Equivalent Circuit of Repeater Antenna for Wireless Power Transfer via Magnetic Resonant Coupling Considering Cross Coupling

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This year is being called the "first year of electric vehicles," and electric vehicles have come on the market in earnest. This trend is expected to continue and even accelerate with the diffusion of electric vehicles. However, manually charging the battery for electric vehicles is a tedious process. Therefore, an automatic, wireless charging system for electric vehicle is greatly desired. There are some types of wireless power transfer systems. In particular, electromagnetic resonant coupling is a promising technology for wireless power transfer because power can be transferred over a large air gap; this method is more practical and efficient than the conventional methods. This technology has been proposed recently, and detailed study on the repeater antenna is yet to begin. The air gap can be extended by placing a repeater antenna between the transmitting antenna and receiving antenna when it is possible to use only the transmitting antenna and receiving antenna because this method is limited by the length of the air gap. This technology offers an easy way to extend the air gap by placing a repeater antenna and expand the feeding zone for electric vehicles at a car park. In future, this method can be used to feed moving electric vehicles on highways by arranging repeater antennas along the road. Until now, repeater antennas have been studied by performing an electromagnetic field analysis; however, the analysis does not include a theoretical study of the equivalent circuit. In this paper, a model of the equivalent circuit for repeater antennas with and without cross coupling is proposed.

Keywords：repeater antenna, wireless power transfer, electric vehicle, magnetic resonance

1 Introduction

This year has been called the "first year of electric vehicles," and electric vehicles have come on the market in earnest. This trend is expected to continue and even accelerate with the diffusion of electric vehicles. The research and development of electric vehicles itself has been smooth. On the other hand, the upgrading of technologies for electric vehicles has been delayed. In particular, charging systems for electric vehicles have not been studied extensively and the upgrading of rapid charging units is now being undertaken in Japan. This problem can be solved just a few years; however, another problem emerges related to charging during diffusion. Currently, there is only way to charge the batteries of electric vehicles, i.e., manually; however, manual charging is very taxing for users. Charging electric vehicles is not the same as charging a mobile phone, because the cable and the plug are large and not easy to use. Therefore, an automatic, wireless system for charging electric vehicles at home is much desired.

There are some types of wireless power transfer technologies. In particular, electromagnetic resonant coupling [(1) - (3)] is most desirable. As compared to typical wireless power transfer technologies such as electromagnetic induction [(4) - (6)], microwave power transmission [(7) (8)], and laser power transmission [(9) (10)], electromagnetic resonant coupling can achieve both a large air gap and high efficiency. Therefore, it has received much attention. However, when this technology was proposed in 2007, there were many technological problems. Until now, the equivalent circuit for only the transmitting and the receiving antennas has been proposed and a description of how it operates at maximum efficiency with a maximum air gap has been provided [(11) (12)]. A detailed study of the repeater antenna has not yet been carried out.

The air gap can be extended by arranging a repeater antenna between the transmitting antenna and receiving antenna when it is possible to use only the transmitting antenna and receiving antenna because they are limited by the length of the air gap. This technology offers an easy way to extend the air gap by placing a repeater antenna and expand the feeding zone for electric vehicles at a car park. In future, this method can be used to feed moving electric vehicles on highways by arranging repeater antennas along the road [(13) - (16)]. Until now, the repeater antenna has been studied by performing an electromagnetic field analysis; however, the analysis does not include a theoretical study of the equivalent circuit. In this paper, a model of the equivalent circuit for a repeater antenna with and without cross coupling has been proposed.

2 Repeater Antenna without Cross Coupling

In this section, the position at which a repeater antenna is not affected by cross coupling is studied.

〈2・1〉 One Repeater Antenna in Linear Arrangement

To study fundamental electromagnetic resonant coupling, an electromagnetic field analysis for wireless power transfer between the transmitting antenna and the receiving antenna is carried out. A schematic of a spiral antenna are shown in Fig. 1. Every antenna in this paper has radius r = 150 mm, turn t = 5.5, pitch p_s = 5 mm, and length between layers p_h = 8 mm, and this antenna is a two-layered open-type spiral antenna, and it operates in self resonance at 13.56 MHz. The input and output impedance is 50 Ω, and the port at the repeater antenna is shorted. The evaluation of efficiency is carried out between the transmitting antenna and the receiving antenna [17] .

