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Beam Efficiency of Wireless Power Transmission via Radio Waves from Short Range to Long Range

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Abstract

Wireless power transmission (WPT) is useful technology in near future. There are some kinds of the WPT technologies, WPT via radio waves, resonance coupling, and inductive. Especially the WPT via radio waves is used for multi-purposes from short range to long range application. However, unfortunately it is misunderstood that it is low efficiency and low power. In this paper, I show the theory of beam efficiency between transmitting antennas and receiving antennas and also show some high efficient applications of the WPT via radio waves. Especially, I pick up a wireless power charging system of an electric vehicle and show the experimental results. I show difference between the theory of beam efficiency and the experimental results of short range WPT. I indicate that reasons of poor beam efficiency in the experiment are (1) change of impedance caused by mutual coupling between transmitting antennas and receiving antennas, (2) oblique direction of microwave power to receiving antennas caused by short distance.

Key words : Wireless Power Transmission, Microwave, Beam Efficiency, Electric Vehicle.

Ⅰ. Introduction

Wireless Power Transmission (WPT) is useful technology. We don't need any wire to charge a battery for high power users or any battery for tiny power users via the WPT. There are several kinds of WPT, WPT via radio waves, especially via microwaves, resonance coupling, and inductive coupling. The characteristics of the WPT are shown in Table 1.

The characteristics of the WPT via radio wave are based on the technologies and system design of wireless communication. We use an antenna for a transmitter and a rectenna, rectifying antenna, for a receiver in the WPT via radio waves. Therefore, it seems the efficiency is low because we use radiation of radio wave to transmit the power. However, we can increase the efficiency close to 100 % via radio waves. The WPT via radio waves is most versatile WPT for applications from short range to long range with higher efficiency. In this paper, I survey the theory and measurement of beam efficiency (BE) of the WPT via radio waves and show the recent experimental results of the WPT via radio waves.

Table 1. Characteristics of the WPT.

	WPT via radio waves	Resonance coupling	Inductive coupling
Field	Electric field	Resonance	Magnetic field
Method	Antenna	Resonator	Coil
Efficiency	Low to high	High	High
Distance	Short to long	Middle	Short
Power	Low to high	High	High
Safety	Electric field	Non (Evanescent)	Magnetic field
Regulation	Radio wave	Under discussion	Under discussion

Ⅱ. Theory

It is easy to use Friis transmission equation to calculate receiving power at distance of far field as follows;

$$P_r = \frac{\lambda^2 G_r G_t}{(4\pi D)^2} = \frac{A_r A_t}{(\lambda D)^2} P_t \tag{1}$$

where $P_r, P_t, G_r, G_t, A_r, A_t, \lambda, D$ are received power, transmitted power, antenna gain of a receiving antenna, antenna gain of a transmitting antenna, aperture area of a receiving antenna, aperture area of a transmitting antenna, wave length and distance between the transmitting antenna and the receiving antenna, respectively.

We can not use Friis transmission equation to calculate receiving power at a distance of near field because we assume plane wave at far field in Friis transmission equation and it is spherical wave at near field where the WPT is used. Therefore, we use the following τ parameter to calculate the receiving power or BE η [1].

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$$\tau^2 = \frac{A_t A_r}{(\lambda D)^2} \tag{2}$$

$$\eta = \frac{P_r}{P_t} = 1 - e^{-\tau^2} \tag{3}$$

BE at far field and near field using τ parameter are shown in Fig. 1. The quantity τ^2 itself indicates the efficiency based on the Friis equation. We can increase the BE close to 100 % with τ>2. The theory does not depend on power. Therefore, we can transmit high power of kWs, MWs···, via radio waves. The BE is almost same with small τ by both formulas. It means that we can assume plane wave at far field. When we shorten distance between a transmitting antenna and a receiving antenna, τ becomes larger and we can not assume plane wave at receiving antenna plane and can not use Friis transmission equation.

The equation (3) is approximation. We can calculate the BE exactly with calculation of near field beam pattern. Fig. 2 shows the BE with the WPT system, for example, wireless charging of electric vehicle, where f, Tx, and Rx are frequency, diameter of a transmitting antenna, and diameter of a receiving antenna, respectively. We can see that the BE keeps 90 % at <5 m distance when we choose parameters of the WPT. Therefore, the efficiency of the WPT via radio waves is high enough compared with the resonance or inductive coupling.

