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WIRELESS POWER TRANSMISSION FOR SOLAR POWER SATELLITE (SPS)

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ABSTRACT

The solar power wireless transmission of energy is completely based on solar energy resources widely available through the outer environment. This paper mainly concerns about the conversion of energy obtained from the sun by satellite to microwaves using a externally paced device called magnetron. Satellites in the earth's atmosphere receives the ultraviolet rays in the form of photons and then broadcast them to the centre by the form of converted microwaves. These microwaves travels a long area to reach the device in the receiving centre called rectenna . These rectennawill convert those microwaves into required energy source and distributes them to all available primary and secondary vectors. Then the transmission and distribution process begins resolving all energy needier.

Keywords: Rectenna, Magnetron, Microwave, Energy source

I. THEORETICAL BACKGROUND

It is known that electromagnetic energy also associated with the propagation of theelectromagnetic waves. We can use theoretically all electromagnetic waves for a wireless powertransmission (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 alldirections. Although we transmit the energy in the communication system, the transmitted energy isdiffused 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 WPTsystem.

Typical WPT is a point-to-point power transmission. For the WPT, we had better concentratepower 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 tapermethod of the transmitting antenna power distribution. Famous power tapers of the transmittingantenna are Gaussian taper, Taylor distribution, and Chebychev distribution.

These taper of thetransmitting antenna is commonly used for suppression of sidelobes. It corresponds to increase thepower transmission efficiency. Concerning the power transmission efficiency of the WPT, there aresome good optical approaches in Russia[5][6].

Future suitable and largest application of the WPT via microwave is a Space Solar PowerSatellite (SPS). The SPS is a gigantic satellite designed as an electric power plant orbiting in theGeostationary Earth Orbit (GEO). It consists of mainly three segments; solar energy collector toconvert the solar energy into DC (direct current) electricity, DC-to-microwave converter, and largeantenna array to beam down the microwave power to the ground. The first solar collector can beeither photovoltaic cells or solar thermal turbine. The second DC-to-microwave converter of the SPScan be either microwave tube

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system and/or semiconductor system. It may be their combination. Thethird segment is a gigantic antenna array. Table 1.1 shows some typical parameters of thetransmitting antenna of the SPS. An amplitude taper on the transmitting antenna is adopted in orderto increase the beam collection efficiency and to decrease sidelobe level in almost all SPS design. Atypical amplitude taper is called 10 dB Gaussian in which the power density in the center of thetransmitting 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 theother application of the WPT. In resent years, mobile devices advance quickly and requiredecreasing power consumption. It means that we can use the diffused weak microwave power as apower source of the mobile devices with low power consumption such as RF-ID. The RF-ID is aradio IC-tug with wireless power transmission and wireless information. This is a new WPTapplication like broadcasting.

Figure.1 Recent Technologies and Researches of Wireless Power Transmission – Antennas andTransmitters

II. 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 anyother 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 inground-to-ground MPT experiment in 1994-95 in Japan .In the fuel-freeairship light experiment with MPT in 1995 in Japan, they changed a direction of the parabolicantenna to chase the moving airship.However, we have to use a phased array antenna for the MPT from/to moving transmitter/receiverwhich include the SPS because we have to control a microwave beam direction accurately andspeedy.

The phased array is a directive antenna which generate a beam form whose shape anddirection by the relative phases and amplitudes of the waves at the individual antenna elements. It ispossible 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 inJapan, the phased array antenna was adopted to steer a direction of the microwave beam All SPS is designed with the phased array antenna. We consider the phased array antenna for allfollowing MPT system.

III. RECENT TECHNOLOGIES FOR TRANSMITTERS

The technology employed for the generationof microwave radiation is an extremely importantPhased 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 thanthat 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 arraysystem for the MPT.

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

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microwave generators/amplifiers, frequency vs. averagedpower [2]. These have electric characteristics contrary to each other. Themicrowave 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. Thesemiconductor amplifier generate low power microwave (below 100W) with a low voltage (belowfifteen volt) imposed. It is still expensive currently. Although there are some discussion concerninggeneration/amplifier efficiency, the microwave tube has higher efficiency (over 70%) and thesemiconductor has lower efficiency (below 50%) in general. We have to choose tube/semiconductor
case by case for the MPT system.

