# Wireless Power Transfer via Electric Coupling

*Mitsuru Masuda*[*1], *Masahiro Kusunoki*[*1], *Daiki Obara*[*1], *Yujiro Nakayama*[*1], *Hiroki Hamada*[*1], *Shoichi Negami*[*1], *Kei Kaizuka*[*2]

**ABSTRACT** This paper describes our research on wireless power transfer via electric coupling with planar electrodes and coils. Major researches of wireless power transfer using electric field are restricted to an area of almost no gap power transfer by the breakdown voltage of air. However, we have achieved long distance and high efficiency power transfer; the power transfer distance is 200 mm and the efficiency is over 90%. Moreover, we succeeded 300 W power transfer experiment. We discovered that the wireless power transfer using electric field has an advantage of that misalignment characteristic of one direction is better than using magnetic field and that it can make power transfer distance longer with repeaters.

## 1. INTRODUCTION

Wireless power transfer technologies are greatly attractive and paid special attention. The reason is because mid-range wireless power transfer named as magnetic resonance was presented by MIT in 2007[1), 2)]. This phenomenon also holds in the electric field[3)]. However, the wireless power transfer using the electric field remained in the study for supplying the electric power in close range because of the limitation of the dielectric breakdown strength of air and the concern about the influence of an electromagnetic wave since human body is constituted of the dielectric materials.

The long distance power transfer can be achieved by a resonance circuit that had a large magnitude Q-value with the main energy of electric field and the frequency 13.56 MHz and 27.12 MHz of Industrial, Scientific and Medical Band (ISM band). However, in case that the electromagnetic radiation increases by the electrode shape, the energies of induction and electrostatic field which carry power by resonance phenomenon cannot be utilized effectively. For that reason, long distance wireless power transfer using electric field has not been much reported.

We indicate, with electromagnetic field simulation, that the electromagnetic radiation level can be lowered with an LC series resonance circuit and a high efficient power transfer is possible by electric resonance coupling and have achieved high a wireless power transfer performance.

[*1] Automotive System & Device Laboratories, Research & Development Division
[*2] Industrial Cable & Power Cable accessories Div. Energy Backcast Group

## 2. THE STUDY OF THE WIRELESS POWER TRANSFER USING THE ELECTRIC RESONANCE COUPLING

### 2.1 The Wireless Power Transfer Using the Magnetic Field and the Electric Field

When we consider the space for transferring the energy wirelessly, there are 2 methods. One is such as the sound wave which transfers energy through material and the other is the transferring energy through fields. The field can be divided into an electric field and a magnetic field.

When we classify the wireless power transfer to think physical system, we can list up (1) Use an electric field. (2) Use a magnetic field. (3) Use an electric field and a magnetic field. (Electromagnetic waves, light) (4) Use a sound wave and etc.

In these systems, (3) the energy transfer using the electric field and the magnetic field has been studied for long time as per Nikola Tesla's experiment that was performed in the early 20th century shows. Recently the study such as Solar Power Satellite (Space Solar Power Systems) is also on-going.

Meanwhile, in recent years, the wireless power transfer using the magnetic field is being applied to a broad range of applications such as portable cell phone based on Qi standard for the electromagnetic induction system and, such as Radio Frequency Identification (RFID) which is a wireless power transfer system that many people use it without being aware.

The study of the wireless power transfer using electric field coupling is continuing in some research organizations.

### 2.2 About the Wireless Power Transfer Using the Electric Field Coupling Resonance

The wireless power transfer using the electric field is limited by the dielectric breakdown voltage in the air[4]. On the other hand, the wireless power transfer using the magnetic field is being considered that a large energy of power transfer can be done because there is no phenomenon corresponding to discharge. It has been thought that the maximum transmissible power using magnetic field is nine orders of magnitude greater than that of the electric field. Further, it is being considered that the wireless power transfer using the electric field has a disadvantage because the capacitance is reduced when the distance between the transmitter and the receiver increases. However, from the viewpoint of Electro-magnetic Compatibility (EMC), there is an advantage to be difficult to affect other apparatuses in the electric field, which attenuated in proportion to the cube of the separation distance.

Therefore, we conducted a comparative study of the electric field type and the magnetic field type. Figure 1 shows the block diagram of the magnetic field resonance coupling scheme and Figure 2 shows the block diagram of the electric field resonance coupling.

