Maximizing Air Gap and Efficiency of Magnetic Resonant Coupling for Wireless Power Transfer Using Equivalent Circuit and Neumann Formula

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***Abstract*—The progress in the field of wireless power transfer in the last few years is remarkable. With recent research, transferring power across large air gaps has been achieved. Both small and large electric equipment has been proposed, e.g., wireless power transfer for small equipment (mobile phones and laptops) and for large equipment (electric vehicles). Furthermore, replacing every cord with wireless power transfer is proposed. The coupled mode theory was proposed in 2006 and proven in 2007. Magnetic and electric resonant coupling allows power to traverse large air gaps with high efficiency. This technology is closely related to electromagnetic induction and has been applied to antennas and resonators used for filters in communication technology. We have studied these phenomena and technologies using equivalent circuits,- which is a more familiar format for electrical engineers than the coupled mode theory. In this study, we analyzed the relationship between maximum efficiency air gap using equivalent circuits and the Neumann formula and propose equations for the conditions required to achieve maximum efficiency for a given air gap. The results of these equations match well with the results of electromagnetic field analysis and experiments.**

***Index Terms*—wireless power transfer, resonance frequency, maximum efficiency**

I. Introduction

Remarkable progress has been made in the field of wireless power transfer, and this technology has been attracting a lot of attention. The progress in the field of wireless power transfer in the last few years shows that traversing larger air gaps with high efficiency is more probable than with previous technologies. Many types of electronic equipment have been proposed for wireless power transfer, e.g., mobile phones [1] and laptops [2], which have secondary batteries, and lighting and TV sets that do not have secondary batteries and thus require continuous power supply. The "direct feeding" method can be used for wireless power transfer with all electrical equipment. Thus, an on-the-go rechargeable society where the wires in the house are replaced with automatic wireless power transfer can be realized. Of course, this technology can be used outside of the house too. It is possible to use wireless power transfer for charging electric bicycles and electric vehicles [3]-[10] in the parking area. Furthermore, it is proposed that electric vehicles and electric trains in motion and robots [11]-[13] can be charged wirelessly [14]-[16]. This technology does not depend on the equipment size. Therefore, any equipment that uses electricity can be fed wirelessly [17].

It is important to achieve the transfer of power over large air gaps with a high efficiency to make this kind of society possible. At present, there is no such technology. Microwave power transfer [9][10] or laser power transfer [18] can be achieved across air gaps larger than a few kilometers; however, it is still not possible to do so with high efficiency. In typical electromagnetic induction, which is a type of nonradiative power transfer, the air gap can be only a few centimeters. Recently, the air gap has been increased to around 10 cm at 20–40 kHz. However, a longer distance is required for an on-the-go rechargeable society [19]. For this purpose, wireless power transfer over 1–2 m is required. Moreover, the efficiency of electromagnetic induction drops when there is misalignment and becomes almost zero even if the misalignment is only a few centimeters. To use wireless power transfer anywhere one might want, conventional electromagnetic induction is not suitable.

Therefore, an electromagnetic resonant coupling technology is proposed. In this technology, power is transmitted wirelessly with high efficiency across large air gaps. The efficiencies are above approximately 90% within 1 m and 45%–50% within 2 m. This is called WiTricity and was proposed theoretically in 2006 and confirmed experimentally in 2007 [20][21]. It has been reported that multiple receivers can be powered wirelessly by magnetic resonant coupling [22]. This might lead us to an on-the-go society. In papers [20] and [21], the phenomenon of electromagnetic resonant coupling has been explained in great detail; however, the theory is based on the coupled mode theory, which most people are not familiar with. From an electrical engineering perspective, electric circuits are required for the design of the antenna itself and the circuit connected to the antenna. Electromagnetic resonant coupling is closely related

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to electromagnetic induction, which uses nonradiative power transfer, antennas, and resonators for filters used in communication technologies [23]–[26].

We have studied the effect of changing the parameters of antennas for magnetic resonant coupling [27] and designed equivalent circuits for both magnetic and electric resonant couplings [28]. In this paper, we derive equations for the relationship between maximum efficiency and air gap using equivalent circuits and the Neumann formula and present electromagnetic field analysis and experimental results.