The air gap between the two antennas S_a = 10 mm. The model of the electromagnetic field and results of the analysis are shown in Fig. 2. The results show that electromagnetic resonant coupling can power devices efficiently even if it is placed near the transmitting antenna. However, if the air gap between the transmitting and receiving antennas is large, e.g., S_a = 320 mm, power is not transmitted at all and it is almost completely reflected, as shown in Fig. 3. Therefore, a repeater antenna should be installed between the transmitting antenna and the receiving antenna to achieve a large air gap, high efficiency, wireless power transfer, as shown in Fig. 4. In this situation, the distance between the transmitting antenna and the repeater antenna and between the repeater antenna and the receiving antenna is S_p = 10 mm. In this case, the distance between the transmitting antenna and the receiving antenna S_a = 320 mm; therefore, there is almost no cross coupling between the transmitting antenna and the receiving antenna and it can be ignored in the equivalent circuit calculation. The antenna for electromagnetic resonant coupling self resonates and can be described by an equivalent resonant LCR circuit. Moreover, the coupling is connected by a magnetic field that is described by mutual inductance L_m. Therefore, an equivalent circuit is proposed as shown in Fig. 5 (a). The self inductance of the transmitting antenna is L_1, the self inductance of the repeater antenna is L_2, and the self inductance of the receiving antenna is L_3. The coupling coefficient between the transmitting antenna and the repeater antenna is k_{12}, and the mutual inductance is L_{12}. The coupling coefficient between the repeater antenna and the receiving antenna is k_{23}, and the mutual inductance is L_{23}. The equivalent circuit is converted to a T-type equivalent circuit, as shown in Fig. 5 (b). The efficiency and ratio of power reflection is calculated. The coupling between the transmitting antenna and the receiving antenna can be ignored; thus, the inductance is given by equation (1) and the impedance of this circuit is shown by equations (2) and (3). The S-parameter is shown in equation (4), and the relation for impedance is shown in equation (5). The parameters related to equation (5) are shown in equations (6)–(9). Characteristic impedance Z_0 is given by equation (6). Finally, the efficiency is expressed by equation (10) in terms of transmission S_{31} and efficiency η_{31}, and the ratio of power reflection is expressed by equation (11) in terms of reflection S_{11} and efficiency η_{11}.

$$[L]=\begin{bmatrix} L_{11} & L_{12} & 0 \\ L_{21} & L_{22} & L_{23} \\ 0 & L_{32} & L_{33} \end{bmatrix} \tag{1}$$

$$[Z]=\begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \tag{2}$$

$$[Z]=\begin{bmatrix} R+j\left(\omega L-\frac{1}{\omega C}\right) & j\omega L_{12} & 0 \\ j\omega L_{21} & R+j\left(\omega L-\frac{1}{\omega C}\right) & j\omega L_{23} \\ 0 & j\omega L_{32} & R+j\left(\omega L-\frac{1}{\omega C}\right) \end{bmatrix} \tag{3}$$

$$[S]=\begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \tag{4}$$

$$[S]=\left\{[\hat{Z}]+[1]\right\}^{-1}\left\{[\hat{Z}]-[1]\right\} \tag{5}$$

$$[Z_0]=\begin{bmatrix} Z_{01} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & Z_{03} \end{bmatrix} \tag{6}$$

$$[Y_0]=[Z_0]^{-1} \tag{7}$$

$$\left[\hat{Z}\right]=\left[\sqrt{Y_0}\right][Z]\left[\sqrt{Y_0}\right] \tag{8}$$

$$[1]=\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{9}$$

$$\eta_{31} = |S_{31}|^2 \quad (10)$$

$$\eta_{11} = |S_{11}|^2 \quad (11)$$

The parameters of the transmitting, receiving, and repeater antennas in Fig. 4 are as follows: self inductance L = 11.0 μH, capacitance C = 12.5 pF, internal resistance R = 0.77 Ω, mutual inductances $L_{12} = L_{23} = 0.542$ μH, coupling coefficients $k_{12} = L_{12}/L$ = 0.049, and $k_{23} = L_{23}/L$ = 0.049, which is obtained from the electromagnetic field analysis. The calculation result obtained using the equivalent circuit is shown in Fig. 6. Compared to Fig. 4, the results for the equivalent circuit correspond to the results of the electromagnetic field analysis. In the situation where cross coupling is ignored, the equivalent circuit can be given as shown in Fig. 5.