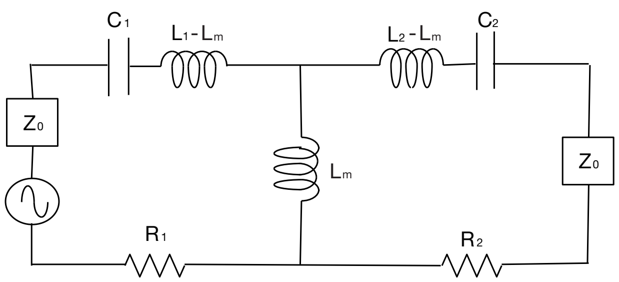


**Figure 1 Magnetic resonance type block diagram.**

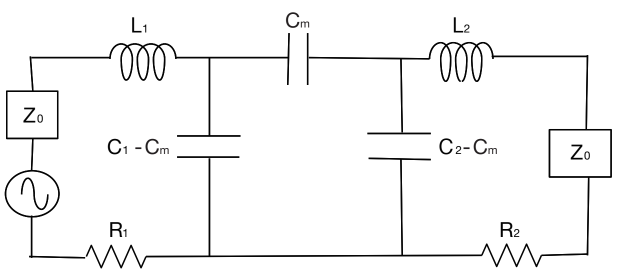


**Figure 2 Electric coupling type block diagram.**

In Figure 1, $L_1$ is the inductance of the transmitter coil, $L_2$ is the inductance of the receiver coil and $C_1$ and $C_2$ are the resonance capacitors of the power transmitter and the receiver. $R_1$ and $R_2$ are the AC resistances between the transmitter and the receiver. $L_m$ is the coupling inductance of the magnetic resonance coupling.

In Figure 2, $C_1$ is the capacitance of the transmitter and $C_2$ is the capacitance of the receiver. $C_m$ is the coupling capacitance of the electric resonance coupling. As the angular frequency is $\omega$, in the magnetic field resonance coupling, the ratio between $\omega(L_1\text{-}L_m)$ and $\omega \times L_m$ is output and in the electric resonance coupling, the ratio between $\omega \times L_1$ and $1/\omega(C_1\text{-}C_m)$ is output. In other words, we thought that if the difference between $C_1$ and $C_m$ is small, the power transfer can be done efficiently even in case of the electric field.

The series resonance type power transfer system can be configured if $L_1$ and $L_2$ of external coils are connected to the plate electrodes of dimensions 118 mm×250 mm. For example, when $L_1$ and $L_2$ are equal to 5 $\mu$H, $C_1$ and $C_2$ are equal to 7 pF. $C_m$ is equal to 0.8 pF. The power transfer efficiency was calculated by SPICE system circuit simulator. These numbers were calculated based on the measured data. As shown in Figure 3 and 4, it was found that the transfer efficiency of more than 85% can be achieved in this configuration.