IV. MAGNETRON

Magnetron is a crossed field tube in which forces electrons emitted from the cathode totake cyclonical path to the anode. The magnetron is self-oscillatory device in which the anodecontains a resonant RF structure. The magnetron has long history from invention by A. W. Hull in1921. The practical and efficient magnetron tube gathered world interest only after K. OkabeAverage RF output power versus frequency for various electronic devices[4] andsemiconductors[2]

V. SEMICONDUCTOR AMPLIFIER

After 1980s, semiconductor device plays the lead in microwave world instead of the microwavetubes. It causes by advance of mobile phone network. The semiconductor device is expected toexpand microwave applications, for instance, phased array and Active integrated antenna (AIA),because of its manageability and mass productivity. After 1990s, some MPT experiments werecarried 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). Presentmaterials for the semiconductor device are Si for lower frequency below

afew GHz andGaAs forhigher frequency. We design microwave circuits with these semiconductor devices. It is easy tocontrol a phase and amplitude through the microwave circuits with semiconductor devices, forexample, amplifiers, phase shifters, modulators, and so on. For the microwave amplifiers, circuitdesign theoretically determines efficiency and gain. A, B, C class amplifiers are classified in biasvoltage in device.

These classes are also applied in kHz systems. In D, E, F class amplifiers formicrowave frequency, higher harmonics are used effectively to increase efficiency, theoretically100%. 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 = (Pout-Pin)/PDC) of 54%, efficiency of about 60%, at 5.8GHz.

These arechampion data in laboratory. To develop the high efficient amplifier, we need strict adjustment incontrary of mass productivity. It causes that the semiconductor amplifiers keep expensive cost forthe MPT system. It potentially has low price capability by the mass production. An efficiency of adriver 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 amplifierbecause power level of the MPT is much higher than that for wireless communication system and wehave to suppress unexpected spurious radiation to reduce interference. The maximum efficiencyusually is realized at saturated bias voltage. It does not guarantee the linearity between input andoutput 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 theMPT.

There are unique development items for the SPS from the microwave point of view

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distinguishedfrom the ordinary use of the microwave technology such as telecommunications.

These three pointsmay be described as 1) pureness in spectrum, 2) high power and high efficient power generation andhigh efficient detector in a small and light fashion, and 3) precise beam control for a large phasedarray antenna combining with a huge number of sub-arrays.

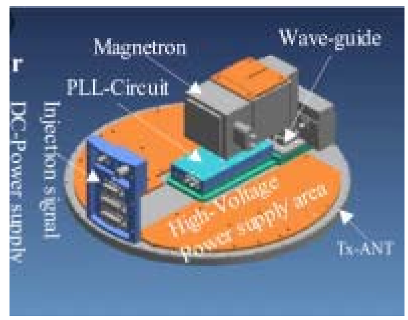
To cope with the second requirement for the microwave technology, the large plate model by alayered configuration in a sandwich fashion was proposed. The point of this configuration is theeffective integration with DC power generation, microwave circuit operation and radiation, and theircontrol. As one 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 integratedcircuit and a planar antenna. The AIA has many features applicable to the SPS. Due to the natureof small-size, thinness, lightness and multi-functions in AIA, a power transmission part of thespacetenna (space antenna) can be realized in thin structure. Prof. Kawasaki’s group have developedsome AIA system for the MPT application[20].In present, new materials are developed fore the semiconductor device to increased output powerand efficiency. They are called wide-bandgap devices such as SiC and GaN. The wide-bandgapdevices can make over hundreds watt amplifier with one chip.

In recent days, there are somedevelopment of microwave amplifiers with SiCMESFET[21][22] or GaN HEMT[23][24]. The othertrend is development of MMIC (Microwave Monolithic Integrated Circuit) to reduce space andweight, especially for mobile applications. Lighter transmitters can be realized with the MMICdevices. 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.

VI. 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 efficiencyto reduce heat problem.

A weight of the microwave tube is lighter than that of the semiconductor amplifier when wecompare the weight by power-weight ratio (kg/kW). The microwave tube can generate/amplifyhigher power microwave than that by the semiconductor amplifier. Kyoto University’s group havedeveloped a light weight phase controlled magnetron called COMET, Compact Microwave EnergyTransmitter with a power-weight ratio below 25g/W [25]. The COMET includes a DC/DCCompact 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 allmicrowave 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 5.8GHz 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[26]. They do not include a heat radiation circuit, a wave guide, andan antenna. The semiconductor amplifier is not light remarkably. Examples of characteristics ofvarious transmitters for

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space use are shown in Table 1. Although it may seem that semiconductoramplifiers are light in weight, they have heavy power-weight ratio because output microwave poweris very small.Heat reduction is most important problem in space. All lost power converts to heat. We needspecial heat reduction system in space. If we use high efficient microwave transmitters, we canreduce weight of heat reduction system. We should aim for over 80 % efficiency for the microwavetransmitter, 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 seriousproblem.