The equation (3) indicates only the transmission efficiency. Therefore we have to consider additionally the radiation or absorption efficiency of an antenna for the WPT via radio waves.

The infinite array can theoretically absorb 100 % of the transmitted radio wave [3, 4]. Itoh *et al*. calculated ab-

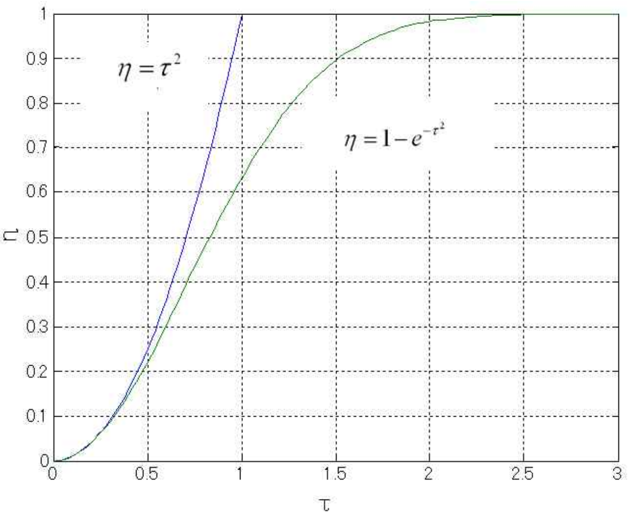


Fig. 1. Beam efficiency at far field and near field using τ parameter.

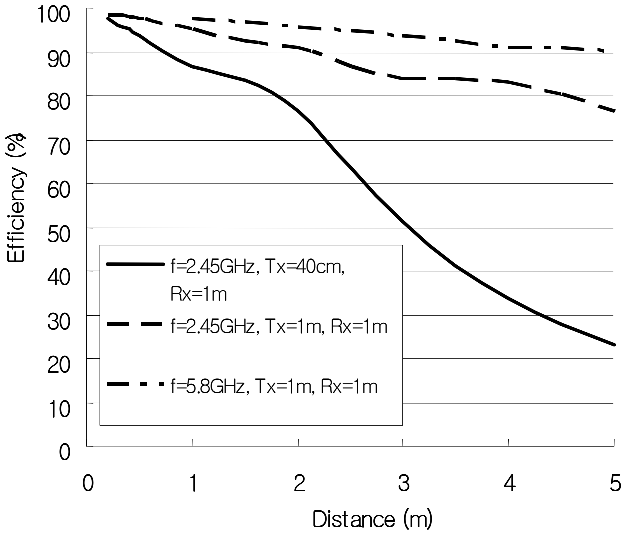


Fig. 2. Beam efficiency of WPT system.

sorption efficiency of rectenna array with circular microstrip antennas (CMSA) [5]. They conclude in the paper that the absorption efficiency of the infinite rectenna array composed of the CMSA is theoretically 100 % [5]. The absorption efficiency of the infinite rectenna array composed of the other antennas is formulated in the other paper [6, 7]. Otsuka *et al*. expanded the theory of the absorption efficiency of the infinite rectenna array to that of the finite rectenna array and carried out WPT experiment to confirm the absorption efficiency of the rectenna array [8]. The experimental results indicate that the absorption efficiency of the rectenna array can be close to 100 %. Based on these studies, we can consider that the BE can be almost 100 % with τ>2 in the WPT system via radio waves.

We have to use microwaves in order to realize τ>2 because the τ is defined with aperture area of a receiving antenna, aperture area of a transmitting antenna, wave length and distance between the transmitting antenna and the receiving antenna. Nicola Tesla carried out the world first WPT experiment in the first of 20th century [9], however, he could not increase τ and the BE because he used 150 kHz radio wave by using a measurable size antenna. In 60's, William C. Brown succeed the WPT via microwaves (GHz) with high efficiency [10] because the wavelength of the microwaves is much shorter than that of 150 kHz. Instead of increase of the BE with microwaves, DC-microwave conversion and RF-DC conversion efficiency decrease compared with lower frequency. Therefore, total efficiency of the WPT via microwave is up to 50 % which includes DC-microwave conversion, beam efficiency, absorption efficiency of the antenna, and microwave-DC conversion efficiency.

