

# Interference Reduction Method Using a Directional Coupler in a Duplex Wireless Power Transmission System

K. Nishimoto<sup>1</sup>, K. Hitomi<sup>2</sup>, T. Oshima<sup>1</sup>, T. Fukasawa<sup>1</sup>, H. Miyashita<sup>1</sup>, Y. Takahashi<sup>2</sup>, and Y. Akuzawa<sup>2</sup>  
<sup>1</sup>Mitsubishi Electric Corporation  
 Kamakura, Kanagawa, Japan  
<sup>2</sup>Mitsubishi Electric Engineering Co., Ltd.  
 Kamakura, Kanagawa, Japan

**Abstract**—We propose a method for reducing interference in a duplex wireless power transmission system that uses electromagnetic resonant coupling. Duplex wireless power transmission acts as a directional coupler if it has no loss and is perfectly matched. The proposed method uses this characteristic and the interference is decreased by connecting a directional coupler to the input (or output) ports of a duplex wireless power transmission system. We validate our method by performing simulations for two configurations of duplex wireless power transmission: two sets of oppositely arranged antenna pairs aligned horizontally, and two sets of coaxially arranged antenna pairs aligned vertically. In addition, we show that the location of the isolation port changes depending on the transmission distance in the former configuration.

## I. INTRODUCTION

Recently, wireless power transmission systems that use electromagnetic resonant coupling have been widely researched [1]–[8]. In these systems, the transmission distance becomes shorter, but the transmission efficiency becomes higher than in wireless power transmission systems that use microwaves [5]. In this paper, a wireless power transmission system that uses electromagnetic resonant coupling is applied to multiplex power transmission. In a multiplex wireless power transmission system, multiple pairs of transmitting and receiving antennas transmit energy independently of each other. This can provide advantages such that the realization of a redundant system. To scale down a multiplex wireless power transmission system, multiple transmitting and receiving antennas are placed closely. Therefore, each antenna couples strongly to two or more antennas, and the interference between multiple transmissions within the system increases.

We propose a method for reducing the amount of interference by connecting a directional coupler to the input (or output) ports of a duplex wireless power transmission system. First, we describe the characteristics of duplex wireless power transmission. Next, the interference reduction method using a directional coupler is detailed. Moreover, we validate our method by performing simulations for the two configurations of the duplex wireless power transmission: two sets of oppositely arranged antenna pairs aligned horizontally, and two sets of coaxially arranged antenna pairs aligned vertically.

duplex wireless power transmission

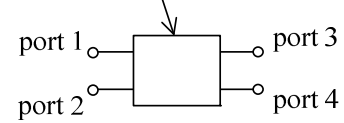


Figure 1. 4-port network.

## II. CHARACTERISTICS OF DUPLEX WIRELESS POWER TRANSMISSION

A duplex power transmission system is composed of two transmitting antennas and two receiving antennas, and it can be expressed as a 4-port network, as shown in Fig. 1. If a 4-port network has no loss and is perfectly matched, it becomes a directional coupler from the condition that the S-matrix is unitary and  $S_{11} = S_{22} = S_{33} = S_{44} = 0$  [9]. Therefore, we consider that the duplex wireless power transmission that has no loss and is perfectly matched acts as a directional coupler.

We now show the relationship between transmission phases. When  $S_{21} = S_{43} = 0$  in a directional coupler, the S-matrix is:

$$[S] = \begin{pmatrix} 0 & 0 & S_{31} & S_{41} \\ 0 & 0 & S_{32} & S_{42} \\ S_{31} & S_{32} & 0 & 0 \\ S_{41} & S_{42} & 0 & 0 \end{pmatrix}. \quad (1)$$