V. RECENT TECHNOLOGIES AND RESEARCHES OF WIRELESS POWER TRANSMISSION – BEAM CONTROL,TARGET DETECTION, PROPAGATION RECENT TECHNOLOGIES OF RETRODIRECTIVE BEAM CONTROL

A microwave power transmission is suitable for a power transmission from/to movingtransmitters/targets. Therefore, accurate target detection and high efficient beam forming areimportant. Retrodirective system is always used for SPS.

A corner reflector is most basic retrodirectivesystem[1]. The corner reflectors consist ofperpendicular metal sheets, which meet at an apex. Incoming signals are reflected backin the direction of arrival through multiple reflections off the wall of the reflector. Van Atta array isalso a basic technique of the retrodirectivesystem[2]. This array is made up of pairs of antennasspaced 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-radiatingelements are inverted with respect to the center of the array, achieving the proper phasing forretrodirectivity. Usual retrodirective system have phase conjugate circuits in eachreceiving/transmitting antenna, which play a same role as pairs of antennas spacedequidistant from the center of the array in Van Atta array. A signal transmitted from the target isreceived and re-radiated through the phase conjugate circuit to the direction of the target. The signalis called a pilot signal. We do not need any phase shifters for beam forming. The retrodirectivesystem is usually used for satellite communication, wireless LAN, military, etc. There are manyresearches of the retrodirective system for these applications [3]-[11]. They use the almostsame frequency for the pilot signal and returned signal with a local oscillator (LO) signal at afrequency twice as high as the pilot signal frequency in the typical retrodirective systems.Accuracy depends on stability of the frequency of the pilot signal and the LO signal. Prof. Itoh'sgroup proposed the pilot signal instead of the LO signal[12].

There are other kinds of the phase conjugate circuits for the MPT applications. Kyoto University'sgroup 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]. ωt indicate a frequency of a transmitter. otherretrodirective system with 1/3 ωt pilot signal and without LO signal. The LO signal isgenerated from the pilot signals. The latter system solve a fluctuation problem of the LO and thepilot signal which cause phase errors because the fluctuations of the LO and the pilot signals aresynchronous. They have used 2.45 GHz for ωt. Mitsubishi Electric Corporation in Japan havedeveloped PLL-heterodyne type retrodirective system in which different frequencies for the pilotsignal 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 conjugatecircuits. There are some methods for target detecting with pilot signal which is separated to beamforming. We call the method "software retrodirective".

Computer is usually used for the softwarerectodirective with the phase data from a pilot signal and for the beam forming with calculation ofthe optimum phase and amplitude distribution on the array. In the software rectodirective, we canform microwave beam freely, for example, multi-beams. On contrary, we need phase shifters in allantennas.After the target detection, we need accurate beam forming. For the optimum beam forming, thereare some algorism, for instance, neural network, genetic algorithm, and multi-objective optimizationlearning. The "optimum" has multi-meanings, to suppress sidelobe level, to increase

beam collectionefficiency, and to make multiple power beams. We can select object of optimum and algorism freelywith consideration of time of calculation.Kyoto University in Japan and Texas A&M University in USA have developed the softwareretrodirective system independently[16][17]. Kyoto University's group use a pilot signal modulatedby spread spectrum in order to use the same frequency band of microwave power beam and the pilotsignal 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 desireddirection Both for beam forming with the software retrodirective and for retrodirective with thephase conjugate circuit. If the standard of the phase/frequency like the LO signal is different on onearray, we cannot form the microwave beam to the desired direction. Although the best way is to useonly one oscillator for the standard of the phase/frequency for one phased array of larger than km insize with more than billion elements, it is quite difficult. A better way is use of some oscillators onsome group of sub-phased array and the oscillators are synchronous with each other. Some trialshave been carried out. One is wireless synchronization of separated units. The present accuracy ofwireless 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 inthe rectenna site. The change gives us information on phase corrections.