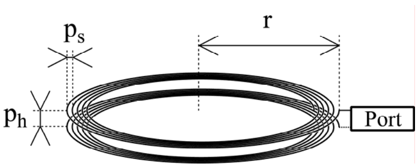
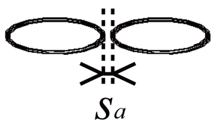
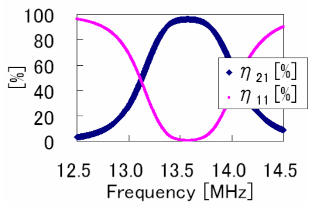


Fig. 1. Parameters of spiral antenna

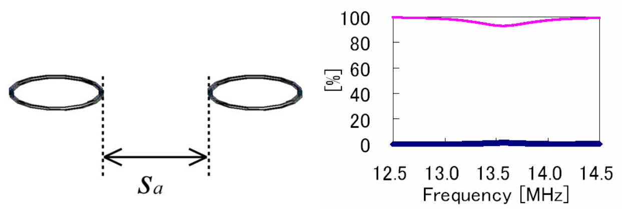


(a) Electromagnetic analysis model



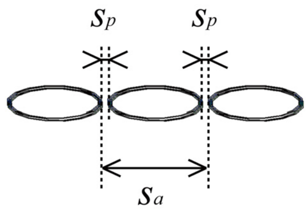
(b) Electromagnetic analysis

Fig. 2. Transmitting and receiving antenna without repeater antenna, s_a = 10 mm

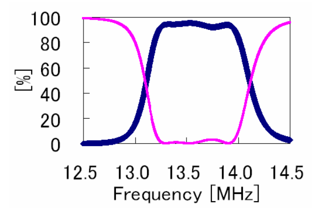


(a) Electromagnetic analysis model (b) Electromagnetic analysis

Fig. 3. Transmitting and receiving antenna without repeater antenna, s_a = 320 mm

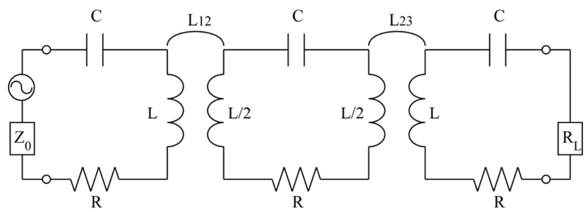


(a) Electromagnetic analysis model

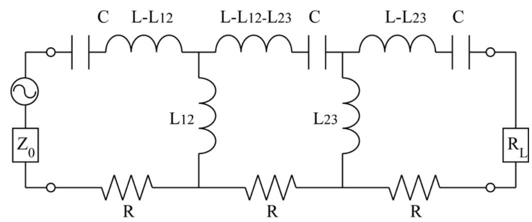


(b) Electromagnetic analysis

Fig. 4. Transmitting and receiving antenna with repeater antenna, s_a = 320 mm, s_p = 10 mm



(a) Equivalent circuit



(b) T-type equivalent circuit

Fig. 5. Equivalent circuit of repeater antenna, ignoring effect of cross coupling

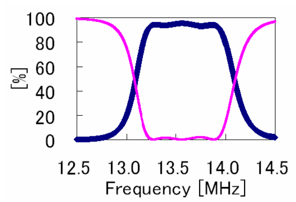


Fig. 6. Results of equivalent circuit analysis with repeater antenna, s_a = 320 mm, s_p = 10 mm

〈2・2〉 Multiple Repeater Antennas in Linear Arrangement

In the preceding section, only one repeater antenna is studied, however the equivalent circuit for repeater antennas is suited to multiple repeater antennas. In the case where the number of repeater antennas is increased to two, the model is shown in Fig. 7 with the results of electromagnetic field analysis shown in Fig.