As  $[S]$  is unitary, we have:

$$|S_{31}| = |S_{42}|, \quad |S_{41}| = |S_{32}|, \quad \text{and} \quad (2)$$

$$S_{31}S_{32}^* + S_{41}S_{42}^* = 0. \quad (3)$$

At this point, we move the port positions by connecting transmission lines to the ports. First, the positions of ports 1, 3 and 4 are chosen in such a way that  $S_{31}$  is pure real and positive and that the phase of  $S_{41}$  is  $\theta$ . Then, the position of port 2 is chosen in such a way that  $S_{42}$  is pure real and positive. Therefore, from (2),

$$S_{31} = a, \quad S_{41} = be^{j\theta}, \quad S_{42} = a, \quad S_{32} = be^{j\phi}, \quad (4)$$

where  $a$  and  $b$  are pure real numbers, and  $\phi$  is the phase of  $S_{32}$ . Substituting (4) into (3), we have:

$$e^{-j\phi} = e^{j(\theta-\pi)}. \quad (5)$$

Then,

$$\theta + \phi = \pi. \quad (6)$$

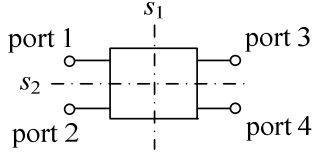


Figure 2. 4-port network with two symmetry planes.

For example,  $\phi = -\pi/2$  when  $\theta = -\pi/2$ , and  $\phi = \pi/2$  when  $\theta = \pi/2$ . Therefore, the differences between the transmission phases from one port to the other two ports (except for the isolation port) can be set to  $\pm \pi/2$  by moving the port positions in an arbitrary directional coupler.

As a special case, we consider the 4-port network that has two symmetry planes, as shown in Fig. 2. The 4-port network is symmetric with respect to the planes  $s_1$  and  $s_2$ . From this symmetry, the S-matrix is:

$$[S] = \begin{pmatrix} 0 & 0 & v & w \\ 0 & 0 & w & v \\ v & w & 0 & 0 \\ w & v & 0 & 0 \end{pmatrix}, \quad (7)$$

where  $v = |v|e^{j\zeta}$  and  $w = |w|e^{j\xi}$ . As  $[S]$  is unitary, we have:

$$\zeta - \xi = \pm \pi / 2. \quad (8)$$

Therefore, the duplex wireless power transmission with two symmetry planes acts as a directional coupler in which the differences between the transmission phases from one port to the other two ports are  $\pm \pi/2$ .

### III. INTERFERENCE REDUCTION METHOD USING A DIRECTIONAL COUPLER

Fig. 3 shows the configuration of the proposed interference reduction method using a directional coupler. Let  $Z_0$  be the impedance of each port. Because the duplex wireless power transmission that has no loss and is perfectly matched becomes a directional coupler, we assume that it is a directional coupler with a coupling coefficient  $k$  in which  $S_{21} = S_{43} = 0$ . The input (or output) ports of the duplex wireless power transmission system are connected to a directional coupler by two transmission lines whose characteristic impedances are  $Z_0$ . As detailed in Sec. II, the differences between the transmission phases from one port to the other two ports can be set to  $\pm \pi/2$  by moving the port positions in an arbitrary directional coupler. Then, the lengths of the transmission lines  $l_1$  and  $l_2$  are determined such that  $\alpha = \arg(S_{51}) - \arg(S_{61})$  becomes  $\pm \pi/2$ . In the additional directional coupler, the coupling coefficient is  $k'$ ,  $S_{65} = S_{87} = 0$ , and  $\beta = \arg(S_{75}) - \arg(S_{85}) = \pm \pi/2$ . There are four combinations of  $\alpha$  and  $\beta$ :  $(\alpha, \beta) = (\pi/2, \pi/2)$ ,  $(\pi/2, -\pi/2)$ ,  $(-\pi/2, \pi/2)$ , and  $(-\pi/2, -\pi/2)$ . Let  $a_1$  be the input wave into port 1, while  $b_1$  and  $b_2$  are the output waves from ports 7 and 8 respectively. When  $(\alpha, \beta) = (\pi/2, \pi/2)$ ,

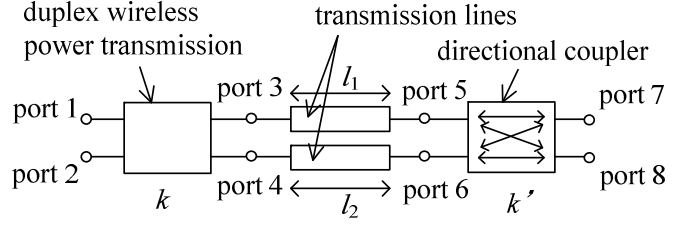


Figure 3. Configuration of the proposed method.