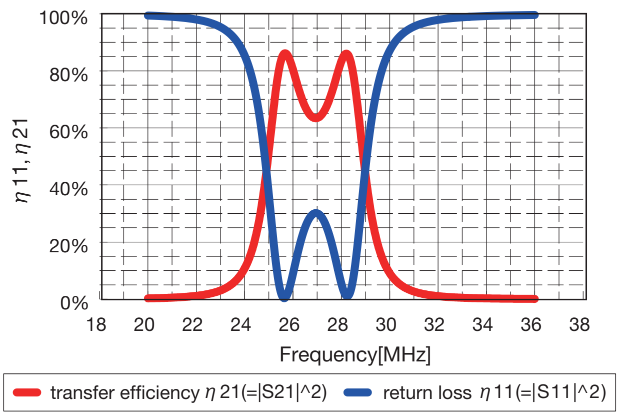


**Figure 3 Power transfer at distance 120 mm.**

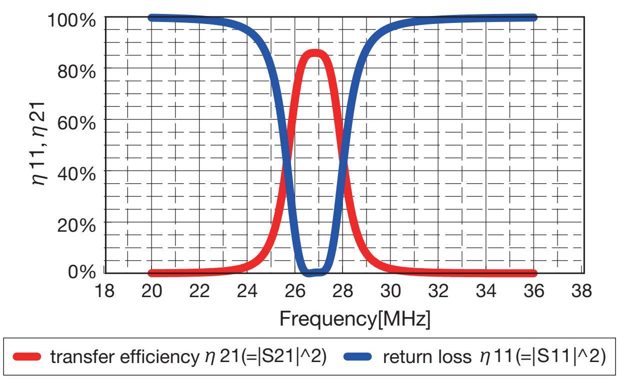


**Figure 4 Power transfer at distance 170 mm.**

### 2.3 The Structure Study Of The Wireless Power Transfer Coupler

The wireless power transfer system of the meander line type using electric field has been studied[3]. But in this method, the line length is increased at the wavelength of 27.12 MHz and 13.56 MHz and it is considered that loss in this part may occur. In order to reduce this loss, we examined the wireless power transfer coupler with a simplified structure shown in Figure 5 using a series resonance coil and a plate electrode. The parameters of the coupler section were designed to be the value that was used in the circuit of the simulator. The examined power transfer coupler is a thin and light configuration and also can be easily fabricated because it has a simple configuration. The dielectric electrodes are sandwiched by plastic resins, so that the coupler can be utilized even if it is folded. The coupler is shown in Figure 6.

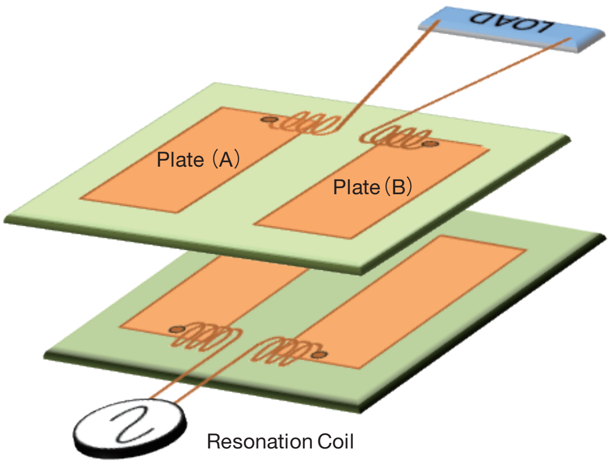


**Figure 5 The electric coupling power system.**

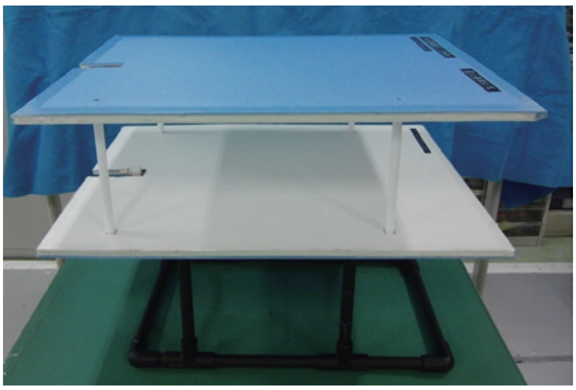

**Figure 6 Electric coupler.**

Then we confirmed the behavior of the examined wireless power transfer coupler with the electromagnetic field simulator, FEKO of FARAD. This simulator can do a kind of finite element analysis based on moment method. This simulator can simulate the state that the dielectric constant of the dielectric material and the permeability of the magnetic material that are entered. The result of the simulation is shown in Figure 7.

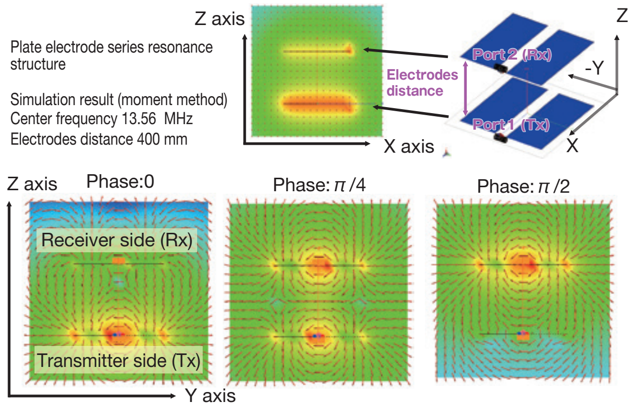


**Figure 7 The result of the computer simulation.**

From Figure 7, it can be shown that the energy transfer can be achieved between the transmitter and the receiver.

Then the change of efficiency of the energy transfer due to the misalignment was compared between the magnetic resonance coupling method and the electric resonance coupling method. The result of the simulation is shown in Figure 8. As shown in Figure 8, the electric field type has the advantage that misalignment characteristic of one direction is better than using magnetic field.