II. Characteristics of Magnetic Resonant Coupling

Wireless power transfer can be achieved using magnetic resonant coupling when the transmitting and receiving antennas are in resonance and the resonance frequency of the receiving and transmitting antennas are the same. This allows transfer of power across large air gaps with high efficiency. Wireless power transfer is achieved using magnetic field couplings that are nonradiative. Therefore, the radiation produced is negligible. A helical antenna is an open-type antenna, which is self-resonant using self-inductance and capacitance, and a short-type antenna, which has separate excitation using self-inductance and an installed capacitor [29]. In this paper, the short-type antenna, which needs a capacitor, is used.

Magnetic resonant coupling uses an antenna that is in resonance and has a very high Q-value; its efficiency is easily influenced by air gaps, mutual influence, and impedance of the antenna. In this chapter, we will study the frequency and efficiency using electromagnetic field analysis for varying lengths of the air gap.

Air gap

The proposed short-type helical antennas, which are used as the model used for the electromagnetic field analysis, are shown in Fig.1. These antennas comprise of two elements, and the transmitting and receiving antenna are the same. The parameters of these antennas and the experimental setup are shown in Fig.2. A vector network analyzer (VNA) is used to measure the transmission and reflection ratio of the system. The transmission equation (1) and the relationship between transmission and efficiency of transmission, as given by equation (2), indicates the efficiency of power transfer. The equation for power reflection is defined in (3).

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

$$\eta_{21} = |S_{21}|^2 \times 100 \ [\%] \quad (2)$$

$$\eta_{11} = |S_{11}|^2 \times 100 \ [\%] \quad (3)$$

The number of turns in the antennas is one, and a capacitor is installed in series. The radius R is 150 mm, and the length of the air gap is denoted as g.

The relationship between frequency the efficiency of wireless power transfer is studied using electromagnetic field analysis by varying the length of the air gap. The method of moments is used in the electromagnetic field analysis. The distance of the air gap is varied between 49, 80, 170, and 357 mm in the efficiency vs. frequency plots shown in Fig.4. The characteristic impedance is 5 Ω. The power is output from port 1 and flows from the transmitting antenna across the air gap to the receiving antenna and enters through port 2, which is the transmitting power. The efficiency is represented by η_{21}. A portion of the power is reflected back to port 1; the ratio of reflected power is denoted as η_{11}.

When g = 49 or 80 mm (small gaps), efficient power transfer is possible at the two resonance frequencies [f_m, f_e ($f_m < f_e$)]. Most of the power that is not transferred is reflected back to port 1. Most of the power that is neither transferred nor reflected is lost in internal resistance. Thus, there is little radiation and it can be ignored. As the air gap is increased from g = 49 mm to g = 80 mm, the two resonance frequencies become almost equal. When the air gap is increased to g = 170 mm, the two resonance frequencies become equal and the efficiency at the resonance frequency is the same as that for small air gaps. The single resonance frequency is the same as the self resonance frequency of a single antenna. As the air gap further increases to g = 357 mm, the efficiency at the resonance frequency reduces.

These results are plotted in detail in Fig.5, which shows the relationship between efficiency and length of the air gap at resonance frequencies. Fig.5 also shows that, as the length of the air gap increases, the two resonance frequencies become equal at g = 170 mm with high efficiency. Then, the efficiency worsens. In this paper, the conditions in which the two resonance frequencies become equal and the efficiency changes are analyzed and discussed.