$$\begin{aligned} b_7 &= \left( -\sqrt{1-k^2}\sqrt{1-k'^2} + kk' \right) a_1, \\ b_8 &= j \left( k'\sqrt{1-k^2} + k\sqrt{1-k'^2} \right) a_1. \end{aligned} \quad (9)$$

As  $k$  is pure real and positive,  $b_7$  can be 0, and then we have:

$$k' = \sqrt{1-k^2}. \quad (10)$$

When  $(\alpha, \beta) = (\pi/2, -\pi/2)$ ,

$$\begin{aligned} b_7 &= j \left( \sqrt{1-k^2}\sqrt{1-k'^2} + kk' \right) a_1, \\ b_8 &= \left( -k'\sqrt{1-k^2} + k\sqrt{1-k'^2} \right) a_1. \end{aligned} \quad (11)$$

As  $k$  is pure real and positive,  $b_8$  can be 0, and then we have:

$$k' = k. \quad (12)$$

Similarly, from the condition that  $S_{71}$  or  $S_{81}$  becomes 0, (12) is derived when  $(\alpha, \beta) = (-\pi/2, \pi/2)$ , and (10) is derived when  $(\alpha, \beta) = (-\pi/2, -\pi/2)$ . In summary, we obtain:

$$k' = \begin{cases} k & \alpha - \beta = \pm \pi \\ \sqrt{1-k^2} & \alpha - \beta = 0 \end{cases}. \quad (13)$$

By deciding  $k'$  and  $\alpha - \beta$  according to (13), the interference between the two transmissions can be reduced. In this method, we have to use a low-loss directional coupler in order not to decrease the transmission efficiency.

### IV. SIMULATED RESULTS

#### A. Two sets of oppositely arranged antenna pairs aligned horizontally

The proposed method is studied by simulations. The simulated frequency is 6.78 MHz, because this frequency is used by A4WP (Alliance for Wireless Power) and CEA (Consumer Electronics Association) 2042.2. Fig. 4 illustrates the simulated model that horizontally aligns two sets of oppositely arranged antenna pairs. We place antennas 1 and 3 opposite to each other, and place antennas 2 and 4 opposite to each other. We separate antennas 1 and 2 by a distance of 20 mm. Antennas 1 and 2 are designated as transmitting antennas, and antennas 3 and 4 are designated as receiving antennas. Each antenna consists of a feed loop and a parasitic loop with a capacitance  $C$ , and is assumed to be a perfect conductor. The directions of ports 1 and 3 are opposite to the directions of ports 2 and 4. This model is symmetric with respect to the  $yz$  and  $xz$  planes. While changing the distance between the transmitting and receiving antennas  $d$ , the simulations are performed using the FEM (Finite Element Method). At each  $d$ , we adjust the distance between the feed and parasitic loops  $d_f$  and  $C$  so that the amount of reflection decreases.

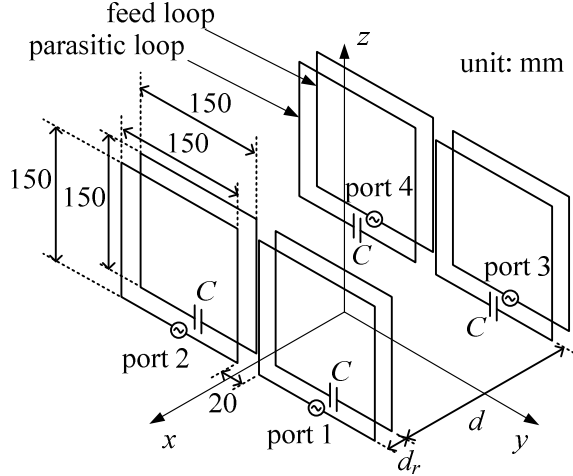


Figure 4. Simulated model that horizontally aligns two sets of oppositely arranged antenna pairs.