Ⅲ. Short Range WPT - Experiment of Wireless Charging of EV -

We proposed wireless charging system of an electric vehicle (EV) via microwaves in order to reduce amount of batteries and to make a convenient charging system. As described in section 2, the WPT via microwaves can be used for long range, a few meters. However, requirement of wireless power is high, >kW, to reduce charging time. We have to consider safety if we design the wireless charging system for the EV in long range and with high power. Therefore, we proposed the wireless charging with high power from road. It satisfies both high power and safety, and large τ in short range, $<\lambda$. Proposed system is shown in Fig. 3. We use linear polarization. We have estimated safety of the system and have carried out some experiments of the wireless charging with some system design [11]. In previous systems, the BE has been still poor even if τ of the system was enough for high BE. We need to increase the BE of the system. The BE includes the T/R antenna efficiency in this section. Except the BE, we have to consider both efficiency of the magnetron which is approximately 72 % and efficiency of rectennas which is approximately 80 %. The magnetron is commonly used one for microwave ovens. The rectennas are developed for the experiment. Total efficiency of the WPT via microwaves are calculated by 72 %×BE×80 % approximately.

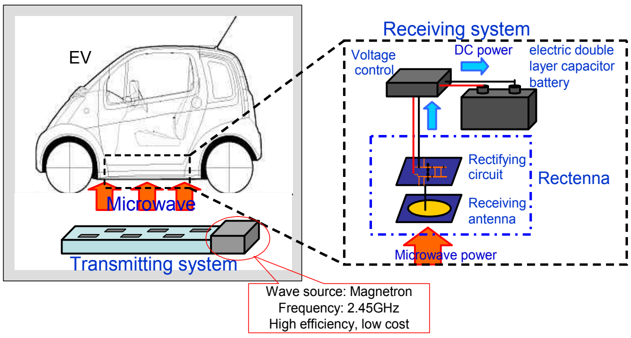
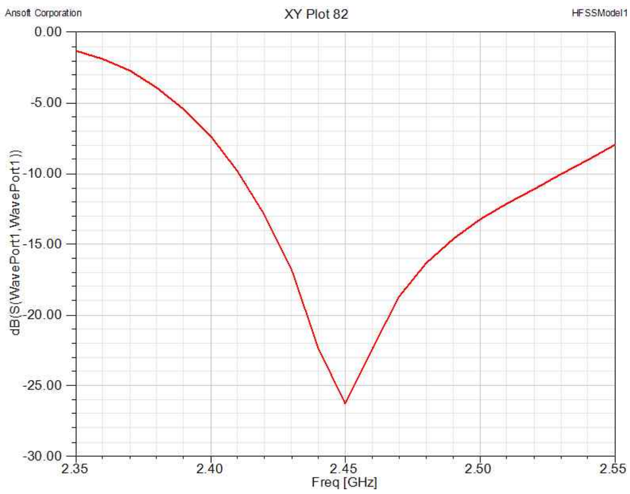
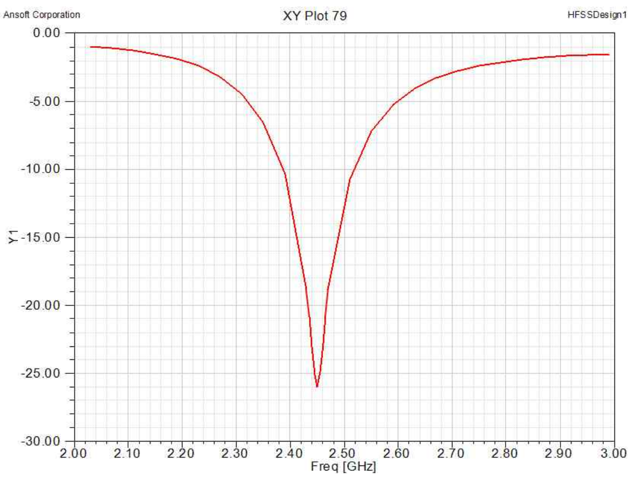


Fig. 3. Proposed wireless charging system for EV from road.



(a) S_{11} of a slot antenna as a transmitting antenna



(b) S_{11} of a CMSA as a receiving antenna

Fig. 4. Simulation results of antennas.

