Experimental Verification of Rectifiers with SiC/GaN for Wireless Power Transfer Using a Magnetic Resonance Coupling

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***Abstract*-This paper demonstrates that SiC and GaN diode rectifiers are used in a magnetic resonant coupling (MRC) for wireless power transfer system. The size of the resonance coils, which are used in the wireless power transfer using a MRC, depends on the transmission frequency. So, the MRC is desired to operate at a high frequency in the Industry Science Medical (ISM) band such as 13.56 MHz. In the receiving side, a rectifier which converts to the DC voltage from high frequency AC voltage is necessary to supply the power to the applications such as a battery charger for EV and home appliances. The experimental results show the maximum efficiency from a Radio Frequency (RF) power supply to DC outputs is 75.2% when the transmission distance is 150 mm. In addition, A power loss separation method of the wireless power transfer system is discussed in this paper. The experimental results verify the reflected power of the resonance coil which dominates the largest amount of the loss in the total loss. Therefore, the suppression of the reflected power is important for the wireless power transfer system using a MRC.**

I. INTRODUCTION

In recent years, the wireless power transfer systems are increasingly studied [1-5]. Especially, the wireless power transfer using a magnetic resonant coupling (MRC) which is reported in 2007 has been attracted in community [6-10]. The MRC has some advantages compared to others wireless power transfer methods such as the electromagnetic induction and microwave power transmission. First, the MRC enables a wireless power transfer at middle range distance such as 1 m in high efficiency of over 90%. Second, the decline in efficiency caused by position gap is smaller. Thus, the MRC is suitable to apply in the battery chargers for electric vehicle (EV). The transmitting device and the receiving device are placed at the ground of the parking areas, and back side of the EV respectively. The batteries of the EV are charged automatically when the EV is parked to the parking areas which have wireless power transfer system.

In the MRC system, the wire length of the resonance coil decreases commensurately with increasing transmission frequency. The resonance coils must be mounted on the EV. Thus, the resonance coils are desired to design with small size and light weight. The wireless power transfer using a MRC respects the standard of Industry Science Medical (ISM) band of 13.56 MHz. It is important that the power converter can operate in high frequency with high efficiency.

Generally, the output side of the power transmission system using a MRC requires DC voltage to supply the power to the applications such as a battery charger. However, it is difficult to obtain DC voltage from high frequency input voltage such as tens of Megahertz because the fast speed diodes are needed.

On the other hand, wide band gap semiconductors are increasingly studied to obtain the high speed switching and high power density of a converter [11][12]. A Silicon Carbide (SiC) and a Gallium Nitride (GaN) offer performance to improve over Silicon (Si) for the power semiconductors. The feature of the switching speeds, the wide band gap semiconductors are suitable for wireless power transfer system using the MRC.

The experimental verification of the rectifier using the SiC diodes has been demonstrated in [13]. However, the behaviors of the transmission characteristics and power loss of the wireless power transfer system is not demonstrated well when the rectifier is connected to the MRC system. This paper discusses the output side converter of the MRC power transfer system. The wide band gap semiconductors, such as the SiC and GaN, are tested to use in the rectifier. In addition, the power loss separation method is proposed in this paper in order to clarify the power loss of the transfer part and the rectifiers.

II. SYSTEM CONFIGURATION

A. Wireless power transfer Part

Fig. 1 illustrates the system configuration of a wireless power transfer using a MRC. The system consists of a function generator (FG), a radio frequency (RF) power supply matched to 50 Ω, two resonance coils and a load. Signals from the FG are amplified by a Radio Frequency (RF) power supply. The RF power supply which can control the output travelling power is composed of the A-class linear amplifier in the test bench. The amplified power is supplied to the resonance coils. The resonance coils are designed according to the specification in Table 1. The resonance coils which placed in the transmitting side, is called as transmitting coil. Also the resonance coil, which place in the receiving side, is called as receiving coil. Additionally, the resonance coils have a same structure of the helical antenna. Thus, the resonance coils have a feeding point at the center of the resonance coil. In addition, the resonance coils have a self-resonance frequency f_0 due to distributed capacitance C of winding pitch and winding inductance L. The self-resonance frequency is obtain0ed by

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad \text{.. (1).}$$

Fig. 2 shows the equivalent circuit of the wireless power transfer using the MRC [14]. The equivalent circuit of the one-sided resonance coil is presented as a series connected LCR circuit. So, the one-sided resonance coil works as a non-radiate antenna. The MRC have a similar equivalent circuit to the magnetic induction. However, the MRC has same capacitances in the primary side and secondary side. The frequency characteristics of the transmitting efficiency have a diphasic with a high quality factor Q due to inductive coupling k between the transmitting side and receiving side.

