction ratio is quite smaller than the absorption and scatter by air and rain. It was estimated below 0.0013 dB in the 2.45

GHz SPS[30]. Total attenuation of the 2.45 GHz SPS is 0.05 + 0.13 + 0.0013 = 0.1813 dB. Total attenuation of the 5.8 GHz SPS is over 5 dB in hard rain circumstance. In the 2.45 GHz SPS, we can neglect the attenuation by air and rain. We have to consider a counterplan the attenuation by rain in the 5.8 GHz SPS.

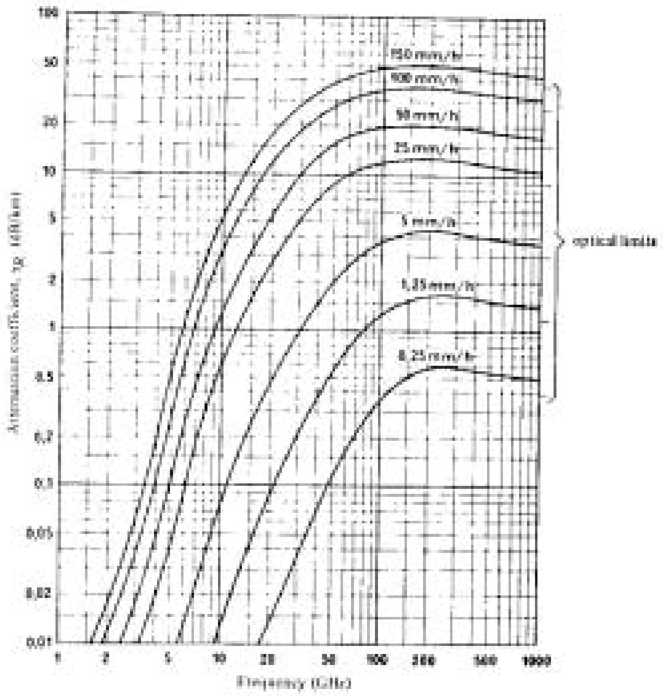

Fig.4.3 Attenuation factor by rain [28]

4.2.4 Interaction with Space Plasmas

When microwave from the SPS propagates through ionospheric plasmas, some interaction between the microwave 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 to the MPT system is negligible. For example, reflection through the ionosphere at 2.45 GHz and 5.8 GHz is only 0.67 m and 0.12 m, respectively, when they calculated theoretically with the Snell's law and total electron contents in the ionosphere[31]. However, there is no inference because diameter of rectenna site will be over km. Although plane of polarization will rotate in approximately 7 degree at 2.45 GHz by Faraday rotation[32], there is also no inference because we will use circular polarized microwave for the MPT of the SPS.

It is nonlinear interaction between intense microwave and the space plasmas that we have to investigate before the commercial SPS. We theoretically predict that it has possibility to occur Ohmic heating of the plasmas, plasma hall effect by Ponderomotive force, thermal self-focusing effect of the microwave beam, and three-wave interactions and excitation of electrostatic waves in MHz bands. These interactions will not occur in existent satellite communication systems because the microwave power is very weak.

Perkins and Roble theoretically calculated the Ohmic heating by the microwave beam from the SPS in 1978[33]. The absorption of the radio waves can be calculated from the electron density and electron-neutral collision frequency profile. The effect is largest in the lower ionosphere (D and E regions) where the collision frequency is highest. The NASA/DOE SPS was designed including the results of the reference [34] and they decided that maximum microwave power density was 23 mW/

cm^2 at the center of the rectenna site.

Concerning the three-wave interactions and excitation of electrostatic waves in MHz bands, Matsumoto predicted in 1982 that the microwaves may decay into forward traveling electron plasma waves (Raman scattering) or ion acoustic waves (Brillouin scattering) and a backward traveling secondary microwave[35]. The electron plasma waves could be Langmuir waves when the excitation is parallel to the geomagnetic field, or electron cyclotron waves for excitation perpendicular to the field. These frequencies are typically 2-10 MHz in the local ionospheric plasma. Matsumoto's group carried out the first rocket MPT experiment called MINIX (Microwave Ionosphere Nonlinear Interaction eXperiment) in 1983 in order to observe the excitation of the plasma waves (Fig.4.4)[36][37][38]. It was found that the excited waves differed from the initial theoretical expectations [39] in that the line spectrum expected from a simple three-wave coupling theory was in fact a broad spectrum, and the electron cyclotron harmonics were stronger than the Langmuir waves. Both these features could be successfully modeled using a more realistic computer simulation[40] where the nonlinear feedback processes were fully incorporated. From these simulation results it was estimated that below 0.01 % of the microwave beam energy from the SPS would be converted to electrostatic waves.