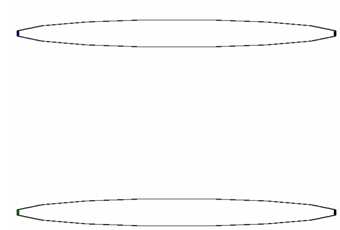


Fig.1. Model of helical antennas used for electromagnetic field analysis. (g = 170 mm)

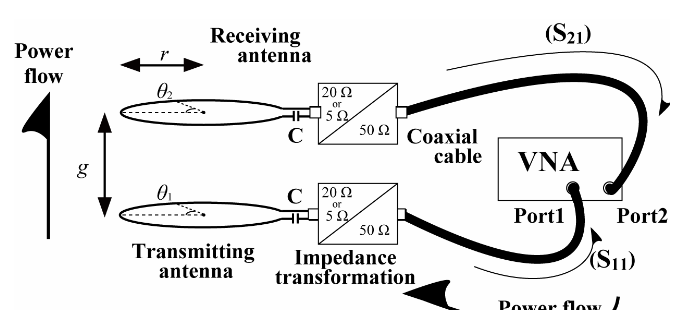


Fig.2. Parameters of helical antennas and experimental setup.

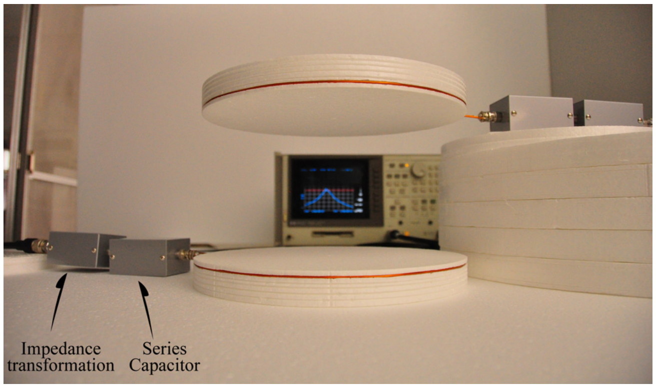
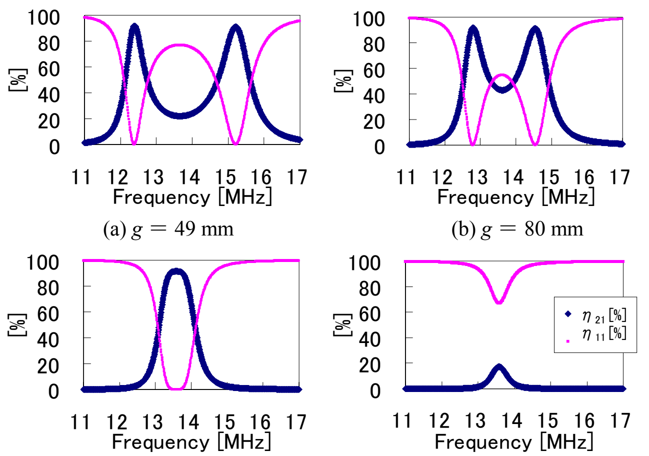


Fig.3. Photograph of experimental setup. (g = 170 mm)



(a) g = 49 mm (b) g = 80 mm

(c) g = 170 mm (d) g = 357 mm

Fig.4. Results of electromagnetic field analysis for efficiency vs. frequency at different gap lengths.

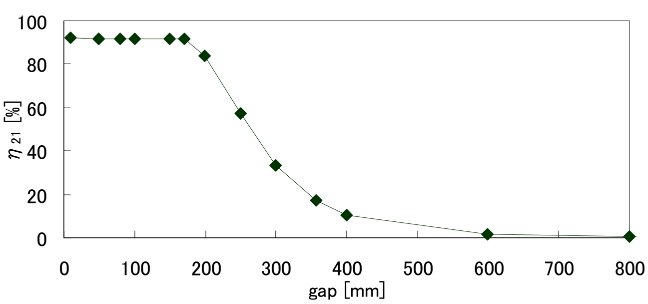


Fig.5. Results of electromagnetic field analysis for peak efficiency vs. air gap length.