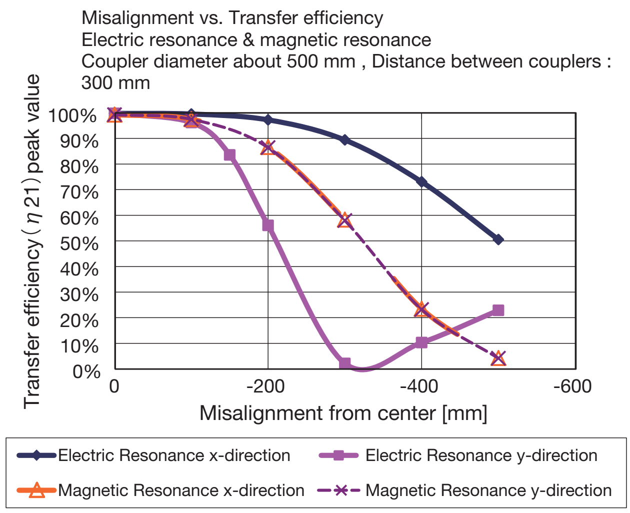


**Figure 8 The power transfer efficiency vs. the misalignment of coupler.**

## 3. THE PROTOTYPE OF THE POWER TRANSFER SYSTEM

### 3.1 The Power Transfer Efficiency Between Couplers

Based on the results obtained from the electromagnetic field simulation, we have developed a wireless power transfer coupler.

The electrode size of the coupler is 110 mm×480 mm and these 2 electrodes are placed on the FR4 substrate at the intervals of 35 mm. Further, the inductance of the coil is adjusted to resonate at 27.12 MHz and 13.56 MHz and the two coils are connected in series. The structures of the transmitter side and the receiver side are same. The Input impedance of the coupler is set to match with 50 Ω.

The power transfer efficiency was measured by varying the distance between the transmitter and the receiver of this coupler. A network analyzer is used for the measurement and the power transfer efficiency was calculated from S21. The measurement results are shown in Figure 9. The power transfer efficiency of 90% was achieved at the distance of 200 mm.

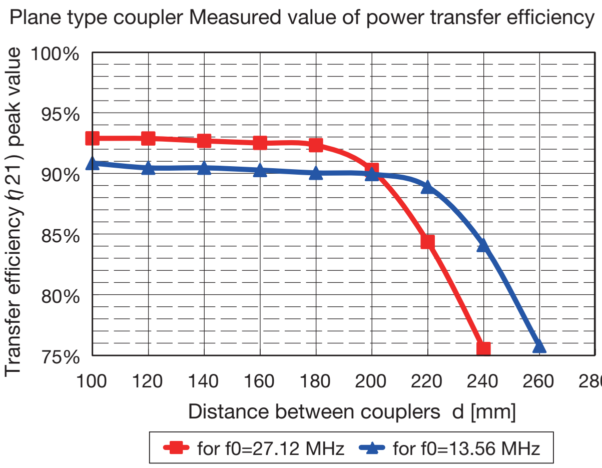


**Figure 9 The power transfer efficiency vs. distance between couplers.**

### 3.2 RF Inverter Circuit

High frequency power supply for driving the coupler operates the lateral Si MOSFET in a half-bridge configuration. As a feature of the Si MOSFET in this frequency band, it is necessary to devise a circuit to drive the gate because the input capacitance is very large about 1400 pF. In the prototype circuit, a primary amplification of a signal of the oscillation circuit is performed by class E amplifier and the signal drives a lateral Si MOSFET by a voltage-current conversion. In addition, the output impedance of this devise is 2.4-j6.8 Ω so it is converted to 50 Ω by using a transformer.

For driving the device much know-how is pooled and it is an area where the power circuit technology and the high frequency circuit technology are combined. And it is expensive, but when using the drive module with built-in gate driver circuit, the configuration can be further simplified.

The circuit generates the high-frequency power with high efficiency by using a soft-switching technology. However, a problem of the soft-switching technology is that, when changing the power supply, the voltage applied between the drain and the source of the FET must be changed. So the power supply unit is equipped with a variable voltage. The output impedance is 50 Ω to match the coupler. The RF inverter block diagram is shown in Figure 10.