Shklyar and Shinohara derived a equation of self-focusing effect of the microwave beam caused by the inhomogeneity of the microwave energy density in 1992[41]. It occurs without the collisional plasma heating. They neglected collisions and based the analysis on kinetic equation in collision free plasma. Though the wave frequency is six orders of magnitude higher than the maximum collision

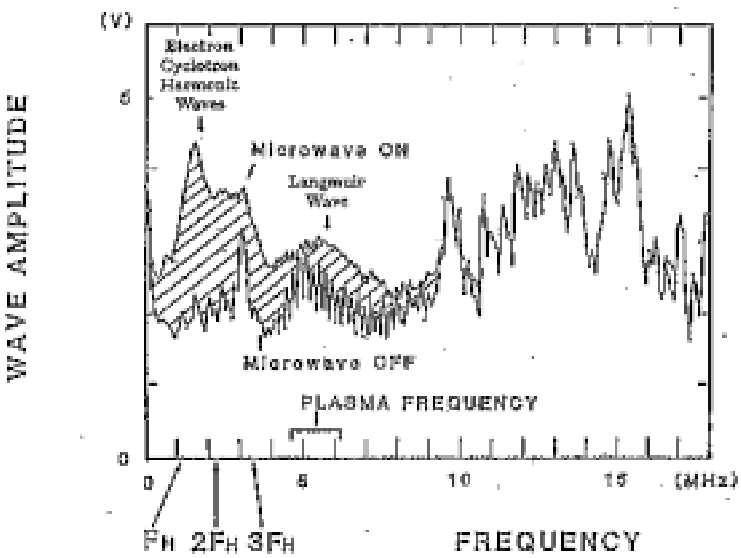

Fig.4.4 Observed Wave Spectrum Concerning Three-wave Interactions and Excitation of Electrostatic Waves by Microwave in MINIX Rocket Experiment [36]

frequency in the ionosphere, the assumption of collisionless plasma is not obvious, since finally they deal with a weak effect of Ponderomotive force. They showed this self-focusing effect will not occur with the SPS and ionopheric parameters, the density and the temperature of the plasmas, the frequency and the intensity of the microwave and its spatial gradient.

Plasma hall effect is predicted theoretically with Ponderomotive force and it is important to consider the effect from the microwave beam to plasma circumstance. However, there have not been advance of the research yet. Japanese group just start computer simulation with electromagnetic particle code from 2004.

Almost all studies are theoretical prediction and computer simulations. There are only two experimental data concerning the interaction between the intense microwave and the space plasmas. Both experiments were carried out in Japan with small rockets[42]. We need advanced space experiment to verify the theoretical studies as soon as possible.

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5. Recent Technologies and Researches of 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.

5.1 Recent Technologies of Rectenna

The word "rectenna" is composed of "rectifying circuit" and "antenna". The rectenna and its word were invented by W. C. Brown in 1960's[1][2][3]. 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. There are many researches of the rectenna elements (Fig.5.1). Famous research groups of the rectenna are Texas A&M University in USA[5][9][14][18], NICT(National Institute of Information and Communications Technology, past CRL) in Japan[8][10][11][17], and Kyoto University in Japan[7][12][23]. The antenna of rectenna can be any type such as dipole[1]-[5], Yagi-Uda antenna[6][7], microstrip antenna[8]-[12], monopole[13], loop antenna[14][15], coplanar patch[16], spiral antenna[17], or even parabolic antenna[18]. The rectenna can also take any type of rectifying circuit such as single shunt full-wave rectifier[4][9][10][11][13][14][16], full-wave bridge rectifier[1][7][12][15], or other hybrid rectifiers[8]. 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[19] or HEMT[20] 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 $\lambda/4$ distributed line, and a capacitor inserted in parallel. In an ideal situation, 100% of the received microwave power should be converted into DC power[21]. Its operation can be explained theoretically by the same way of a F-class microwave amplifier. The $\lambda/4$ distributed line and the capacitor allow only even harmonics to flow to the load. As a result, the wave form on the $\lambda/4$ distributed line has a π cycle, which means the wave form is a full-wave rectified sine form. The world record of the RF-DC conversion efficiency among developed rectennas is approximately 90% at 4W input of 2.45 GHz microwave[1]. Other rectennas in the world have approximately 70 – 90 % at 2.45GHz or 5.8GHz microwave input.