8. The equivalent circuit is shown in Fig. 9. The results of the calculation using the equivalent circuit with two repeater antennas are shown in Fig. 10. The mutual inductance is 0.542 μH and the coupling coefficient is 0.049. The results of the equivalent circuit analysis and electromagnetic field analysis in Fig. 8 match and show that the equivalent circuit theory is useful for multiple repeater antennas. In these studies, the repeater antenna is arranged in a very simple way. Placing repeater antennas in a line will make it possible for electric vehicles to be fed while moving on the highway in the future. Only the results of the electromagnetic field analysis for larger numbers of repeater antennas are shown in Fig. 11.

Fig. 7. Electromagnetic analysis model with two repeater antennas at s_p = 10 mm

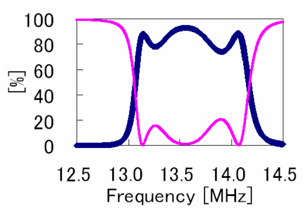
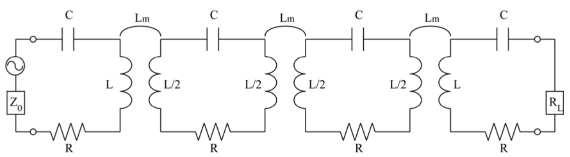
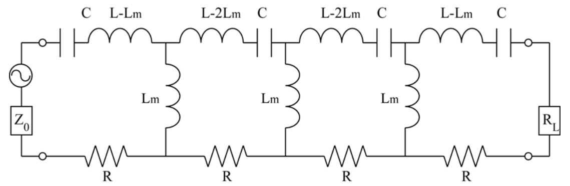


Fig. 8. Electromagnetic analysis with two repeater antennas at s_p = 10 mm



(a) Equivalent circuit



(b) T-type equivalent circuit

Fig. 9. Equivalent circuits with multiple repeater antennas, ignoring effects of cross coupling

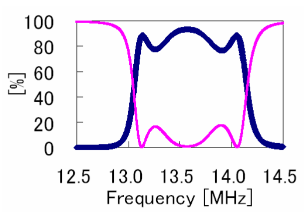
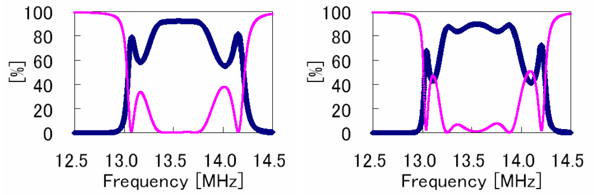
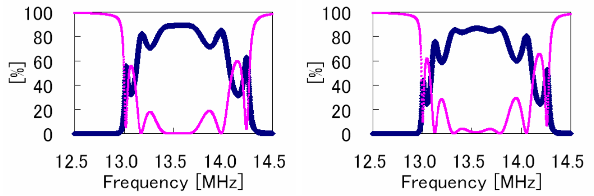


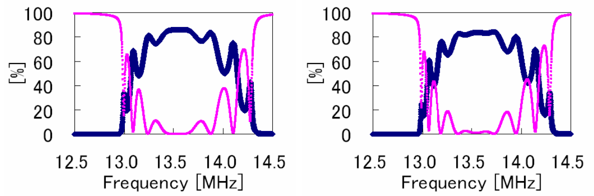
Fig. 10. Results of equivalent circuit analysis with two repeater antennas, s_p = 10 mm



(a) Three repeater antennas (b) Four repeater antennas



(c) Five repeater antennas (d) Six repeater antennas



(e) Seven repeater antennas (f) Eight repeater antennas

Fig. 11. Electromagnetic analysis with multiple repeater antennas, s_p = 10 mm

3 Repeater Antenna Considering Cross Coupling

When the air gap between the transmitting and receiving antennas is large, i.e., when straight coupling between the two antennas is negligible, its effects can be ignored. This situation is shown in Fig. 5 and Fig. 9 where the equivalent circuit can be described by the T-type equivalent circuit that is connected in the form of a ladder. However, if the model includes cross coupling between the transmitting antenna and the receiving antenna, the T-type equivalent circuit is not an accurate representation. In this chapter, an equivalent circuit that considers the effects of cross coupling is studied.