III. Air Gap and Mutual Inductance Using Neumann Formula

The mutual inductance L_m of coils of one turn is given by equations (4) and (5), i.e., the Neumann formula [3][27]. D is the distance between dl_1 and dl_2. Mutual inductance becomes large as the radius of the coil and the number of turns is increased. In this paper, the number of turns is one and the radius is 150 mm.

$$L_m = \frac{\mu_0}{4\pi}\oint_{C1}\oint_{C2}\frac{dl_1 dl_2}{D} \tag{4}$$

$$L_m = \frac{\mu_0}{4\pi}\int_0^{2\pi}\int_0^{2\pi}\frac{r^2\cos(\theta_1-\theta_2)}{\sqrt{2r^2+g^2-2r^2\cos(\theta_1-\theta_2)}}d\theta_1 d\theta_2 \tag{5}$$

The coupling coefficient k is defined in equation (6); k is related to two resonance frequencies when the characteristic impedance is 0 and the internal resistance R is 0 (Fig.6).

Equation (7) shows that mutual inductance L_m is obtained from the division of self inductance L and the coupling coefficient k.

$$k = \frac{\omega_e^2-\omega_m^2}{\omega_e^2+\omega_m^2} \tag{6}$$

$$k = \frac{L_m}{L} \Leftrightarrow L_m = kL \tag{7}$$

The theoretical result, as obtained from the Neumann formula, and the electromagnetic result, as obtained from the method of moments, are shown and compared in Fig.7. The results are the same. The mutual inductance is inversely proportional to the length of the air gap.

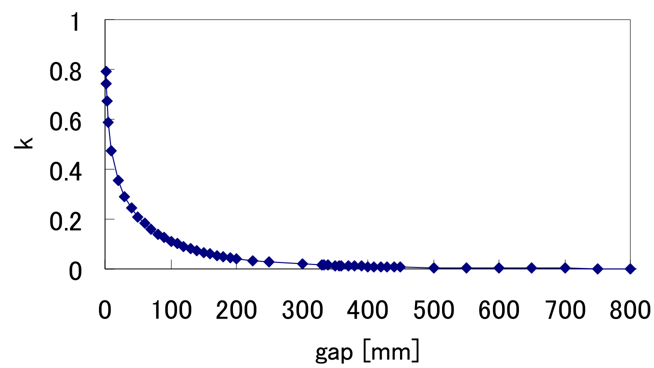


Fig.6. Coupling coefficient k vs. gap length.

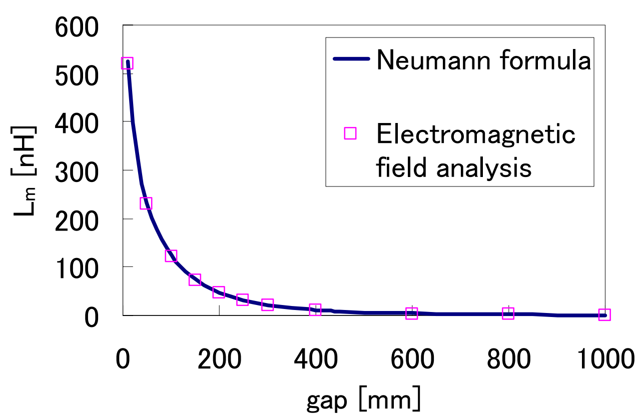
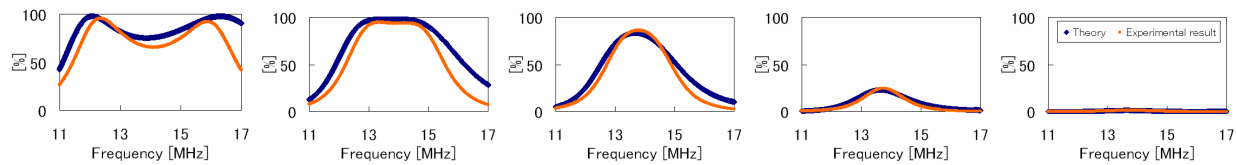


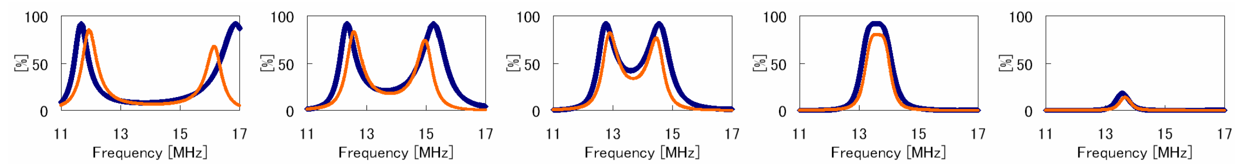
Fig.7. Optimized parameters of mutual inductance and characteristic impedance in relation to maximum efficiency for different air gap lengths.