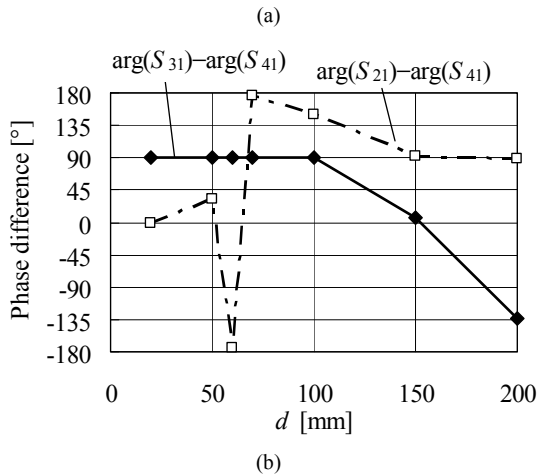
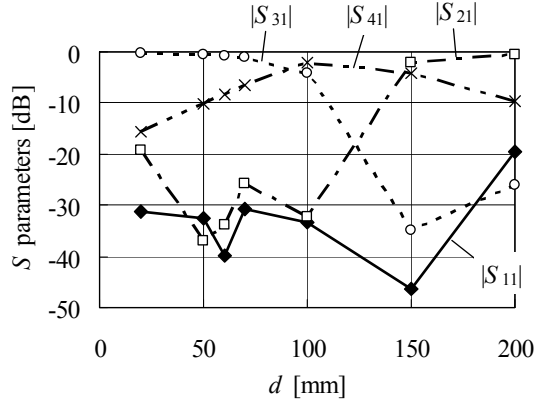


Figure 5. Calculated S-parameters for the system without a directional coupler: (a) amplitude and (b) phase.

Fig. 5 shows the calculated S-parameters for the system without a directional coupler. As the model is symmetric, only the case in which port 1 is an input port is shown. In Fig. 5,  $|S_{11}|$  is less than  $-19.5$  dB. When  $d \leq 125$  mm,  $|S_{21}|$  is less than  $|S_{31}|$  and  $|S_{41}|$ , and is also less than  $-19.3$  dB. On the other hand, when  $d \geq 125$  mm,  $|S_{31}|$  is less than  $|S_{21}|$  and  $|S_{41}|$ , and is also less than  $-26.0$  dB. Therefore, port 2 (the adjacent antenna)

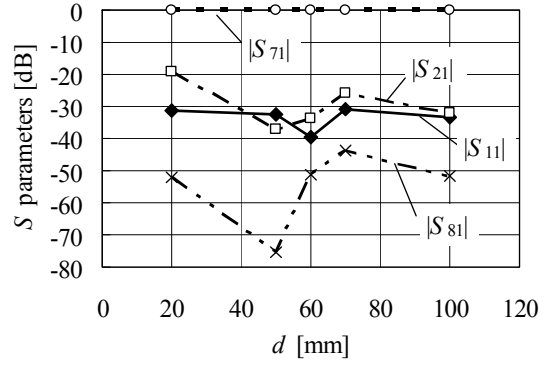


Figure 6. Calculated S-parameters for the system with a directional coupler.

becomes an isolation port at  $d \leq 125$  mm, and port3 (the opposite antenna) becomes an isolation port at  $d \geq 125$  mm. In effect, the location of the isolation port changes depending on the transmitting distance. In Fig. 5(b),  $\arg(S_{31}) - \arg(S_{41})$  is about  $90^\circ$  at  $d \leq 125$  mm, and  $\arg(S_{21}) - \arg(S_{41})$  is about  $90^\circ$  at  $d \geq 125$  mm. Therefore, the differences between the transmission phases from one port to the other two ports (except for the isolation port) are shown to be approximately  $90^\circ$ . This is because the model in Fig. 4 has two symmetry planes.

When port 2 is an isolation port,  $|S_{31}|$  and  $|S_{41}|$  are greater than  $-10.0$  dB for  $50 \text{ mm} \leq d \leq 100 \text{ mm}$ . Then, a directional coupler is added when  $d \leq 125$  mm, as shown in Fig. 3. Because  $\arg(S_{31}) - \arg(S_{41}) \approx \pi/2$ , the choice  $l_1 = l_2$  gives  $\alpha = \arg(S_{51}) - \arg(S_{61}) \approx \pi/2$ . According to (13), we choose  $k' = k = |S_{41}|$ , and  $\beta = \arg(S_{75}) - \arg(S_{85}) = -\pi/2$ . Fig. 6 shows calculated S-parameters for the system with a directional coupler. We find that  $|S_{71}| \geq -0.05 \text{ dB}$ , and  $|S_{81}| \leq -40 \text{ dB}$  for  $20 \text{ mm} \leq d \leq 100 \text{ mm}$ . In addition,  $|S_{82}| \geq -0.05 \text{ dB}$ , and  $|S_{72}| \leq -40 \text{ dB}$ . From these results, we confirm that the interference between the two transmissions is reduced from above  $-10$  dB to below  $-40 \text{ dB}$  by adding a directional coupler.

