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

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***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.

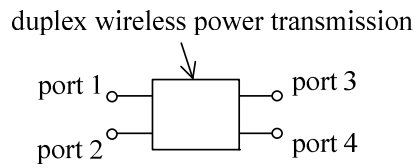


Figure 1. 4-port network.

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:

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

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

$$|S_{31}| = |S_{42}|,\ |S_{41}| = |S_{32}|, \text{ and} \tag{2}$$

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

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 θ. Then, the position of port 2 is chosen in such a way that S_{42} is pure real and positive. Therefore, from (2),

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

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

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

Then,

$$\theta + \phi = \pi. \tag{6}$$

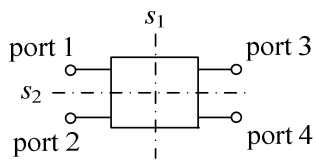


Figure 2. 4-port network with two symmetry planes.

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:

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

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

$$\varsigma - \xi = \pm\pi/2 . \tag{8}$$

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 α and β : $(\alpha, \beta) = (\pi/2, \pi/2)$, $(\pi/2, -\pi/2)$, $(-\pi/2, \pi/2)$, 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 $(\alpha, \beta) = (\pi/2, \pi/2)$,

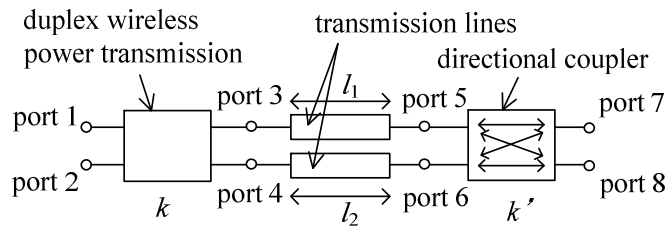


Figure 3. Configuration of the proposed method.

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

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

$$k' = \sqrt{1-k^2} . \tag{10}$$

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

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

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

$$k' = k . \tag{12}$$

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:

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

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 zx 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_r and C so that the amount of reflection decreases.

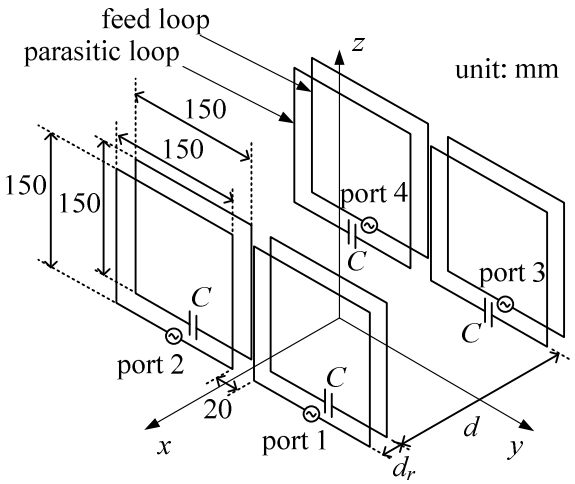
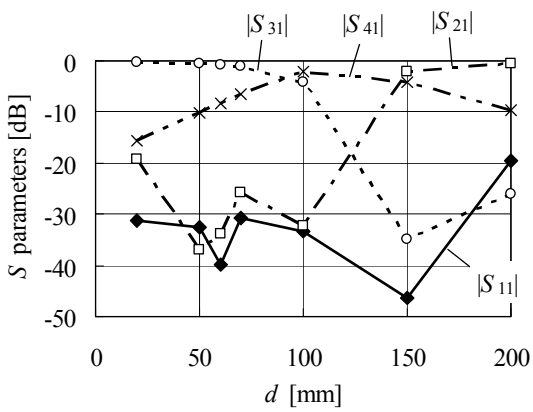
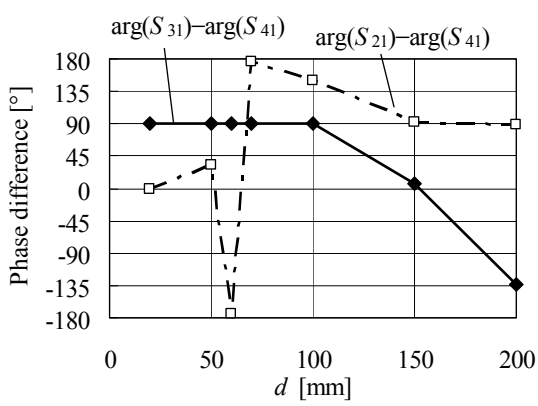


Figure 4. Simulated model that horizontally aligns two sets of oppositely arranged antenna pairs.