We find that reasons of poor BE are 1) change of impedance caused by mutual coupling between transmitting antennas and receiving antennas, (2) oblique direction of microwave power to receiving antennas caused by short distance. The experimental results do not agree with the theoretical value because the shape of the antenna for the experiments is 1 dimensional array. The theory described in section 2 is applied for aperture antennas. However, we would like to point out that both reasons we found are not considered in the theory described in section 2.

Mutual coupling between transmitting antennas and receiving antennas occurs in short distance. Fig. 4(a), (b) indicate simulation results of S_{11} of a slot antenna as a transmitting antenna and a CMSA as a receiving antenna, respectively. The S_{11} are calculated in free space by HFSS, FEM simulator. Designed frequency is 2.45 GHz. They are enough to transmit or to receive 2.45 GHz microwave power. On contrary, the wireless power charging system is used in short distance. There are receiving antennas in front of transmitting antennas as shown in Fig. 5. Distance between the transmitting antennas and the receiving antennas is only 9 cm, $<\lambda$. The simulation results of S_{11} and S_{22} in short distance are shown in Fig. 6. Four slot antennas and four CMSA are used. Resonant frequencies move from 2.45 GHz and radiation/absorption efficiency decreases.

We redesign the transmitting/receiving antennas in short distance in order to increase BE as shown in Fig. 7.

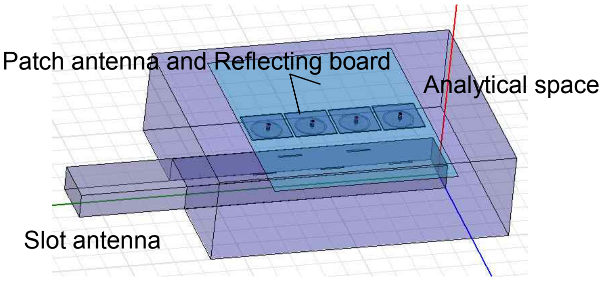


Fig. 5. Antenna positioning in HFSS simulation.

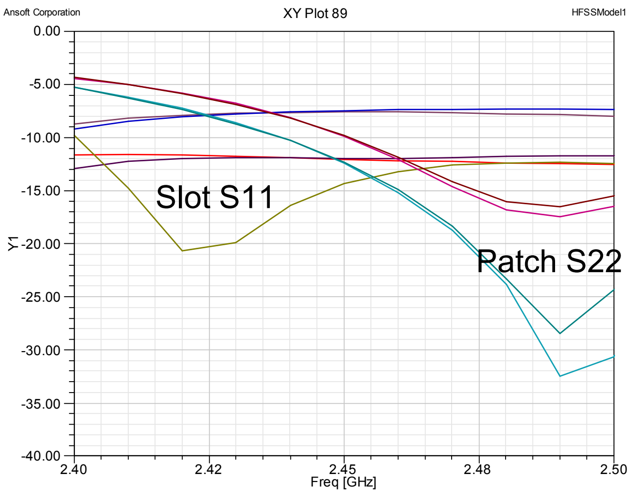


Fig. 6. Simulation results of S_{11} and S_{22} in short distance, whose antennas are designed in free space.

As a result, resonant frequencies are fixed in 2.45 GHz. The BE increases to 53.7 % in this simulation parameters shown in Fig. 5. If we do not adjust the impedance of antennas, periodicity of the BE occurs as shown in Fig. 8 [12].

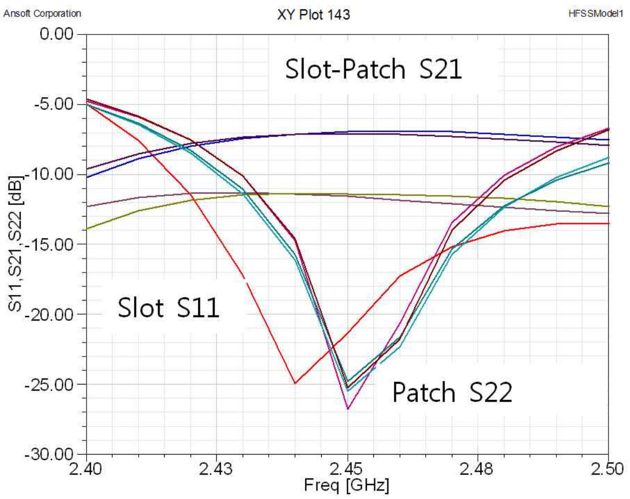


Fig. 7. Simulation results of S_{11} and S_{22} in short distance, whose antennas are designed in short distance.