IV. Theory of Air Gap and Maximum Efficiency

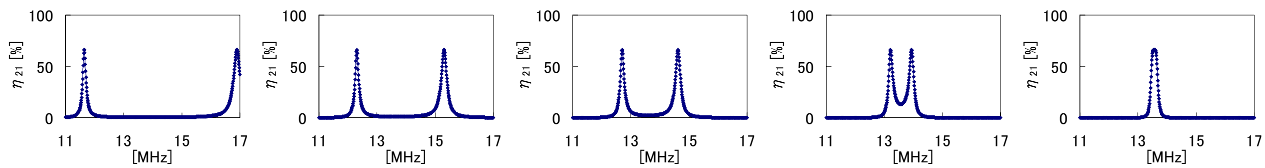
In the previous sections, we have studied magnetic resonant couplings using electromagnetic field analysis; however,



(a-1) 20 Ω, 20 mm (a-2) 20 Ω, 49 (50) mm (a-3) 20 Ω, 80 mm (a-4) 20 Ω, 170 mm (a-5) 20 Ω, 357 (360) mm



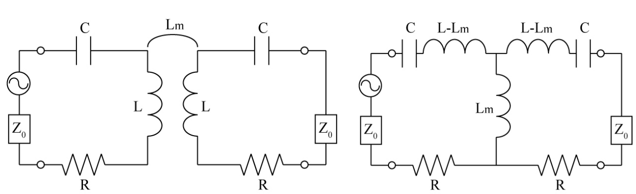
(b-1) 5 Ω, 20 mm (b-2) 5 Ω, 49 (50) mm (b-3) 5 Ω, 80 mm (b-4) 5 Ω, 170 mm (b-5) 5 Ω, 357 (360) mm



(c-1) 1 Ω, 20 mm (c-2) 1 Ω, 49 mm (c-3) 1 Ω, 80 mm (c-4) 1 Ω, 170 mm (c-5) 1 Ω, 357 mm

Fig.9. Efficiency and frequency at characteristic impedance and different air gap lengths using equivalent circuit and experimental results. The parameters are characteristic impedance [Ω] and air gap length [mm] of theoretical and experimental results. For the case when the parameters of the equivalent circuit are different from those of the experiment, the experimental parameters are added within parentheses. Bold lines denote the theoretical results, and fine lines denote results of the experiments.

magnetic resonant coupling can also be explained by the theory of equivalent circuits. Wireless power transfer using magnetic resonant coupling is achieved when the transmitting and receiving antennas are in resonance. The resonance is twofold; one resonance is self resonance, being driven by the self inductance and parasitic- and self-capacitance of the antenna, and the other is external, separated, excited resonance, being driven by the self-inductance of the antenna with the installed capacitance. Antennas can be replaced with their equivalent circuit; the antenna and the phenomenon of electromagnetic resonant coupling can be represented by the series resonance of L and C, as shown in Fig.8. In this paper, the same antennas are used for transmitting and receiving so that the parameters of L and C are the same in the equivalent circuit and the electromagnetic field analysis. The self inductance L of the antennas is 1115 nH, internal resistance R is 0.22 Ω, and installed capacitance C is 124 pF in both the equivalent circuit and the electromagnetic field analysis. In the experiment, L of the transmitting and receiving antennas is 1037 nH and 1050 nH, internal resistance R is 0.48 Ω and 0.46 Ω, and installed capacitance C is 139 pF and 138 pF, respectively.



(a) Equivalent circuits of magnetic resonant coupling of two antennas
(b) Equivalent circuit of T-type coupling.
Fig.8. Equivalent circuit of two antennas in magnetic coupling.