Equation (2) presents the transmitting efficiency, where $S_{21}(\omega)$ is the transmission coefficient which is obtained by (3) [15], L_m is the mutual inductance, R is the simulated resistance of the radiation loss and copper loss, Z_0 is the characteristic impedance of the transmission line, and ω is the transmission angular frequency.

$$\eta(\omega) = \left|S_{21}(\omega)\right|^2 \times 100 \quad \text{... (2)}$$

$$S_{21}(\omega) = \frac{2jL_m Z_0 \omega}{L_m^2\omega^2 - \left\{R + \left(\omega L - \frac{1}{\omega C}\right)\right\}^2 + 2jZ_0\left\{R + \left(\omega L - \frac{1}{\omega C}\right)\right\} + Z_0^2}$$

$$\text{... (3)}$$

The transmission coefficient is proportion of the transmission power to travelling power. By substituting the resonance angular frequencies ω_m and ω_e into the equation, (4) is obtained.

$$S_{21}(\omega_m) = \frac{2}{2 - j\frac{1}{kQ}}\ ,\ S_{21}(\omega_e) = \frac{2}{2 + j\frac{1}{kQ}} \quad \text{.......................... (4)}$$

where the ω_m and ω_e are the resonance frequencies between the transmission coils, the transmission coefficient S_{21} has maximum value. Note that the ω_e is larger than ω_m. An electromagnetic field distribution between the transmitting coil and the receiving coil for the wireless power transfer is difference in terms of the resonance frequency of ω_e and ω_m. Equation (4) indicates that the product of inductive coupling k and quality factor Q affect to the transmission efficiency. The inductive coupling k decreases with increasing transmission distance. However, the $k{\cdot}Q$ still remains high because of high quality factor Q. Generally, the magnetic induction is operated with low quality factor Q, therefore the magnetic induction cannot delivers the power in the middle range transmission distance at high efficiency.

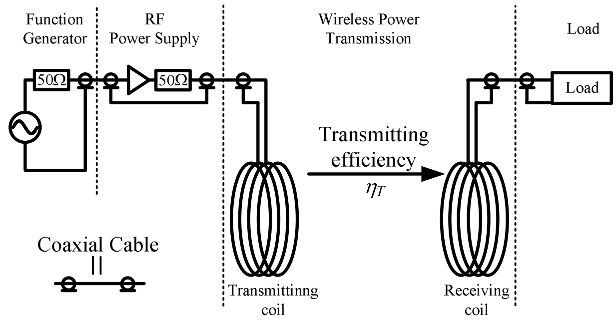
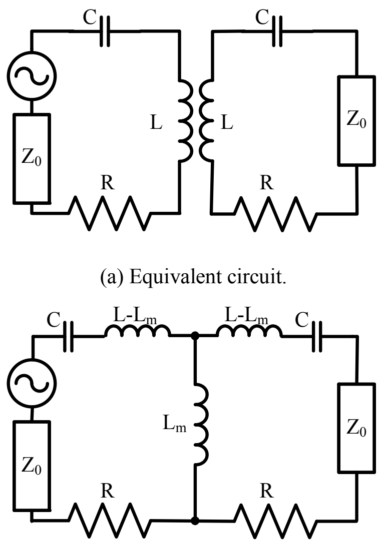


Fig. 1. System configuration of a wireless power transfer. The FG and RF power supply is matched to 50 Ω. The Transmitting and Receiving coil is designed according Table 1. The load includes the rectifier illustrated in Fig. 3.