#### B. Two sets of coaxially arranged antenna pairs aligned vertically

Fig. 7 illustrates a simulated model that vertically aligns two sets of coaxially arranged antenna pairs. We stack antennas 1 and 3 coaxially, and stack antennas 2 and 4 coaxially. We arrange antennas 1 and 2 at an interval of  $d$  on the center axis. Antennas 1 and 2 are transmitting antennas, and antennas 3 and 4 are receiving antennas. The directions of ports 1–4 are the same. This model is symmetric with respect to the  $yz$  and  $zx$  planes. While changing  $d$ , the simulation is performed by using the FEM. At each  $d$ , we adjust  $d_{rs}$ ,  $d_{rl}$ ,  $C_s$ , and  $C_l$  so that the amount of reflection decreases.

Fig. 8 shows the calculated S-parameters for the system without a directional coupler. In Fig. 8,  $|S_{11}|$  is less than  $-25.0$  dB. In addition, we find that  $|S_{21}|$  is less than  $|S_{31}|$  and  $|S_{41}|$ , and is also less than  $-14.5$  dB. Therefore, port 2 is an isolation port. In Fig. 8(b),  $\arg(S_{31}) - \arg(S_{41})$  is about  $90^\circ$ , because the model in Fig. 7 has two symmetry planes.

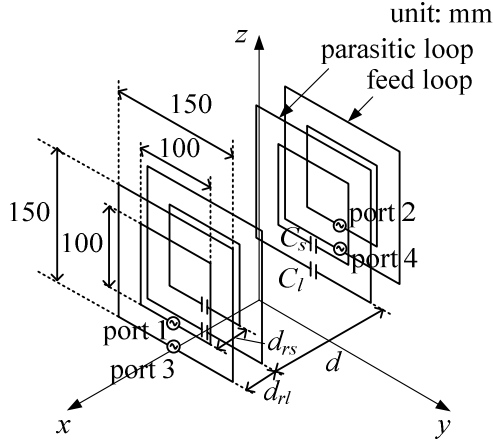


Figure 7. Simulated model that vertically aligns two sets of coaxially arranged antenna pairs.

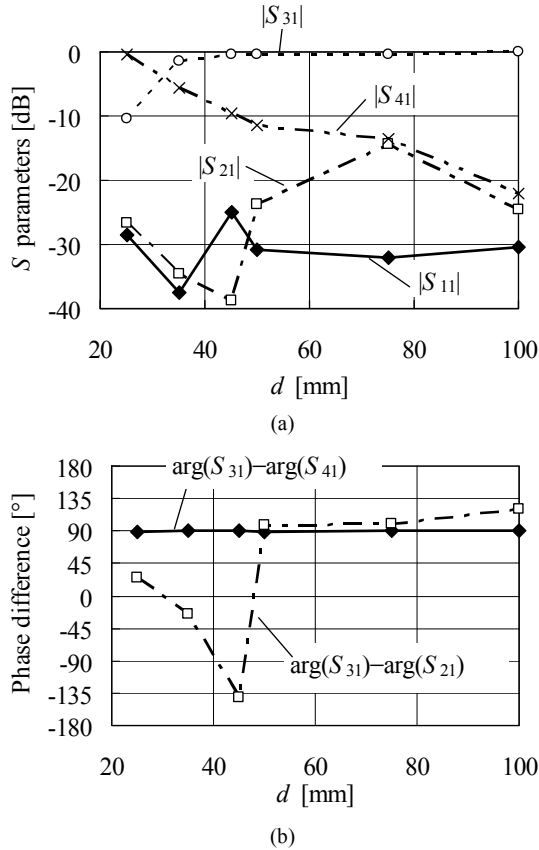


Figure 8. Calculated S-parameters for the system without a directional coupler: (a) amplitude and (b) phase.