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,

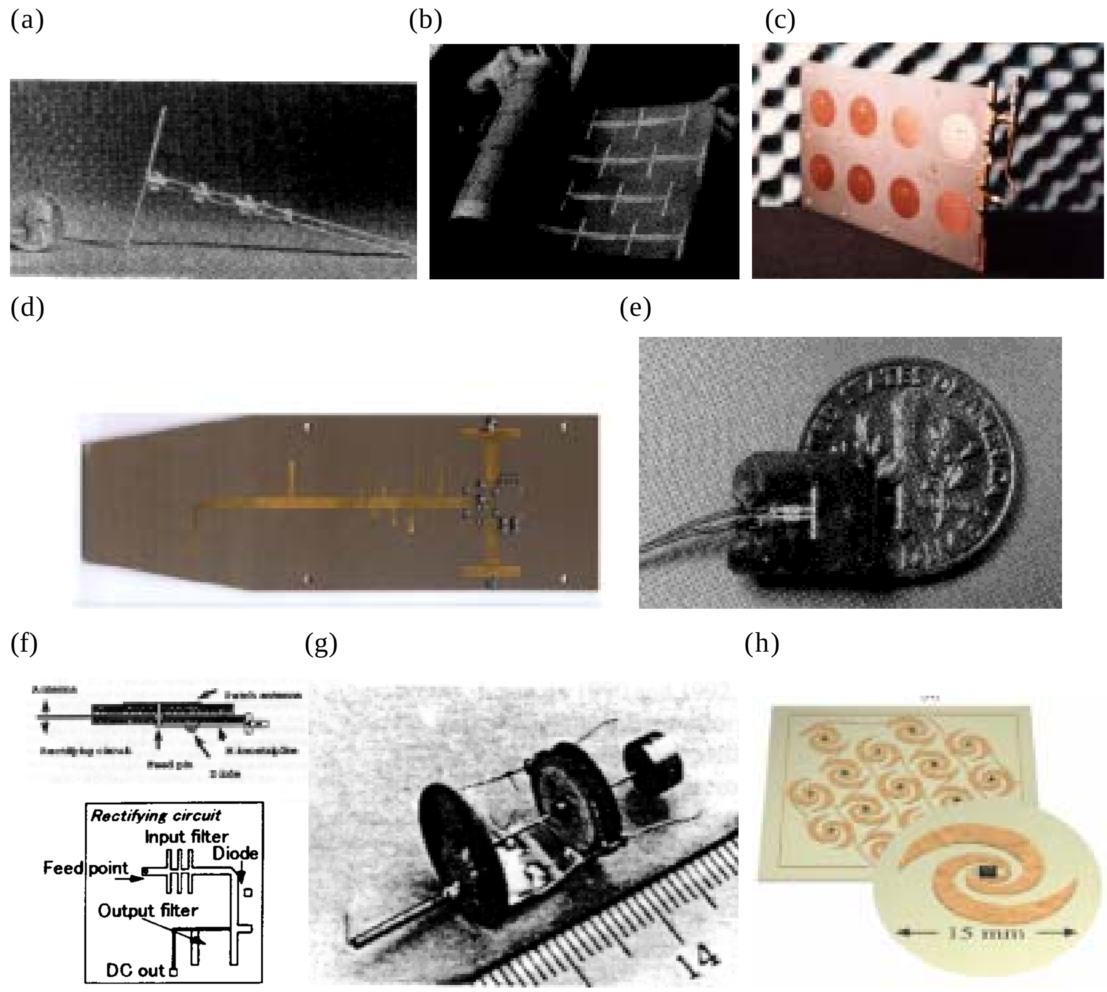


Fig.5.1 Various Rectennas (a) Brown's Rectenna (2.45GHz)[2] (b) Brown's Thin-Film Rectenna (2.45GHz)[3] (c) Hokkaido University's Rectenna (2.45GHz) (d) Kyoto University's Rectenna (2.45GHz)[7] (e) Texas A&M University's Rectenna (35GHz) [5] (f) CRL's Rectenna (5.8GHz)[11] (g) Denso's Rectenna for Microrobot (14-14.5GHz)[12] (h) University of Colorado's Rectenna (8.5-12.2GHz)[16]

the efficiency becomes quite low (Fig.5.2). 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.

In recent years, major research topic in the rectenna is to research and develop new rectennas which are suitable for a weak-wave microwave, which can be used in experimental power satellites and RF-ID. The weak-wave means in the "micro-watt" range. The RF-ID is the first commercial MPT system in the world. The weak microwave will be transmitted from the experimental satellite