(a)



(b)

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)

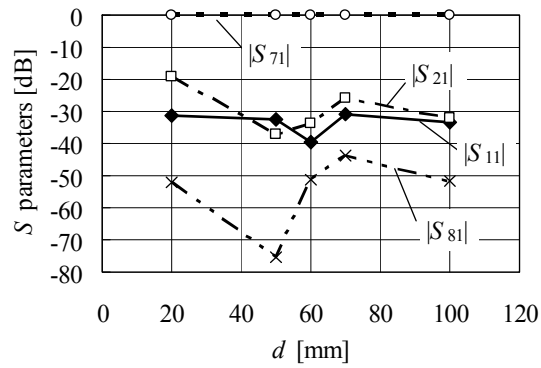


Figure 6. Calculated S-parameters for the system with a directional coupler.

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° at $d \leq$ 125 mm, and $\arg(S_{21})$–$\arg(S_{41})$ is about 90° 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°. 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 50mm $\leq d \leq$ 100mm. 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 $|S_{71}| \geq$ –0.05dB, and $|S_{81}| \leq$ –40dB for 20mm $\leq d \leq$ 100mm. In addition, $|S_{82}| \geq$ –0.05dB, and $|S_{72}| \leq$ –40dB. From these results, we confirm that the interference between the two transmissions is reduced from above –10 dB to below –40dB 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°, because the model in Fig. 7 has two symmetry planes.

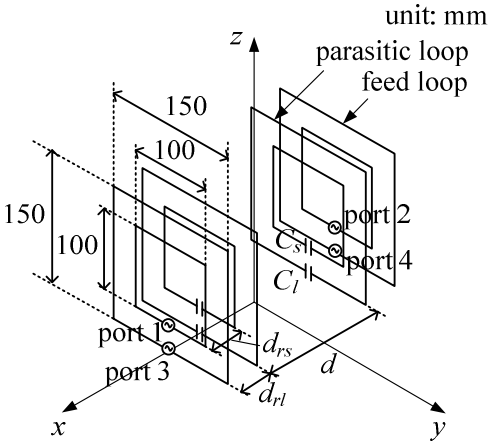
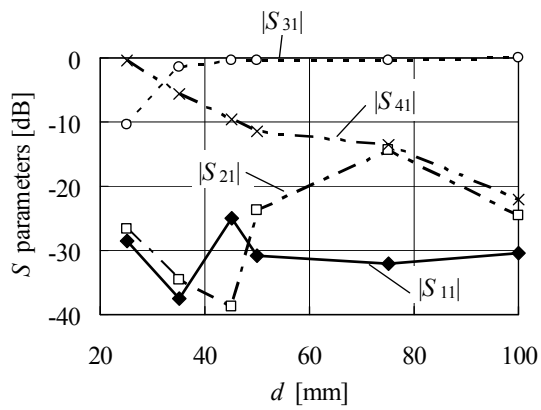
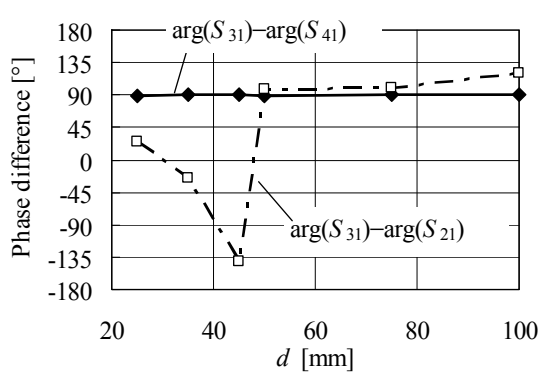


Figure 7. Simulated model that vertically aligns two sets of coaxially arranged antenna pairs.



(a)



(b)

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

For 25mm ≤ d ≤ 50mm, $|S_{31}|$ 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 $|S_{71}| \geq -0.02$dB, and $|S_{81}| \leq -40$dB for 25mm ≤ d ≤ 50mm. In addition, $|S_{82}| \geq -0.02$dB, and $|S_{72}| \leq -40$dB. From these results, we confirm that the interference between the two transmissions is reduced

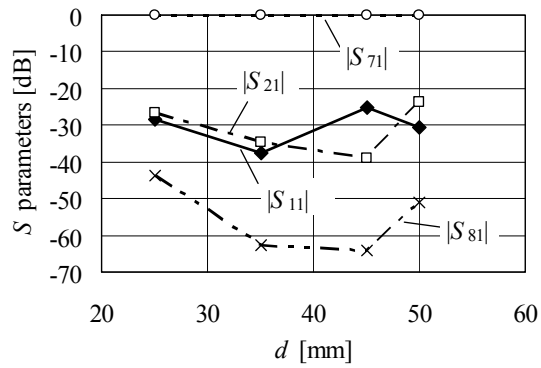


Figure 9. Calculated S-parameters for the system with a directional coupler.

from above –11.4 dB to below –40dB 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.

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