Table 1. Specifications of resonance coils in the wireless power transfer part. The resonance coils is helical antenna which has feeding point in the center of coil.

Number of turn	6 [turn]
Material	Magnet wire φ2.3[mm]
Radius	20 [cm]
Vertical Height	9.9 [cm]



(b) Equivalent circuit of type-T.

Fig. 2. Equivalent circuit of the wireless power transfer using a MRC. The equivalent circuit of the one-sided resonance coil is presented as series connected LCR circuit. The primary side and secondary side are coupled due to inductive coupling.

B. Rectifier

Fig. 3 illustrates a diode rectifier using the SiC or GaN or Si. The diode bridge rectifier is employed. The ratings of the power devices which have voltage rating of 600 V and the current rating of several amperes are shown in Table 2.

Note that the schottky barrier diode (SBD) is chosen for SiC, and the fast recovery diode (FRD) is chosen for Si. The rectifier is mounted on the printed circuit board (PCB) in terms of the high frequency operation. The rectifiers have an input terminal of a coaxial connector. So, the rectifier is connected using a coaxial cable which has characteristics impedance of 50 Ω to operate in high frequency region such as 13.56 MHz. In addition, the laminated ceramic capacitor of 0.46 μF is used as a smoothing capacitor in purpose of improvement of high frequency characteristics.

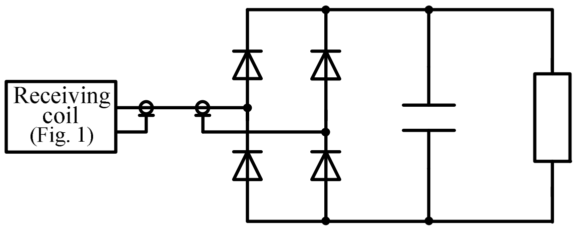


Fig. 3. The diode bridge rectifier. The input terminal is connected to the receiving coil in Fig. 1 using a coaxial cable and coaxial connector. Additionally, all components are placed on the printed circuit board. The SiC or GaN or Si diode is used as power devices. The laminated ceramic capacitor is used as a smoothing capacitor to improve the high frequency characteristics.

Table 2. Ratings of the diodes in Fig. 3.

Diode	Rated Voltage [V]	Rated Current[A]
SiC-SBD	600	4
GaN diode		6
Si-FRD		3

III. FUNDAMENTAL CHARACTERISTICS OF THE REFLECTED POWER

Fig. 4 presents the experimental circuit which clarifies the relationship between the travelling power and the reflected power. In Fig. 4, P_F is the travelling power, P_R is the reflected power and P_{Load} is the transmitted power which equals to the consumed power at the load resistance. The resistance load is connected to RF power supply directly through the coaxial cable which has characteristic impedance of 50 Ω. In the high frequency region, the reflected power occurs in boundary point of the impedance when the impedance is mismatched.

Fig. 5 shows the characteristics of the reflected power and transmitted power when the travelling power is 100 W in the circuit drawn in Fig. 4. The reflected and transmitted powers depend on the load resistance when the characteristic impedance has a constant value. The consumed power is decreased with increasing reflected power due to impedance mismatching. The theoretical formulas of the reflected power and transmitted power are obtained by (5) and (6) respectively.

$$P_{Load}^* = P_F\left(1-\Gamma^2\right) \quad (5)$$

$$P_R^* = P_F\Gamma^2 \quad (6)$$

where Γ is the reflection coefficient which is expressed by;

$$\Gamma = \frac{Z_0 - Z_{Load}}{Z_0 + Z_{Load}} \quad (7)$$

The reflection coefficient is decided by using the characteristic impedance of the transmission line Z_0 and impedance of the load Z_{Load}. The reflection coefficient Γ indicates the proportion of the reflection voltage to travelling voltage. On the other hand, the reflection coefficient Γ follows the proportion of the reflection current to travelling current. Therefore, the ratio of the travelling power to reflected power is squared reflection coefficient Γ^2. Additionally, the transmitted power is obtained by subtracting reflected power from travelling power. If the characteristic impedance of the transmission line equals to impedance of the load, reflection coefficient is zero. Therefore, the reflected power does not occur. From basic experimental result, it is clarified that the reflected power which is not consumed at the load has to be suppressed.