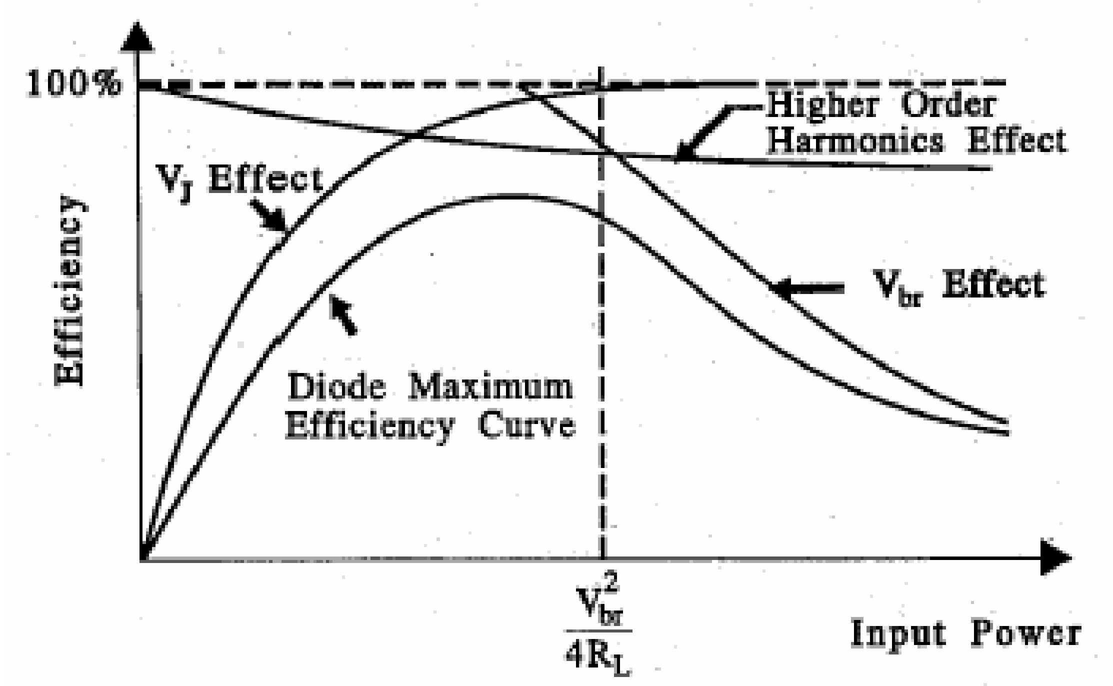


Fig.5.2 Typical characteristic of RF-DC conversion efficiency of rectenna [5]

on LEO to the ground because microwave power and size of transmitting antenna on the experimental satellite will be limited by the capacity of the present launch rockets. We have two approaches to increase the efficiency at the weak microwave input. One is to increase an antenna aperture under a weak microwave density[14][18]. There are two problems for this approach. It makes sharp directivity and it is only applied for the SPS satellite experiment and not for the RF-ID application. The other approach is to develop a new rectifying circuit to increase the efficiency at a weak microwave input[22]-[25]. We can apply this type of the rectenna for the commercial RF-ID.

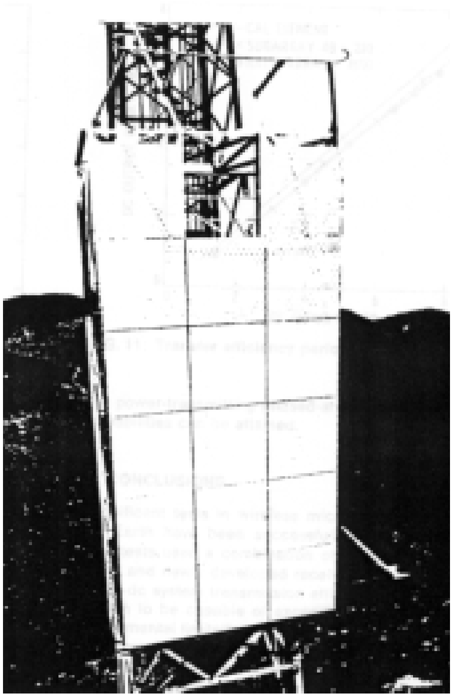
5.2 Recent Technologies of Rectenna Array

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 rectennas 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[21]. It is caused by characteristic of the RF-DC conversion efficiency of the rectenna elements shown in Fig. 5.1. It was experimentally and theoretically reported that the total power decrease with series connection is more than that with parallel connection[26]. It was further confirmed with simulation and experiments that current equalization in series connection is worse than voltage equalization in parallel connection[27]. There is the optimum connection of the rectenna array.