VI. 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 onerectenna element receives and creates only a few W. Especially for the SPS, we need ahuge rectenna site and a power network connected to the existing power networks onthe ground. On contrary, there are some

MPT applications with one small rectennaelement such as RF-ID.

VII. RECENT TECHNOLOGIES OF RECTENNA

The word "rectenna" is composed of "rectifying circuit" and "antenna". The rectenna and its wordwere invented by W. C. Brown in 1960's[1][2][3]. The rectenna can receive and rectify a microwavepower to DC. The rectenna is passive element with a rectifying diode, operated without any powersource. There are many researches of the rectenna elements. Famous research groups of therectenna are Texas A&M University in USA[5][9][14][18], NICT(National Institute of Informationand Communications Technology, past CRL) in Japan[8][10][11][17], and Kyoto University inJapan[7][12][23]. The antenna of rectenna can be any type such as dipole[1]-[5], Yagi-Udaantenna[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 rectifyingcircuit such as single shunt full-wave rectifier[4][9][10][11][13][14][16], full-wave bridgerectifier[1][7][12][15], or other hybrid rectifiers[8]. The circuit, especially diode, mainly determinesthe RF-DC conversion efficiency. Silicon Schottky barrier diodes were usually used for the previousrectennas. New diode devices like SiC and GaN are expected to increase the efficiency. Therectennas with FET[19] or HEMT[20] appear in recent years. The rectenna using the active devicesis not passive element.The single shunt full-wave rectifier is always used for the rectenna. It consists of a diode insertedto the circuit in parallel, a λ/4 distributed line, and a capacitor inserted in parallel. In an idealsituation, 100% of the received microwave power should be converted into DC power[21]. Itsoperation 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, thewave form on the λ/4 distributed line has a π cycle, which means the wave form is a full-waverectified sine form.

The world record of the RF-DC conversion efficiency among developedrectennas is approximately 90% at 4W input of 2.45 GHz microwave[1]. Other rectennas in theworld 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 powerinput 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 ofthe diode. The diode has its own junction voltage and breakdown voltage. If the input voltage to thediode is lower than the junction voltage or is higher than the breakdown voltage, the diode does notshow a rectifying characteristic. As a result, the RF-DC conversion efficiency drops with a lower orhigher input than the optimum.

In recent years, major research topic in the rectenna is to research and develop new rectennaswhich are suitable for a weak-wave microwave, which can be used in experimental power satellitesand RF-ID. The weak-wave means in the "micro-watt" range. The RF-ID is the first commercialMPT system in the world. LEO to the ground because microwave power and size of transmitting antenna on theexperimental satellite will be limited by the capacity of the present launch rockets. We have twoapproaches to increase the efficiency at the weak microwave input. One is to increase an antennaaperture under a weak microwave density[14][18]. There are two problems for this approach. Itmakes sharp directivity and it is only applied for the SPS satellite experiment and not for the RF-IDapplication. The other approach is to develop a new rectifying circuit to increase the efficiency at aweak microwave input[22]-[25]. We can apply this type of the rectenna for the commercial RF-ID.

VIII. RECENT TECHNOLOGIES OF RECTENNA ARRAY

The rectenna will be used as an array for high power MPT because one rectenna element rectifiesa few W only. For usual phased array antenna, mutual coupling and phase distribution are problemsto solve. For the rectenna array, problem is different from that of the array antenna because therectenna 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 optimumpower output and their combined power output will be less than that if operated independently. Thisis theoretical prediction[21]. It is caused by characteristic of the RF-DC conversion efficiency of therectenna elements shown in. It was experimentally and theoretically reported that the totalpower decrease with series connection is more than that with parallel connection[26].

It was furtherconfirmed with simulation and experiments that current equalization in series connection is worsethan voltage equalization in parallel connection[27]. There is the optimum connection of theThe 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 rectennaarrays were developed and used for experiments. is that used for a ground to ground experiment in Goldstone by JPL, USA, in 1975[28] as shown inthe section of MPT history. The size was 3.4 m x 7.2 m = 24.5 m2. A rectenna array that had 2,304elements and whose size was 3.54 m x 3.2 m was developed for a ground to ground experimentconducted 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 areapproximately 1mφ. Another rectenna array with the size of 2.7 m x 3.4 m was developed for MPTto fuel-free airship experiment with conducted by CRL (Communication Research Laboratory, NICTin present) in Japan and Kobe University in 1995[10].