1. Characteristic Impedance and Air Gaps

In the previous section, only the characteristics for varying lengths of the air gap were studied; here, we also study the characteristic impedances (which are due to the circuits that are connected to the antennas) are examined. The results of efficiency vs. frequency measurements for varying air gap lengths and characteristic impedances from equivalent circuit analysis and experiment are shown in Fig.9. That is, we changed other characteristics for a given, fixed air gap length. The characteristic impedances are changed from 20 Ω to 5 Ω to 1 Ω. The length of the air gap is varied between 20 mm, 49 mm, 170 mm, and 357 mm. The results are shown in Fig.9 (a-1)–(a-5), (b-1)–(b-5), and (c-1)–(c-5). At each characteristic impedance, as the air gap length increases, the two resonance frequencies come closer together and become one resonant frequency. Until the two resonance frequencies become equal, the efficiency of the power transfer remains constant at a high level. After they have formed one resonant peak, as the air gap length increases, the efficiency of power transfer worsens. In this situation, the efficiency of the power transfer becomes higher if the characteristic impedance is higher; however, the air gap length is very small. On the other hand, the efficiency is lower at the lower characteristic impedance when the air gap length is very large. The situation in which the characteristic impedances are changed (with a fixed air gap length) is examined in Fig.9. Results for air gap lengths of 49 mm, 170 mm, and 357 mm are shown in Fig.9 (c-2), (b-2), (a-2); Fig.9 (c-4), (b-4), (a-4); and Fig.9 (c-5), (b-5), (a-5). Data when the air gap length is 170 mm (which is between g = 49 mm and 357 mm), as shown in Fig.9(c-4), (b-4), (a-4), indicate that when the characteristic impedance is low (1 Ω) the number of resonance frequencies is two and the efficiency is not maximized. At this air gap length, when the characteristic impedance is 5 Ω, the values of resonance frequency become equal and the efficiency for this air gap length is at its maximum. Furthermore, as the characteristic impedance increases to 20 Ω, the efficiency worsens at the equal resonant frequency. This indicates that, as the characteristic impedance increases, the two resonance frequencies become equal and the efficiencies at resonance are improved to their maximum for a given air gap length. After that point, as the characteristic impedance becomes even larger, the efficiency at the equal resonance frequency worsens. When the air gap length is small (g = 49 mm) it can be shown that the process of two resonance frequencies merging into one resonant frequency is possible; therefore, the efficiencies increase as the characteristic impedance increases. On the other hand, when the air gap length is large at g = 357 mm, the two resonance frequencies have already become equal. After this point the efficiency worsens as the characteristic impedance increases. The results of the experiment are almost the same as the theoretical results for the equivalent circuit. The losses at the impedance transformation section are 0.8% and 5.9% at 20 Ω and 5 Ω, respectively. Therefore, when the characteristic impedance is 5 Ω the error is larger than that at 20 Ω.

The details of the relation of the efficiencies of the two resonance frequencies vs. air gap lengths (Fig.9) are shown in Fig.10. Not only the results using equivalent circuits but also the results using electromagnetic field analysis are shown in Fig.10 to verify the accuracy of the results from the equivalent circuit. The lines are the results of the equivalent circuit and the dots are the results of the electromagnetic field analysis. These data show good agreement between the two analyses. The efficiency of the resonance frequencies is constant when the air gap length increases and when the resonance frequencies become equal, which is confirmed in Fig.9. The efficiency drop is also shown in Fig.10. The efficiency is high and air gap length is small when characteristic impedance is high. On the other hand, the efficiency is low and air gap length is large when the characteristic impedance is low (Fig.10).

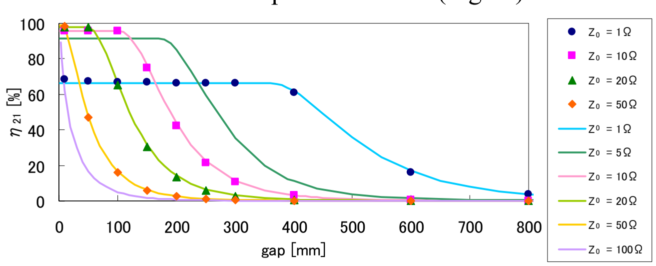


Fig.10. Peak efficiency for each gap length related to characteristic impedance. Dots denote the results of electromagnetic field analysis, and lines denote the theoretical results based on equivalent circuits.