The SPS requires a rectenna array whose diameter of over km. Although there are many researches of rectenna elements as shown in references [1]-[25] and more , only a few rectenna arrays were developed and used for experiments (Fig.5.3). The maximum rectenna array in the world

(a)



(b)

(c)

(d)

Fig. 5.3 Large Rectenna Array Used for (a) G-to-G Experiment in Goldstone in 1975 [27], (b) G-to-G Experiment in Japan in 1994-95 [28], (c) fuel-free airship experiment in 1995 [10], (d) Experimental Equipment in Kyoto University [29]

is that used for a ground to ground experiment in Goldstone by JPL, USA, in 1975[28] as shown in the section of MPT history. The size was 3.4 m x 7.2 m = 24.5 m^2. A rectenna array that had 2,304 elements and whose size was 3.54 m x 3.2 m was developed for a ground to ground experiment conducted by Kyoto University, Kobe University, and Kansai Electric Corporation in 1994[26][29]. Kyoto University has several types of rectenna arrays at 2.45 GHz and 5.8 GHz[30]. These sizes are approximately 1mϕ. Another rectenna array with the size of 2.7 m x 3.4 m was developed for MPT to fuel-free airship experiment with conducted by CRL (Communication Research Laboratory, NICT in present) in Japan and Kobe University in 1995[10]. There is a large gap between these arrays of a few meters in size and the SPS array of kilometers in diameter. Research of larger scale rectenna arrays is required.

5.3 Recent Technologies of Cyclotron Wave Converter

If we would like to use a parabolic antenna as a MPT receiver, we have to use Cyclotron Wave Converter (CWC) instead of the rectenna. The CWC is a microwave tube to rectify high power microwave directly into DC. The most studied cyclotron wave converter (CWC) comprises an electron gun, a microwave cavity with uniform transverse electric field in the gap of interaction, a region with symmetrically reversed (or decreasing to zero) static magnetic field and a collector with depressed potential as shown in Fig.5.4. Microwave power of an external source is converted by this coupler into the energy of the electron beam rotation, the latter is transformed into additional energy of the longitudinal motion of the electron beam by reversed static magnetic field; then extracted by decelerating electric field of the collector and appeared at the load-resistance of this collector.

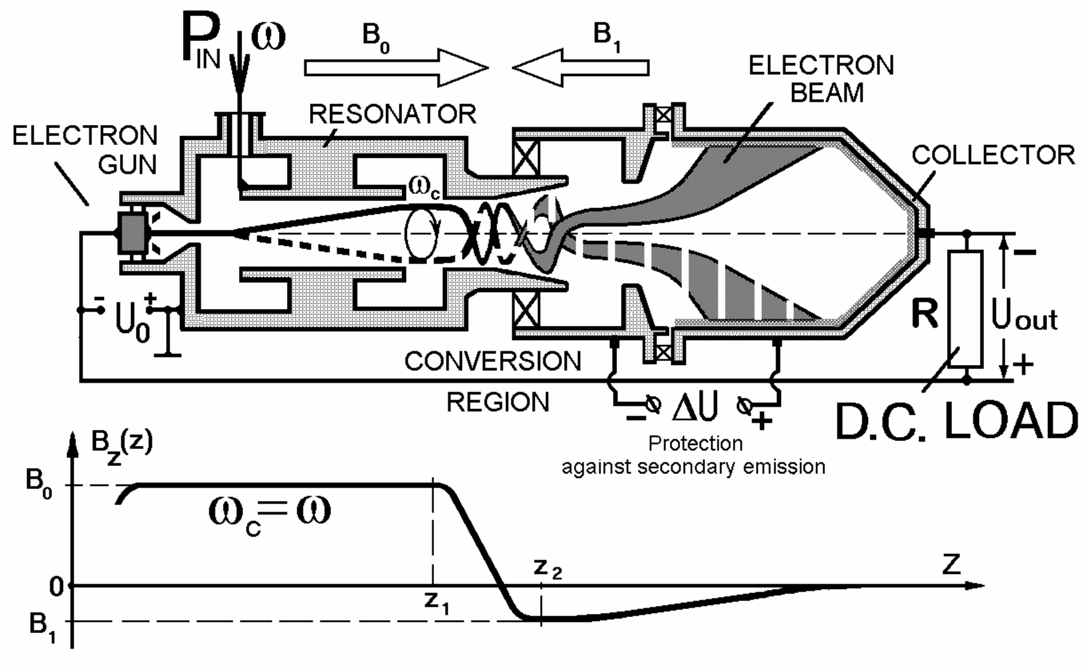


Fig.5.4 Schematic Picture of Cyclotron Wave Converter

The first CWC experiment was carried out by D. C. Watson, R. W. Grow, and C. C. Jonson[31]-[33]. The first CWC could rectify only 1-1.5 W input with 56% efficiency. At Moscow State University, a variant of the CWC was tested and its efficiency was 70-74% at 25-25W. The TORIY Corporation and Moscow State University collaborate to create a several high power CWC with the efficiency of 60-83% at 10-20 kW[34]-[36]. They demonstrated the CWC at the WPT'95 conference in Kobe, Japan. Vanke's group continue to improve the CWC in present[37][38]. European group planed to apply the CWC for a ground-to-ground MPT experiment in Re-union Island[39].