An equivalent circuit that considers cross coupling between antennas is shown Fig. 12. In this case, the cross coupling between the transmitting antenna and the receiving antenna is considered; the coupling coefficient is k_{13}, mutual inductance is L_{13}, inductance of the entire circuit is given by equation (12), and impedance of the entire circuit is given by equation (13).

$$[L]=\begin{bmatrix} L_{11} & L_{12} & L_{13} \\ L_{21} & L_{22} & L_{23} \\ L_{31} & L_{32} & L_{33} \end{bmatrix} \qquad (12)$$

$$[Z]=\begin{bmatrix} R+j\left(\omega L-\dfrac{1}{\omega C}\right) & j\omega L_{12} & j\omega L_{13} \\ j\omega L_{21} & R+j\left(\omega L-\dfrac{1}{\omega C}\right) & j\omega L_{23} \\ j\omega L_{31} & j\omega L_{32} & R+j\left(\omega L-\dfrac{1}{\omega C}\right) \end{bmatrix} \quad (13)$$

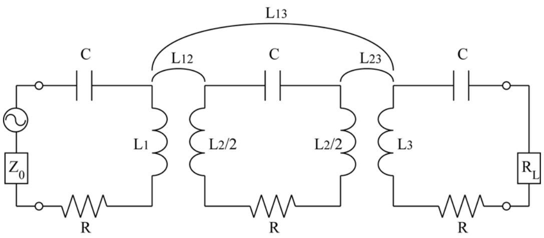
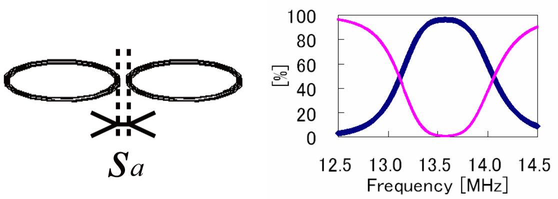
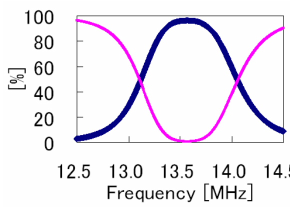


Fig. 12. Equivalent circuit of repeater antenna, considering effect of cross coupling

The model and results of the electromagnetic field analysis and the results of the equivalent circuit (considering only the transmitting and receiving antennas) are shown in Fig. 13. The coupling coefficient k = 0.049 and L_m=0.542 μH is used in the calculations for the equivalent circuit shown in Fig. 13 (c). This result shows that the efficiency is very high and that the results of the equivalent circuit and those of electromagnetic field analysis match.



(a) Electromagnetic analysis model (b) Electromagnetic analysis



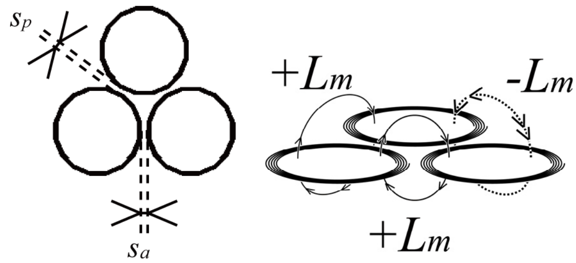
(c) Results for equivalent circuit

Fig. 13. Wireless power transfer for planar direction, s_a = 10 mm

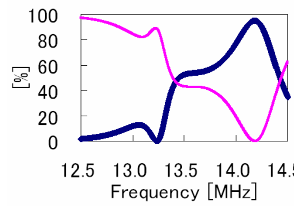
The equivalent circuit for the repeater antenna, which is used for expanding the feeding zone at a car park, is not linear, but its planar position is studied. In this position, the gap between the transmitting antenna and the receiving antenna is smaller. In this case, the cross coupling between the transmitting antenna and the receiving antenna should be considered. The models for the electromagnetic field, magnetic field, and results of the electromagnetic field analysis at S_a = 10 mm and S_p = 10 mm are shown in Fig. 14. Fig. 15 shows the above three for S_a = 10 mm, S_p = 50 mm. The lower left antenna is the transmitting antenna, center (top) antenna is the repeater antenna, and lower right antenna is the receiving antenna. The parameters of cross coupling for the structure shown in Fig. 14 are $k_{12} = k_{13} = k_{23}$ = 0.049 and $L_{12} = L_{13} = -L_{23}$ = 0.541 = μH. The parameters of cross coupling for the structure shown in Fig. 15 are k_{12} = 0.049, $k_{13} = k_{23}$ = 0.025, L_{12} = 0.541 μH, and $L_{13} = L_{23}$ = 0.280 μH.