For  $25\text{mm} \leq d \leq 50\text{mm}$ ,  $|S_{31}|$  and  $|S_{41}|$  are greater than  $-11.4$  dB. Then, a directional coupler is added, as shown in Fig. 3. Because  $\arg(S_{31}) - \arg(S_{41}) \approx \pi/2$ , the choice  $l_1 = l_2$  gives  $\alpha \approx \pi/2$ . According to (13), we choose  $k' = k = |S_{41}|$ , and  $\beta = -\pi/2$ . Fig. 9 shows the calculated S-parameters for the system with a directional coupler. We find that  $|S_{71}| \geq -0.02\text{dB}$ , and  $|S_{81}| \leq -40\text{dB}$  for  $25\text{mm} \leq d \leq 50\text{mm}$ . In addition,  $|S_{82}| \geq -0.02\text{dB}$ , and  $|S_{72}| \leq -40\text{dB}$ . From these results, we confirm that the interference between the two transmissions is reduced

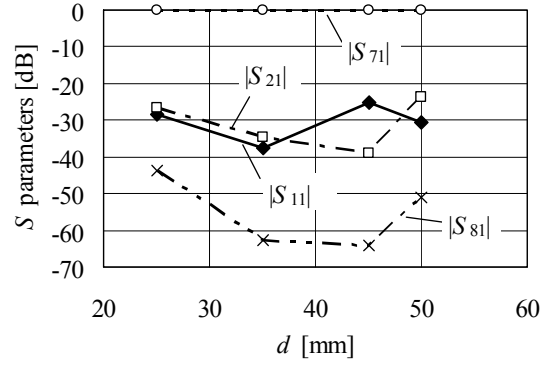


Figure 9. Calculated S-parameters for the system with a directional coupler.

from above  $-11.4$  dB to below  $-40\text{dB}$  by adding a directional coupler.

## V. CONCLUSIONS

We have proposed a method for reducing interference in a duplex wireless power transmission system by adding a directional coupler. Furthermore, we have validated our method by performing simulations for two configurations of duplex wireless power transmission: two sets of oppositely arranged antenna pairs aligned horizontally, and two sets of coaxially arranged antenna pairs aligned vertically. Moreover, we have shown that the location of the isolation port changes depending on the transmission distance in the former configuration.

## REFERENCES

- [1] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, "Wireless power transfer via strongly coupled magnetic resonators," *Science Express*, vol. 317, no. 5834, pp. 83-86, Jul. 2007.
- [2] A. Karalis, J.D. Joannopoulos, and M. Soljačić, "Efficient wireless non-radiative mid-range energy transfer," *Ann. Phys.*, vol. 323, no. 1, pp. 34-48, Jul. 2008.
- [3] H. Hirayama, T. Ozawa, Y. Hiraiwa, N. Kikuma, and K. Sakakibara, "A consideration of electro-magnetic-resonant coupling mode in wireless power transmission," *IEICE Electronics Express*, vol. 6, no. 19, pp. 1421-1425, Oct. 2009.
- [4] Q. Yuan, Q. Chen, and K. Sawaya, "Maximum transmitting efficiency of wireless power transfer system with resonant/non-resonant transmitting/receiving elements," *2010 IEEE AP-S*, Jul. 2010.
- [5] H. Shoki, "Issues and initiatives for practical use of wireless power transmission technologies in Japan," *IEEE IMWS-IWPT 2011*, pp. 87-90, May 2011.
- [6] N. Inagaki and S. Hori, "Classification and characterization of wireless power transfer systems of resonance method based on equivalent circuit derived from even- and odd mode reactance functions," *IEEE IMWS-IWPT 2011*, pp. 115-118, May 2011.
- [7] T. Imura and Y. Hori, "Maximizing air gap and efficiency of magnetic resonant coupling for wireless power transfer using equivalent circuit and Neumann formula," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4746-4752, Oct. 2011.
- [8] I. Awai and T. Ishizaki, "Superiority of BPF theory for design of coupled resonator WPT systems," *APMC 2011*, pp. 1889-1892, Dec. 2011.
- [9] C.G. Montgomery, R.H. Dicke, and E.M. Purcell, *Principles of Microwave Circuits*. London, UK: The Institution of Engineering and Technology, 2007.