Fig.5.5 CWCs Developed in Russia [37]

5.4 Rectenna Site Issue

It is widely assumed that a commercially feasible SPS will be on the order of GW. It delivers significant electric power, and can contribute to any national power grid. The technology for connection to the grid already exists, although the output of the SPS is a direct current. The output of thermal or nuclear power plant is an AC, because they must first drive a kind of turbine-generators.

The SPS will be steady state base power system without CO_2 emission. Its output is predictable. We have no problems economically and technologically with connecting the SPS to an existent power grid. Moreover, a GW class power plant is similar to a nuclear power plant or large hydropower plant. Most of the grid connection issues, therefore, are the same.

In Japan, some simulations concerning the connection with the rectennas and the existent power grid are carried out[40]. When The SPS connect to existent power grid, it has possibility that accidents can occur at either the SPS side or the grid side. The grid is designed to take up the slack if the SPS dropouts without warning. In some cases the output of the rectenna may lapse. However, the DC power converter may be able to handle these lapses in most cases -- within a certain specified range of lapses. If the lapse or power failure is too large, then output may cease. If connected to a large existent grid, then the grid should be able to take up the slack, somehow. If an accident occurs on the grid side, there is potential for trouble for the rectenna (power source to the grid). The grid may be hit by electrical storms (thunder storms), but the power failure duration should be very short, short enough for the SPS to manage with such hits to the grid. However, a major accident at another power source (resulting output failure for hours or days), may be difficult for the SPS to cope with. More careful studies are needed on this matter.

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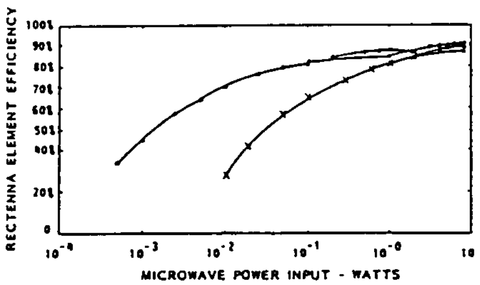
6. Efficiency

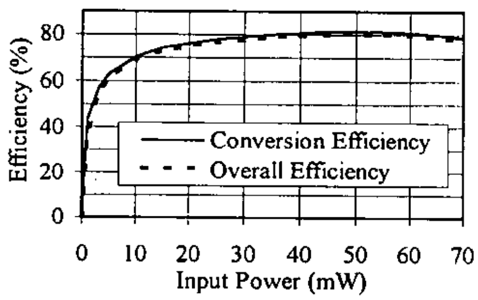
We classify the MPT efficiency roughly into three stages; DC-RF conversion efficiency which includes losses caused by beam forming, beam collection efficiency which means ratio of all radiated power to collected power on a receiving antenna, and RF-DC conversion efficiency.

6.1 RF-DC Conversion Efficiency

The RF-DC conversion efficiency of the rectenna or the CWC is over 80 % of experimental results as shown in Fig.6.1. 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. However, it is easier to keep high efficiency than that on the other two stages.



(a) Efficiency of 2.45GHz Rectenna[1]



(b) Efficiency of 5.8GHz Rectenna[2]

Fig. 6.1 Efficiency of Rectenna Element

6.2 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 as shown in the section 1. For example, it was calculated approximately 89% in the SPS reference system with the parameters as follows; the transmitter aperture is 1 kmϕ, the rectenna aperture is 10x13 km, the wavelength is 12.24 cm (2.45GHz), and the distance between the SPS and the rectenna 36,000 km[3]. They assume 10dB Gaussian power taper on the transmitting antenna. The beam pattern on the ground is shown in Fig.6.2.

Decline of the efficiency is caused by phase/frequency/amplitude error on a phased array. Phase/frequency/amplitude error on a phased array causes difference of beam direction and rise of sidelobes. If we have enough large number of elements, the difference of the beam direction is negligible. The rise of the sidelobe decreases antenna gain and beam collection efficiency.

If antenna planes separate each other structurally, grating lobes, whose power level is the same as main beam, may occur and power can not be concentrated to the rectenna array. This problem occurs in module-type phased array. The idea of random array has risen in order to suppress the grating lobes. However, a sidelobe level increases, beam collection efficiency decreases and have to search for special techniques. Power in grating lobes diffuses not to a main lobe but to sidelobes. Therefore, we have to fundamentally suppress the grating lobes for a MPT system.