2. *Theory of air gap and maximum efficiency*

The maximum efficiencies that are achieved at each air gap length and the characteristic impedance when the two resonance frequencies become equal have been discussed above. Based on these results, the conditions for maximum efficiency are discussed. The resonance frequency, where the two resonance frequencies become equal is the same as the resonant frequency of one element, is defined in (8). Equation (9) is the efficiency at resonance of ω_0, which is defined by equations (1) and (8). The maximum value in equation (8) is the maximum of one resonant frequency, which is described by the equation for the maximum efficiency. The conditions of the equation of maximum efficiency at a given resonant frequency are defined by equation (12), which is derived from equations (10) and (11). Equation (12) is defined by only 4 parameters, L_m, Z_0, R, and ω_0, which define the conditions for maximum efficiency. Condition equation (13) has two resonance frequencies and equation (14) is the condition equation when there is one resonance frequency with worse efficiency. The discussed equation for the maximum efficiency is defined in equation (15) or (16) from equations (9) and (12). Equations (15) and (16) are essentially the same. Equation (15) is defined by the relation of R and Z_0. Equation (16) is defined by the relation of Z_0, R, ω_0 and L_m; L_m is related to the air gap length. Equation (16) expresses the relationship between air gap lengths and maximum efficiency.

$$\omega = \frac{1}{\sqrt{LC}} \Leftrightarrow \omega L - \frac{1}{\omega C} = 0 \tag{8}$$

$$S_{21}(\omega_0) = \frac{2jL_m Z_0 \omega_0}{L_m^2\omega_0^2 + (Z_0 + R)^2} \tag{9}$$

$$\frac{\partial |S_{21}(Z_0)|}{\partial Z_0} = \frac{2L_m\omega_0 \left(R^2 + L_m^2\omega_0^2 - Z_0^2\right)}{\left(Z_0^2 + 2RZ_0 + R^2 + L_m^2\omega_0^2\right)^2} \tag{10}$$

$$\frac{\partial |S_{21}(\omega_0)|}{\partial \omega_0} = 0 \tag{11}$$

$$L_m^2 = \frac{Z_0^2 - R^2}{\omega_0^2} \tag{12}$$

$$L_m^2 > \frac{Z_0^2 - R^2}{\omega_0^2} \tag{13}$$

$$L_m^2 < \frac{Z_0^2 - R^2}{\omega_0^2} \tag{14}$$

$$\eta_{21}(\omega_0) = \frac{Z_0 - R}{Z_0 + R} \tag{15}$$

$$\eta_{21}(\omega_0) = \frac{(Z_0 - R)^2}{L_m^2\omega_0^2} = \frac{L_m^2\omega_0^2}{(Z_0 + R)^2} \tag{16}$$

The main plots of efficiency vs. air gap length in the case of characteristic impedances at 1 Ω, 5 Ω, and 20 Ω in Fig.10 are plotted again in Fig.11. The dots in Fig.11 are the maximum air gap lengths for maximum efficiencies at each characteristic impedance. The dots shown in Fig.11 are also shown in Fig.12. The line is the theoretical result and the dots are the experimental result. This curve shows the maximum efficiency of each air gap length in magnetic resonant coupling. This condition is defined by equation (12) and the parameters are when internal resistance R is 0.22 Ω and the resonance frequency is 13.56 MHz. Therefore, L_m and Z_0 vs. air gap lengths are shown in Fig.13 from equations (12) and (16). The coupling coefficient k is shown in Fig.6 and the maximum efficiency is shown in Fig.12. High efficiency wireless power transfer is possible when the mutual inductance is small and the coupling coefficient k is below 0.1 because of the large air gap lengths that are indicated in Fig.6 and Fig.12.

Also, the internal resistance R in (12), that is the condition equation for maximum efficiency, was examined. In the case in which R doubles and triples (starting from 0.22 Ω), the results for maximum efficiency at each air gap length are shown in Fig.14. As is expected, the efficiency and the air gap length worsen as R increases. These results show that the loss from internal resistance should be minimized.