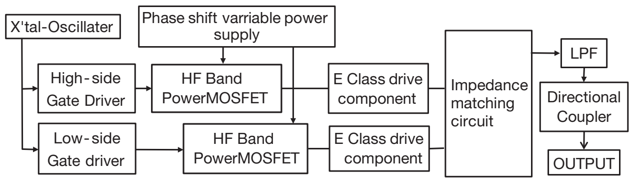


**Figure 10 RF inverter block diagram.**

GaN HFET device has a smaller input capacity in comparison to the Si MOSFET because the input stage has a Schottky structure. So in the present circumstance, the loss for the circuit which drives the Si MOSFET can be reduced. We expect that high power device such as a GaN HFET will emerge in future.

### 3.3 Matching Equipment

A matching circuit was provided between the RF inverter output and the power transmitter coupler and between the receiver coupler and the rectifier circuit. This is to prevent the characteristic change by the reflection and the damage of the circuit because of a large reflected wave that returns to the RF inverter. Figure 11 shows a block diagram of an L type circuit by the coil and the variable capacitance device.

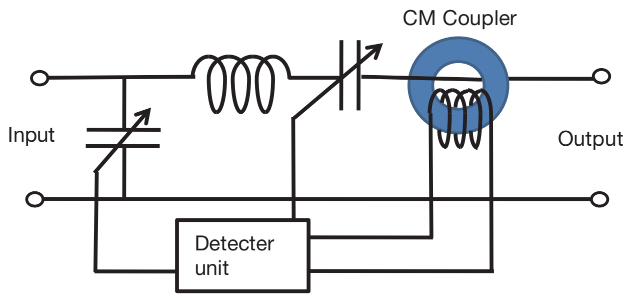


**Figure 11 The Impedance matching network circuit.**

### 3.4 Rectifying Section

The power that is required for the power electronics is communicated to the chopper circuit which is a control circuit after converting the commercial frequency of 50/60 Hz into direct current. In the wireless power transfer, the circuit for converting the power of a carrier wave (27.12 MHz and 13.56 MHz) HF band into the direct current is required. In this case because the power which has largely different frequency must be rectified, the impedance matching becomes an important issue.

As an example, if the wireless power transfer is done by applying a power of 300 W to the 50 Ω power transfer line, the voltage is 122 V and the current is 2.45 A by Ohm's law. Because a reflection wave occurs when the rectifier circuit is connected to the power transfer line that has different impedance, the matching circuit must be connected. Meanwhile, when the input impedance of the half-wave rectifier circuit that combines a capacitor and a diode is measured, it was Z=1.9-j14.5 Ω in the frequency of 13.56 MHz. Assuming that there is no loss of the rectifier circuit and the matching circuit when 300 W is applied as before, the voltage developed across the capacitors and the current flowing through the diode become 66.2 V and 4.53 A each. This means that it became very low impedance by the rectifier circuit.

When the rectifying is done by the device of PN junction diode, the loss will occur by the characteristic called the reverse recovery time. This effect will be remarkable in the frequency of 13.56 MHz and 27.12 MHz. Because of this fact, Schottky Barrier Diode (SBD) without PN junction is used. However, because the SBD mainly composed of silicon has the low withstand voltage of 200 V in maximum, the diode using SiC or GaN is effective. In particular, when considering the power transfer of kW orders, high breakdown voltage characteristic may be required for elements as voltage level after rectification is high. So the benefits of using GaN and SiC are great. In future, easy availability for these devices is expected.

## 4. THE CHARASTERISTICS OF POWER TRANSFER SYSTEM

### 4.1 Power Transfer Amount

The power transfer amount was measured using the developed system shown Figure 12. The experiment was done in an anechoic chamber. The power transfer amount of 300 W was achieved at the electrode distance of 200 mm.

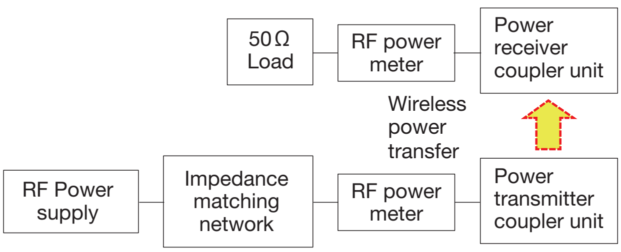


**Figure 12 The measurement system block diagram.**

### 4.2 EMC Noise

The conductive noise from the RF power supply is evaluated using the current measurement system shown in Figure 13. As a current pseudo-power supply networks, KNF-244 F manufactured by Kyoritsu Electronics Industry is used. The measured results are shown in Figure 14. The results show that the system meets the criteria of the CISPR11[5)] standards for such electromagnetic interference of high frequency devices.