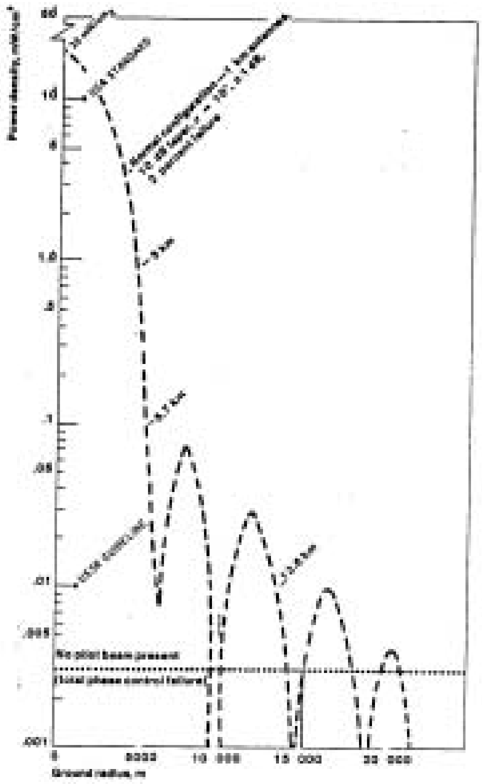


Fig.6.2 Beam Pattern on the Ground[1]

6.3 DC-RF Conversion Efficiency

If we do not have to steer a microwave beam electrically in a MPT, we can use a microwave transmitter with high DC-RF conversion efficiency over 70-80 % like microwave tubes. However, if we need to steer a microwave beam electrically without any grating lobes, we have to use phase shifters with high loss. Especially in the SPS system, the optimum and economical size of the transmitting phased array and microwave power are calculated as around a few km and over a few GW, respectively. It means that microwave power from one antenna element is much smaller than that from one microwave tube or high power (over a several tens watts) semiconductor amplifier. It also means that phase shifter have to be installed after the microwave generation/amplification (Fig.6.3) if microwave beam will be steered to directions of larger than 5 degrees without grating lobes. In that case, development of

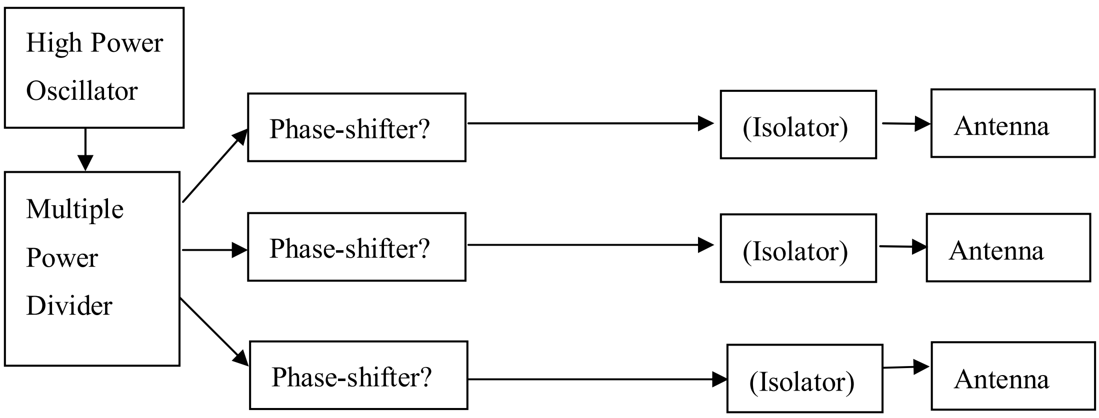


Fig. 6.3 Implementation of microwave transmission with a high power microwave oscillator and phase-shifters for high precision control of microwave beam direction to large angles without grating lobes

low loss phase shifter is very important for construction of a phased array with high efficiency. In present, the power loss of the phase shifter is over 4-6 dB. It means that DC-RF conversion efficiency in the MPT system in Fig.6.4 is below 20% if we use over 70% efficiency high power oscillator/amplifier. However, the phase shifter problem will be solved if microwave beam will be steered to directions within 0.1 degree because the phase shifters do not need to be installed without grating lobes with large sub-array. Another way to solve the phase shifter problem is use of low power amplifiers after the high loss phase shifters (Fig.6.4).