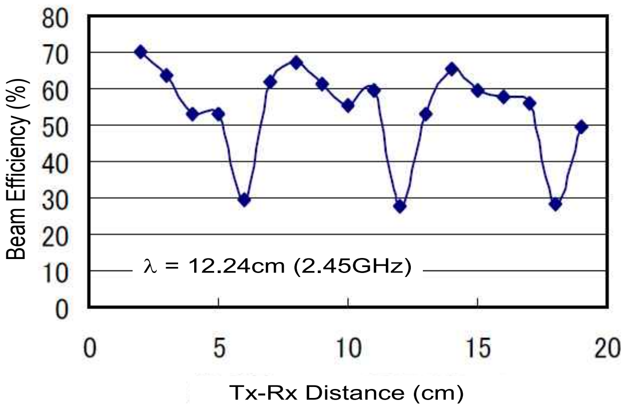


Fig. 8. Change of beam efficiency against distance (FDTD simulation).

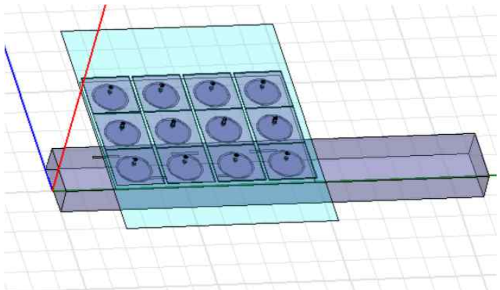


Fig. 9. Antenna positioning in HFSS simulation to increase the BE.

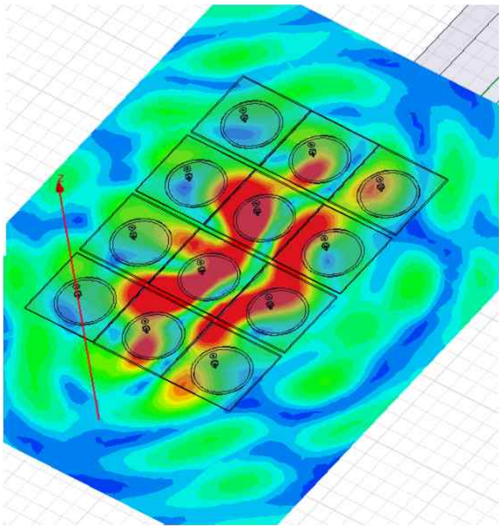
Depending on the theory of τ parameter, it is possible to increase the BE by increasing antenna aperture compared with that shown in Fig. 5. However, we could not increase the BE only with larger antenna aperture. The BE is only 58.9 % with 12 receiving antennas shown in Fig. 9. It is because microwave power flows in oblique direction from the transmitting slot antenna and it is not enough gain and antenna aperture of the receiving CMSA, which are put on the side, against oblique direction (Fig. 10). Front gain of the CMSA is 9.1 dBi, however, gain of 30° is only 4.8 dBi.

Therefore, we replace the receiving antennas on bent in order to increase the BE as shown in Fig. 11. As a result, the BE is 83.7 % and it is enough to transmit the wireless power.

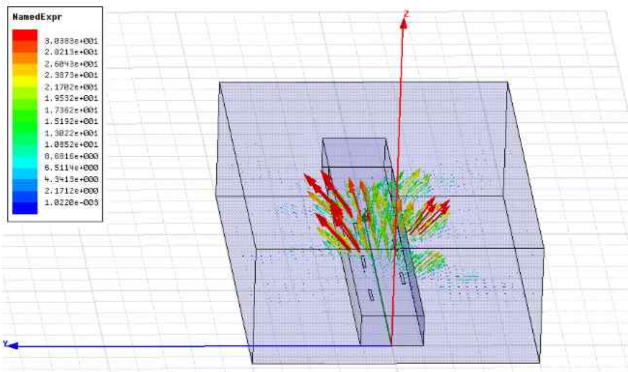
We also carried out an experiment to measure the BE as shown in Fig. 12. The 12 antennas could receive 76.0 % of the transmitted microwave power.