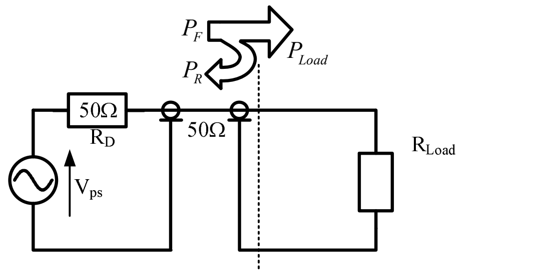


Fig. 4. The experimental circuit which clarifies the relationship among a travelling, a reflected and transmitted power. The reflected power occurs at the boundary point of the impedance.

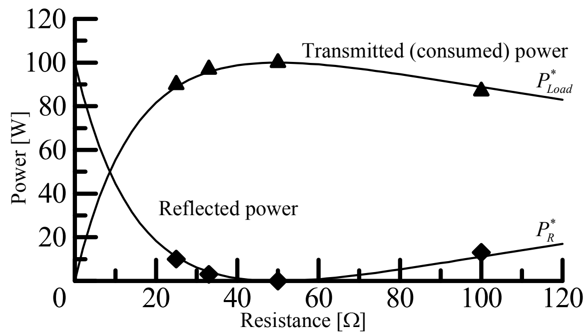


Fig. 5. Characteristics of the reflected and transmitted power. Note that the travelling power is 100 W. The proportion of the reflected power and transmitted power which is equals to consumed power of the load resistance depends on the load resistance when the characteristic impedance has constant value.

IV. POWER LOSS SEPARATION METHOD

In this section, the power loss separation method is proposed. In the wireless power transfer system, the power loss occurs in the transfer part and the rectifier part. The power loss of the transfer part should be separated from loss of the rectifier part to clarify the characteristics of the MRC system. However, it is difficult to measure the power loss in the high frequency system because of the effects of the measuring instruments such as a probe. In addition, high frequency system has the reflected power. The proposed power loss separation method estimates the each efficiency from the travelling power and reflected power which is observed in the RF power supply and output power of the rectifier. If the power losses of the coaxial cables are assumed to be neglected, the MRC system has four elements which cause the power loss; that is the reflected power from coils, the reflected power from rectifier, the transmission and rectifier losses.

Fig. 6 shows a principle of the loss separation method of the MRC system. Note that although the figure of the wireless power transfer in Fig. 6 is simplified to the transformer, the structure of the wireless power transfer is the same to the Fig. 1. The relationship between the travelling power and the transmitted power is expressed by (5). Additionally, the relationship between the travelling power and the reflected power is also expressed by (6). The reflected power and the transmitting power occur at each boundary point of the impedance; in front side of the resonance coils and in front side of the rectifier. If it is assumed that the power which is reflected twice at the boundary points of the impedance, is small enough to neglect, the relationships among the travelling power and reflected power are observed in the RF power supply side and output power of the rectifier which are expressed by;

$$\begin{cases} P_F\left(1-\Gamma_c^2\right)\eta_T\left(1-\Gamma_r^2\right)\eta_{rec} = P_{out} \\ P_F\left(1-\Gamma_c^2\right)\eta_T^2\Gamma_r^2 + P_F\Gamma_c^2 = P_R \end{cases} \quad \text{.............................} (8)$$

where P_{out} is the output power of the rectifier, P_F is the travelling power observed in the RF power supply side using a power meter for high frequency region with directional coupler, P_R is the reflected power observed in the power supply side, Γ_c is the reflection coefficient of the resonance coils, Γ_r is the reflection coefficient of the rectifier, η_T is the transmission efficiency, and η_{rec} is the conversion efficiency of the rectifier. The reflection coefficient of the rectifier and conversion efficiency of the rectifier can be measured easily if the rectifier is connected to the RF power supply directly in the condition which has same output voltage of the rectifier. Note that the conversion efficiency is measured when the output voltage of the rectifier has the same value for the wireless power transfer part is connected. The reflected powers occur at the boundary point of the impedance. The reflected power can be assumed as a power loss because the reflected power is not fed to the load. So, the proportion of the transmitted power to the travelling power (1-Γ_c^2) can be considered to the efficiency at the input point of the resonance coils. On the other hand, the proportion of the transmitted power to the travelling power (1-Γ_r^2) can be considered to the efficiency at the input of the rectifier. It is found that the efficiencies of the rectifier and transfer part are obtained to solve the simultaneous equation in terms of Γ_c and η_T. The transmission efficiency is obtained by