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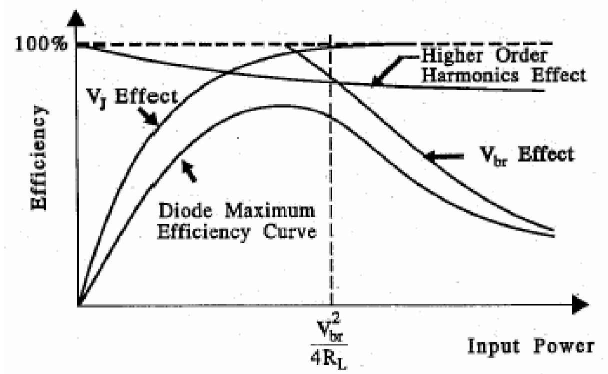
There is a large gap between these arrays of afew meters in size and the SPS array of kilometers in diameter. Research of larger scale rectennaarrays is required.



IX. RECENT TECHNOLOGIES OF CYCLOTRON WAVE CONVERTER

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

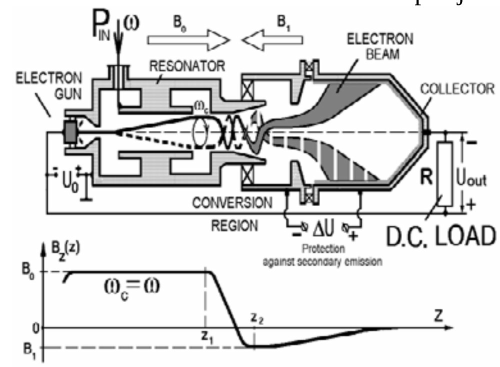


Fig.5.4 Schematic Picture of Cyclotron Wave Converter

Efficiency

We classify the MPT efficiency roughly into three stages; DC-RF conversion efficiency whichincludes losses caused by beam forming, beam collection efficiency which means ratio of allsaradiated 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 experimentalresults as shown in Fig.6.1. Decline of the efficiency is caused by array connection loss, change ofoptimum operation point of the rectenna array caused by change of connected load, trouble of therectenna, and any losses on the systems, for example, DC/AC conversion, cables, etc. However, it iseasier to keep high efficiency than that on the other two stages.

Beam Collection Efficiency

The beam collection efficiency depends on the transmitter and receiver aperture areas, thewavelength, and the separation distance between the two antennas as shown in the section 1. Forexample, it was calculated approximately 89% in the SPS reference system with the parameters asfollows; the transmitter aperture is 1 kmφ, the rectenna aperture is 10x13 km, the wavelength is12.24 cm (2.45GHz), and the distance between the SPS and the rectenna 36,000 km[3]. They assume10dB Gaussian power taper on the transmitting antenna.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 ofsidelobes.

If we have enough large number of elements, the difference of the beam direction isnegligible. 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 asmain beam, may occur and power cannot be concentrated to the rectenna array. This problem occursin module-type phased array. However, a

sidelobe level increases, beamcollection efficiency decreases and have tosearch for special techniques. Power in gratinglobes diffuses not to a main lobe but to sidelobes.Therefore, we have to fundamentally suppressthe grating lobes for a MPT system.

DC-RF Conversion Efficiency

If we do not have to steer a microwave beamelectrically in a MPT, we can use a microwavetransmitter with high DC-RF conversionefficiency over 70-80 % like microwave tubes.However, if we need to steer a microwave beamelectrically without any grating lobes, we haveto use phase shifters with high loss. Especially inthe SPS system, the optimum and economicalsize of the transmitting phased array andmicrowave power are calculated as around a fewkm and over a few GW, respectively. It meansthat microwave power from one antenna element is much smaller than that from one microwave tubeor high power (over a several tens watts) semiconductor amplifier. It also means that phase shifterhave to be installed after the microwave generation/amplification (Fig.6.3) if microwave beam willbe steered to directions of larger than 5 degrees without grating lobes. In that case, development oflow loss phase shifter is very important for construction of a phased array with high efficiency. Inpresent, the power loss of the phase shifter is over 4-6 dB. It means that DC-RF conversionefficiency in the MPT system in Fig.6.4 is below 20% if we use over 70% efficiency high poweroscillator/amplifier. However, the phase shifter problem will be solved if microwave beam will besteered to directions within 0.1 degree because the phase shifters do not need to be installed withoutgrating lobes with large sub-array. Another way to solve the phase shifter problem is use of lowpower amplifiers after the high loss phase shifters .

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