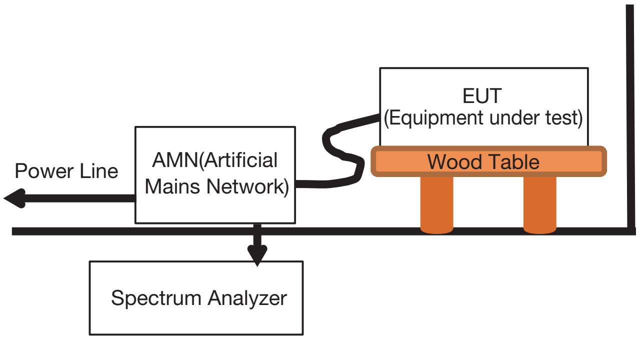


**Figure 13 The measurement system block diagram of CISPR11.**

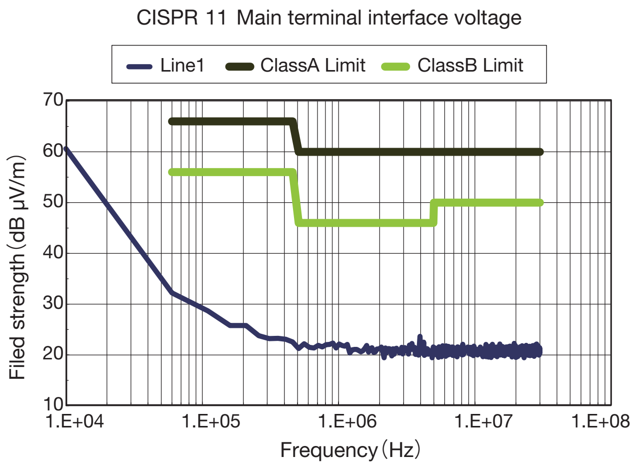


**Figure 14 The feeding conduction power noise vs. frequency.**

Next, the EMC noise was measured using the measurement system shown in Figure 15. The results are shown in Figure 16.

It can be seen that the radial noise level is fluctuating depending on the direction of the coupler.

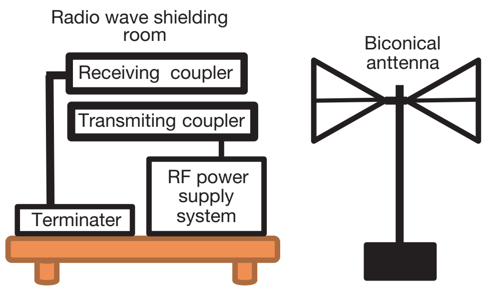


**Figure 15 The measurement system block diagram of CISPR22[6)].**

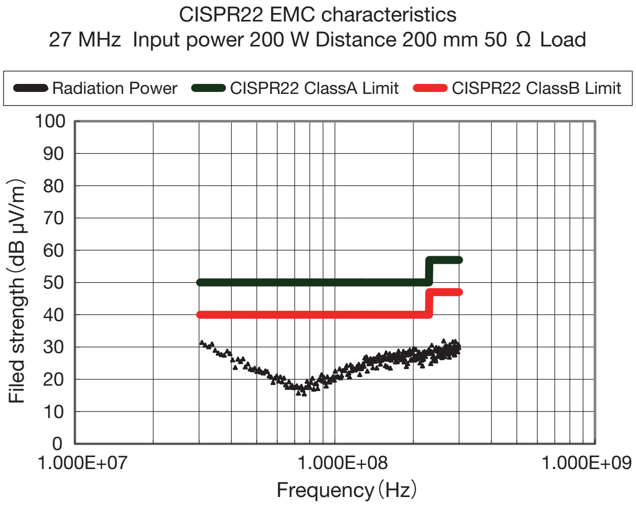


**Figure 16 The feeding EMC power vs. frequency.**

## 5. CONCLUSION

It is demonstrated that by using the electric field resonance coupling, the thin and light wireless power transfer system can be designed.

Furthermore, by measuring its efficiency by prototype system, it was shown that the efficiency of the power transfer at the distance of 200 mm between the transmitter and the receiver is more than 90%. Also, 300 W power transfer experiment was successful. In the future, we are planning to perform a study of the wireless power transfer system that can transfer larger power between the transmitter and receiver.

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