$$\eta_T = \frac{P_{out}}{P_F\left(1-\Gamma_c^2\right)\left(1-\Gamma_r^2\right)\eta_{rec}} \quad \text{..............................} (9).$$

where the reflection coefficient Γ_c is presented by;

$$\Gamma_c = \frac{P_F + P_R \pm \sqrt{\left(P_F + P_R\right)^2 - 4\left\{P_F P_R - \dfrac{P_{out}^2\alpha_r}{\left(1-\alpha_r\right)^2\eta_{rec}^2}\right\}}}{2P_F}$$

$$\text{..} (10)$$

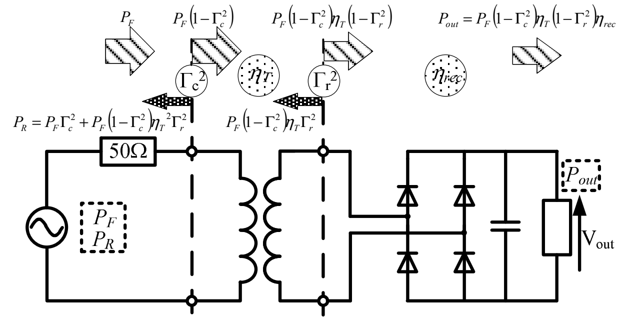


Fig. 6. Relationship of the power for each part. The reflected power occurs at a boundary point of the impedance. So, the reflected power increases with increasing the square of reflection coefficient.

V. EXPERIMENTAL VERIFICATIONS

A. Operation Waveforms

Fig. 7 indicates the operation waveforms of the rectifiers, which uses the SiC, GaN and Si diode when the power supply frequency is 11.18 MHz and transmission distance is 150 mm. Note that, the resonance frequency does not matched to ISM band of 13.56 MHz in these experiments due to the relationship between design of coils and the transmission distance. In addition, the vertical axis is different among the SiC, GaN and, Si. The resonance frequency depends on the transmission distance. The DC voltage with the low voltage ripple is obtained when the SiC and GaN diode are used as shown in (a) and (b) in Fig. 7. However, the DC voltage has large voltage ripples when the Si diode is used as shown in (c). The transmitting coil voltage includes a large component of second harmonics from the transmission frequency due to standing wave. Generally, the standing wave becomes power loss in the transmission line. So, the standing wave should be suppressed, because the standing wave radiates the electromagnetic wave from transmission line. The total efficiency η_{total} which includes the reflection loss, transmission loss and conversion loss; of the wireless power transfer system which consists of SiC, GaN and Si diodes are 75.2%, 69.2%, 5.2% respectively. The experimental results verified that the power device which has wide band gap semiconductor, the SiC and GaN, are more suitable for the wireless power transfer system.

B. Total Efficiency characteristics

Fig. 8 shows a relationship between the load resistance R_{Load} and total efficiency η_{total} of the wireless power transfer system. The total efficiency is a product of each components of the power loss; the ratio of the transmitted power to travelling power (1-Γ_c^2), the ratio of the transmitted power to travelling power (1-Γ_r^2), transmission efficiency η_T and conversion efficiency of the rectifier η_{rec}. Therefore, the total efficiency is expressed by

$$\eta_{total} = \left(1-\Gamma_c^2\right)\left(1-\Gamma_r^2\right)\eta_T\eta_{rec} \quad \text{..............................} (11).$$

The total efficiency using the SiC diode in the rectifier is higher than using the GaN at total range of the load resistance.