Ⅳ. Long Range WPT
- Space Solar Power Satellite/Station -

In section Ⅲ, we showed the BE formulated by the equation (3) is different from the theory in short range



(a) Density of electric field below 3cm from receiving antennas calculated by HFSS



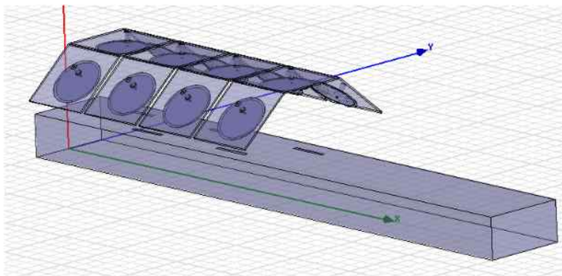
(b) Poynting vector of slot antenna radiation

Fig. 10. Power density and Poynting vector of slot antenna radiation.

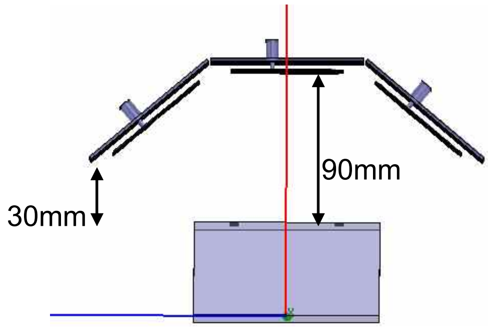
because of (1) a mutual coupling of the transmitting and the receiving antennas and (2) of direction of Poynting vector from the transmitting antennas. If distance between the transmitting and receiving antennas is far enough, the equation (3) is effective.

W. C. Brown carried out the WPT via 2.45 GHz microwave in laboratory in 1975. The BE was 95 % with a horn antenna as a transmitting antenna and rectennas, rectifying antennas, with dipole antennas as a receiving antennas (Fig. 13) [10, 13]. Total DC-microwave-DC conversion efficiency was 54 % which included DC-microwave conversion efficiency of 68.9 % and microwave-DC conversion efficiency of 82.4 %. The distance between the horn antenna and the rectennas were far enough (Fig. 13).

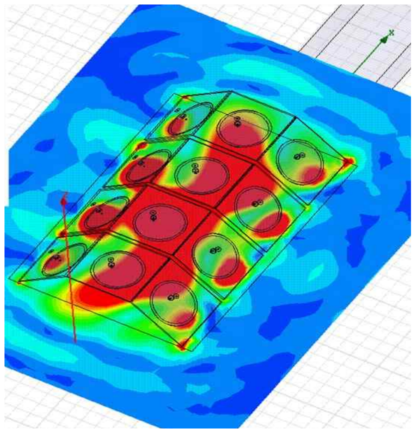
In Kyoto University, we carried out same laboratory experiment with 2.45 GHz to measure the BE with a horn antenna [14]. The distance was 50 cm. The horn antenna had a length of 1m and an aperture of 24.8×34.8 cm.



(a) Bent receiving antenna



(b) Simulation parameters



(c) Electric field

Fig. 11. Revised WPT system.

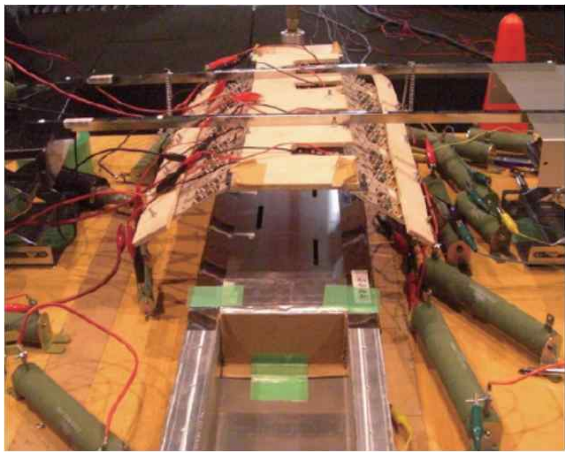


Fig. 12. Experimental set up with bent receiving antennas.