First, the result of an equivalent circuit without cross coupling is shown in Fig. 16. In this case, the $k_{13} = L_{13} = 0$. For the position at which the cross coupling is strong, the results of equivalent circuit analysis without cross coupling do not match at all. Therefore, the results of the equivalent circuit with cross coupling (shown in Fig. 17) are a close match to the results of electromagnetic field analysis which means that cross coupling should be considered if mutual inductance is a strong effect.

If the number of repeater antennas is increased, considering the equivalent circuit with cross coupling is also useful. In this paper, these results are shown in Fig. 18 and Fig. 19.

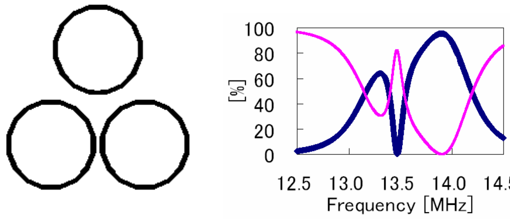


(a) Electromagnetic analysis model (b) Magnetic field



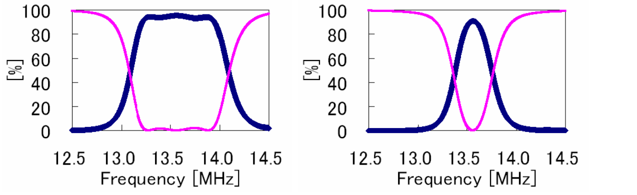
(c) Results of electromagnetic analysis

Fig. 14. Electromagnetic analysis for repeater antenna in planar direction, s_a=10 mm, s_p=10 mm



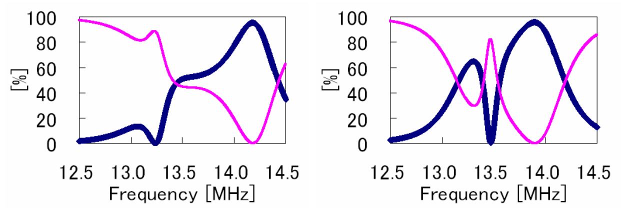
(a) Electromagnetic analysis model (b) Electromagnetic analysis

Fig. 15. Electromagnetic analysis for repeater antenna in planar direction, s_a=10 mm, s_p=50 mm



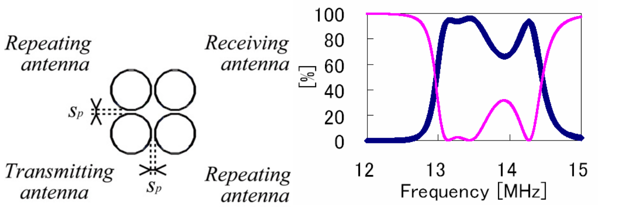
(a) s_p = 10 mm (b) s_p = 50 mm

Fig. 16. Calculation by equivalent circuit for repeater antenna in planar direction, without cross coupling, s_a = 10 mm



(a) s_p = 10 mm (b) s_p = 50 mm

Fig. 17. Calculation by equivalent circuit analysis for repeater antenna in planar direction, s_a = 10 mm



(a) Electromagnetic analysis model (b) Electromagnetic analysis

Fig. 18. Electromagnetic analysis for two repeater antennas in planar direction, s_p = 10 mm

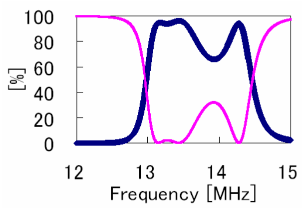


Fig. 19. Calculation by equivalent circuit for two repeater antennas in planar direction, s_p = 10 mm

4 Summary

An equivalent circuit for repeater antennas with and without cross coupling is proposed, and the effects of cross coupling and the validity of the equivalent circuit were confirmed. In future, this technology of repeater antennas will be used to expand the feeding zone at car parks and feed moving electric vehicles on highways. The latter development is expected.

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