C. Power Loss Separation

Fig. 9 shows the stacked bar chart which indicates the loss separation results of the wireless power transfer system including the diode rectifier using the SiC and GaN diodes. The SiC and GaN follow the similar characteristics. In the region of the high load resistance, the conversion loss of the rectifier using the SiC or GaN decrease with increasing load resistance. The voltage drops of the diodes are decided in each material. Therefore, the conduction loss of the diodes decreases because the input current is reduced when the input travelling power has configured with constant. On the other hand, the sum of the reflection loss of the resonance coils and reflection loss of the rectifier is lowest value at the load resistance of 50 Ω. Since the characteristic impedance of the power supply and the coaxial cable is matched in 50 Ω, the characteristic of the sum of the reflection loss seems to be caused by the impedance matching. The loss of the reflected power dominates a partial amount of the power loss in a wireless power transmission system. The reflection loss can be suppressed by a matching circuit. In the theoretical consideration, the reflection loss can be suppressed to zero. So, the total loss can offer the improvement of the total efficiency from 75.2% to 92.2% when the load resistance of 100 Ω and the switching devices are SiC diodes.

VI. CONCLUSION

This paper clarifies the characteristics of the rectifier which is composed by the SiC and GaN diodes in a wireless power transfer. The MRC is desired to operate in high frequency such as 13.56 MHz. So, the rectifier which converts to the DC voltage from high frequency AC voltage is needed to supply the power to the applications such as a battery charger for the EV and home applications. Therefore, the rectifier using the SiC and GaN power devices is required to obtain DC voltage at high frequency such as over 10 MHz. The experimental results confirmed the maximum efficiency from a RF power supply to DC output is 75.2% using SiC-SBD when the transmission distance is 150 mm.

In addition, the power loss separation method of the wireless power transfer system including the rectifier is proposed to clarify the power loss. The loss separation method is considered to focus attention on the reflection coefficient. The experimental result demonstrated the reflected power of the rectifier and resonance coils dominate the largest amount of the total loss. The reflected power can be suppressed the impedance matching.

In the future work, the wireless power transfer system using the MRC, which present a higher efficiency due to the suppression of reflection power, will be shown.