The resonance frequency ω_0 is examined in equation (12) which is the condition equation for maximum efficiency. The resonance frequency ω_0 can be varied by changing L and C, which are connected to the antenna. The air gap lengths become large as the resonant frequency increases; the air gap length reduces as the resonance frequency decreases.

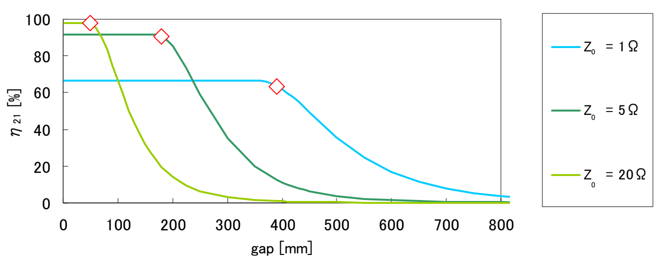


Fig.11. Peak efficiency at each gap length related to characteristic impedance. Dots are the boundary conditions at maximum efficiency.

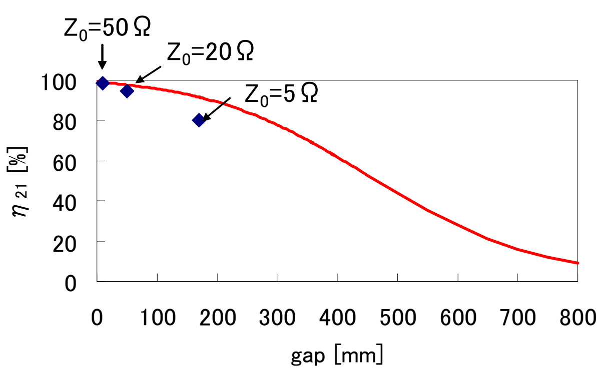


Fig.12. Maximum efficiency vs. air gap length.
The line is the theoretical result, and the dots are the results of experiments.

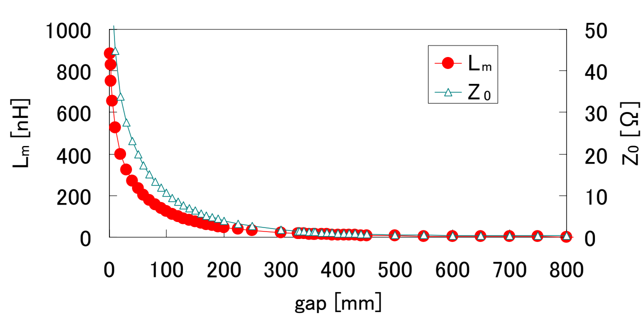


Fig.13. Optimized parameters of mutual inductance and characteristic impedance with maximum efficiency at each air gap length.

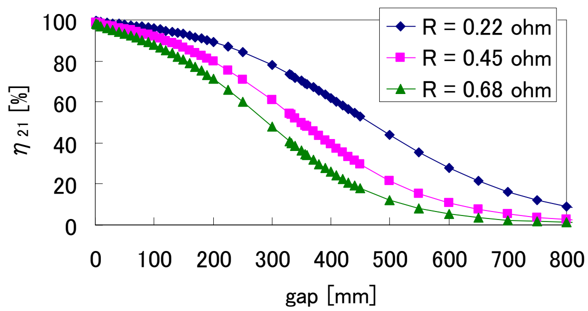


Fig.14. Maximum efficiency vs. air gap length for internal resistances.

V. Conclusion

The equations for the relationship between maximum efficiency and air gap length in magnetic resonant coupling are proposed using the Neumann formula and the equivalent circuit method.

Using the Neumann formula, the air gap length was confirmed to be related to the radius and number of turns of the coils. Maximum efficiencies are achieved at various air gap lengths via four parameters: mutual inductance L_m, characteristic impedance Z_0, internal resistance R, and resonance frequency ω_0. The maximum efficiency at each air gap length is achieved by setting the optimized characteristic impedances in each case.

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