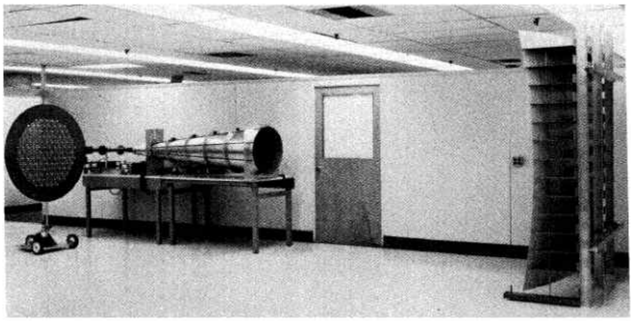


Fig. 13. WPT Laboratory experiment by W. C. Brown [13].

The diameter of the rectenna was approximately 1 m. We achieved the BE of 93.6 % in the experiment.

Ultimate and optimum application of the WPT via microwaves is a Space Solar Power Satellite/Station (SPS). The SPS is a huge power station of approximately 1GW in geostationary orbit above 36,000 km (Fig. 14). The generated electric power is transmitted via microwave to ground. The SPS is a hopeful power station in near future whose power is CO_2 free and stable through night and day even if it rains on ground. Technological hurdle of the SPS is its size. The size of the transmitting antenna should be over 1 km with 2.45 GHz or 5.8 GHz in order to increase the BE. Parameter τ of the SPS designed by NASA/DOE in 1980 [15] is 3.56 and the BE is approximately 95 % in 36,000 km power transmission. 36,000 km against 1 km transmitting antenna is still near field with 2.45 GHz or 5.8 GHz.

We have a long history of research and development of the SPS in Japan [16]. Based on the R&D projects in Japan, 'Basic plan for space policy' was established by Strategic Headquarters for Space Policy in June 2009. This Basic Plan for Space Policy forged this time is based on the Basic Space Law established in May 2008 and is Japan's first basic policy relating to space activities. In the plan, the SPS was selected as one of the major nine systems and programs for the use and R&D of space as follows;

"As a program that corresponds to the following major social needs and goals for the next 10 years, a Space Solar Power Program will be targeted for the promotion of the 5-year development and utilization plan." and "Government will conduct ample studies, then start technology demonstration project in orbit utilizing "Kibo" or small sized satellites within the next 3 years to confirm the influence in the atmosphere and system check" [17, 18].

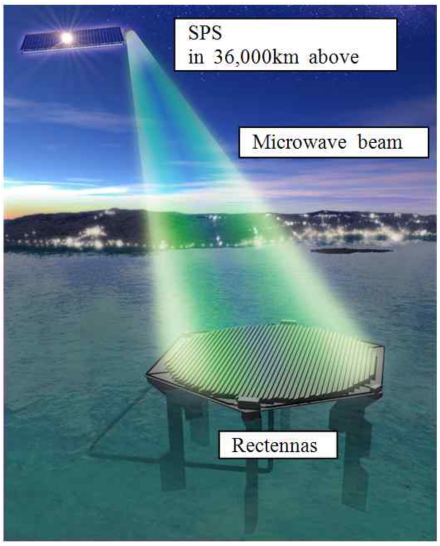


Fig. 14. Concept of SPS with WPT via microwaves.

Ⅴ. Conclusion

The WPT via radio waves, especially microwaves, is misunderstood as low efficiency system. As I showed in this paper, the WPT via microwave is highlt efficient system when we choose optimum τ shown in the equation (3). It can be applied for short range to long range. However, we should consider in short range system (1) change of impedance caused by mutual coupling between transmitting antennas and receiving antennas, (2) oblique direction of microwave power to receiving antennas caused by short distance. Including the effects, we can realize highly efficient WPT system from short range to long range, even if the distance between transmitting antennas and receiving antennas is 36,000 km.

For future works, we have not estimated amount of the mutual coupling yet. It is important to estimate amount of the mutual coupling to consider the physics of the short range WPT. The higher modes may exist in such a short distance. It is also important to consider the higher modes and additional matching. We have only re-designed the T/R antennas to get resonant at 2.45 GHz. It is our next research topic.

The work of the section Ⅲ is collaborative study with Kyoto University and UD Tracks, Inc. and is done by Mr. Masayuki Koizumi who was a student of Kyoto University.

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