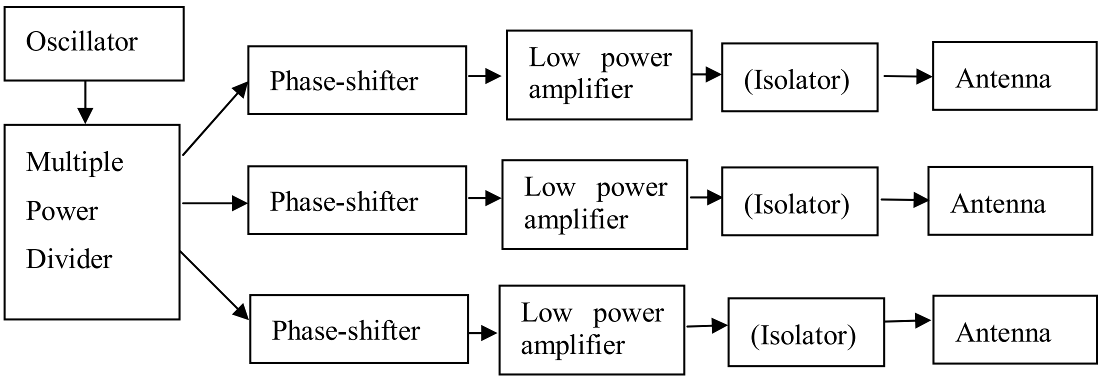


Fig. 6.4 Implementation of microwave transmission with phase-shifters and low power amplifiers for high precision control of microwave beam direction without grating lobes

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7. Summary

The MPT is very old concept with newest technologies. We can advance energy systems from RF-ID to the SPS. The SPS is the largest and most suitable MPT application. To realize the commercial SPS, there are some research subjects to solve in order to decrease its cost. We have already achieved a point-to-point MPT in 1970's (Fig.6.1). We have also achieved a phased array technologies with low efficiency. The problem in order to realize the SPS is high efficient phased array for the MPT. The higher efficiency can suppress a cost of the SPS. There are some methods to increase the efficiency of the MPT. One is a superconducting to reduce a loss in resistance. The other is an achievement of higher accurate beam control to reduce a loss in beam focusing. New semi-conductor device is expected for increasing the DC-RF and RF-DC conversion efficiency. The SPS is future system. Based on the MPT application on the ground, we have to advance the MPT technologies.

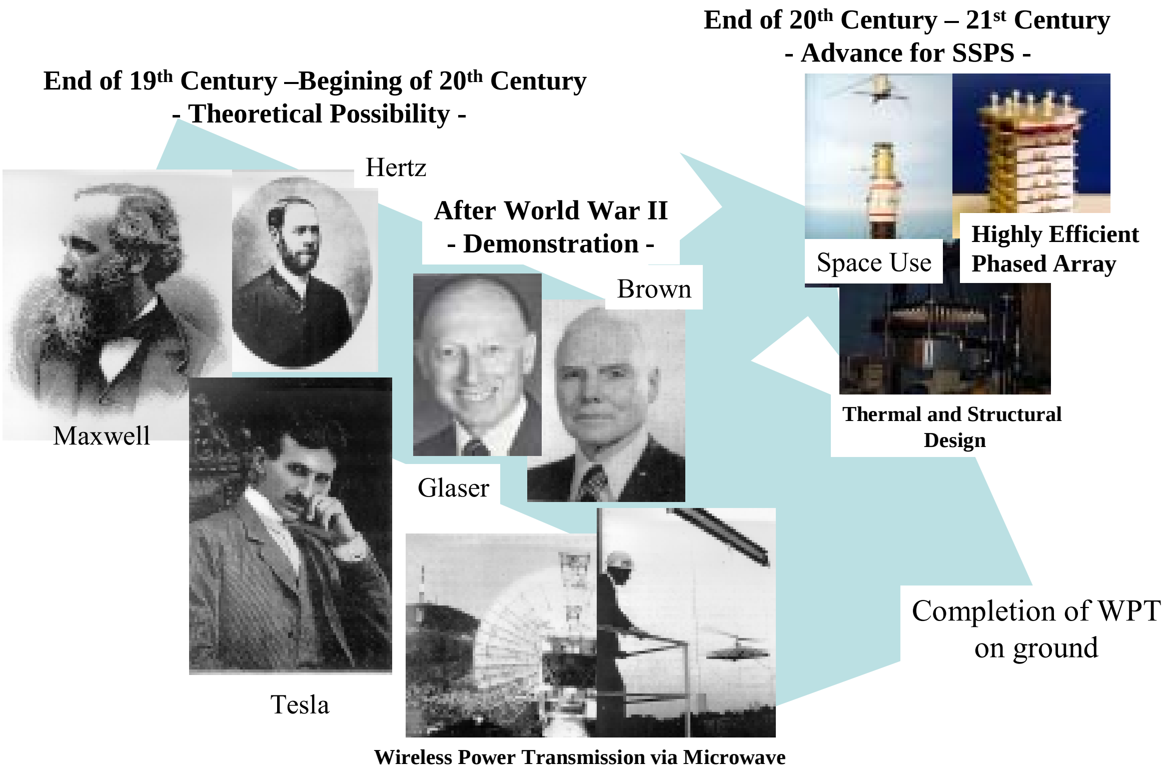

Fig.6.1 History and Future of the MPT