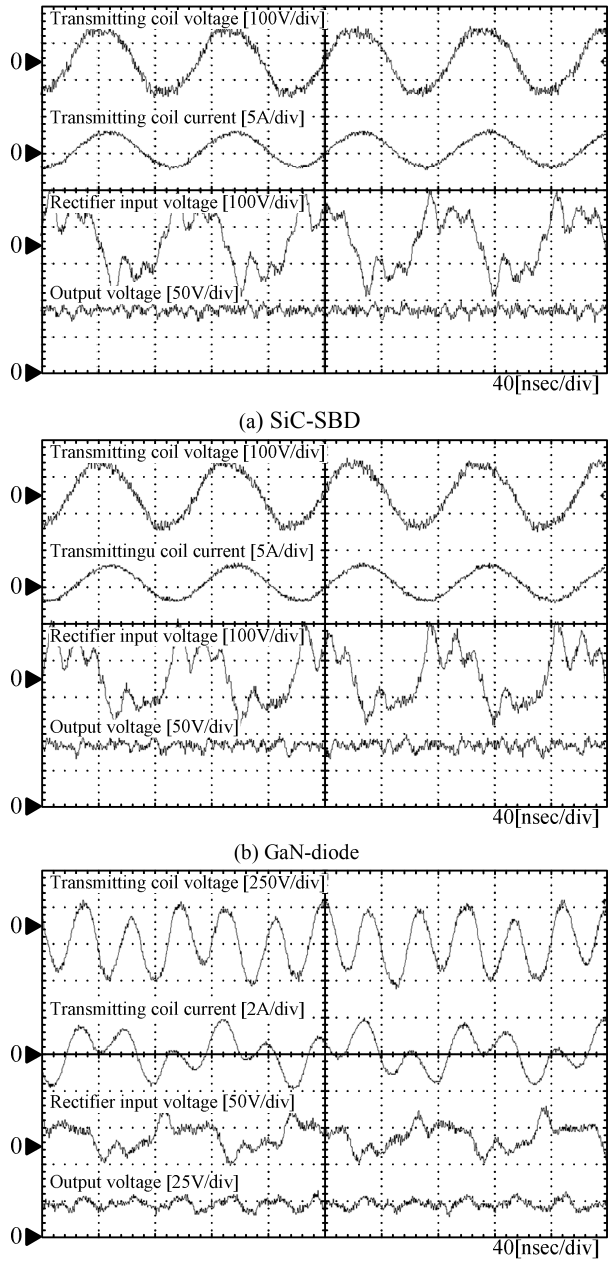


Fig. 7. Experimental waveforms when the rectifier is connected to the wireless power transfer using a MRC as a load. The travelling power at the RF power supply is 100 W and the transmission distance is 150 mm. The rectifier using the SiC and GaN diodes can be obtain the DC output voltage from high frequency AC voltage of over 10 MHz. The rectifier using the Si diodes cannot operate in the high frequency region.

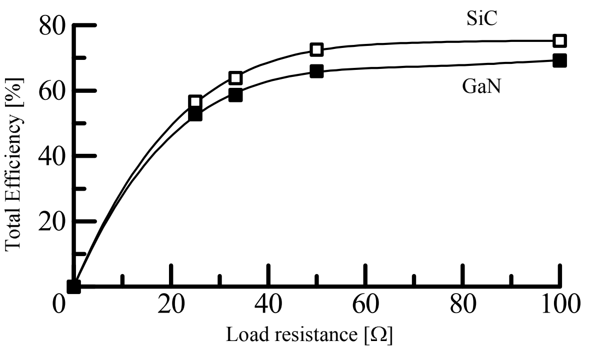
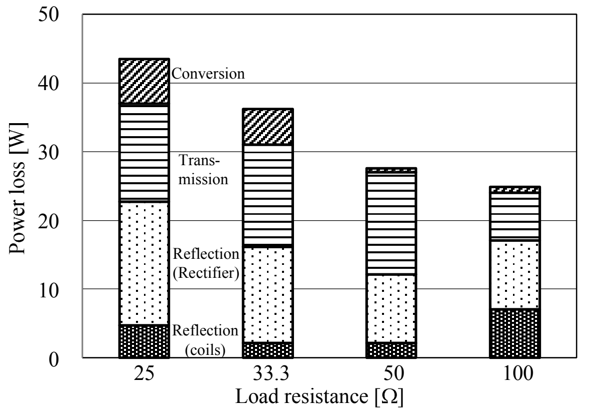
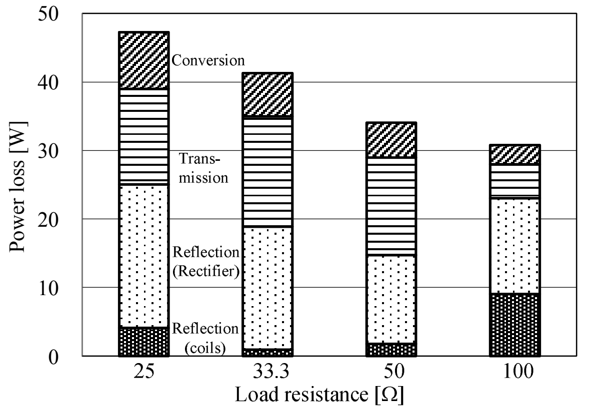


Fig. 8. The relationship between the load resistance and total efficiency when the transmission distance is 150 mm. The total efficiency includes the reflection loss, transmission loss, conversion loss of the rectifier. The maximum total efficiency η_{total} which includes the reflection loss, the transmission loss and the conversion loss of the SiC or GaN diodes rectifier are 75.2%, 69.2% respectively when the load resistance is 100 Ω.



(a) SiC diodes are used.



(b) GaN diodes are used.

Fig. 9. Loss separation results of the wireless power transmission system connected the SiC and GaN rectifier. The reflected power is suppressed using SiC compared to GaN. In addition, the conversion loss of the rectifier using GaN is larger than SiC. Therefore, Total efficiency of GaN is lower than SiC.

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