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Omnidirectional Resonator in X-Y Plane Using a Crisscross Structure for Wireless Power Transfer

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Abstract

Magnetic resonant coupling is more efficient than inductive coupling for transferring power wirelessly over a distance. However, a conventional resonant wireless power transfer (WPT) system requires a transmitter and receiver pair in exactly coaxial positions. We propose a resonator that can serve as an omnidirectional WPT system. A magnetic field will be generated by the current flowed through the transmitter. This magnetic field radiates omnidirectionally in the x-y plane because of the crisscross structure characteristic of the transmitter. The proposed resonator is demonstrated by using a single port. To check the received S_{21} and transfer efficiency, we moved the receiver around the transmitter at different distances (50–350 mm). As a result, the transmission efficiency is found to be 48%–54% at 200 mm.

Key Words: Crisscross Structure, Omnidirectional Resonator in X-Y Plane, Resonant Coupling, Transfer Efficiency, Wireless Power Transfer.

I. INTRODUCTION

Wireless power transfer (WPT) is a technology that can be used to charge or supply power to electronic devices wirelessly. Recently, WPT has been actively researched worldwide because of the convenience it affords. In 1899, Tesla first started researching a wireless transfer device at his laboratory in Colorado. WPT technology includes inductive coupling, magnetic resonant coupling, and microwave power transfer [1, 2].

Kurs and his research group at the Massachusetts Institute of Technology (MIT) first investigated magnetic resonant coupling technology. Magnetic resonance, which uses the phenomenon of strong magnetic coupling, has a long transmission distance compared to the induction coupling method [3].

However, one disadvantage is that the high transmission efficiency can only be achieved when the receiver and transmitter are matched in the same axis. Regardless of the transfer method, for WPT to find various applications, the receiver and transmitter should be freely positioned relative to each other because angle changes in real-world applications are inevitable.

Recently, researchers have actively focused on this problem and proposed a three-dimensional magnetic resonator structure [4]. This structure consists of crossed split-ring resonators. If it were to be simplified, the transmitter coils of the WPT system can be constructed orthogonally [5]. The two closed loops then cross each other. The free position problem is solved; however new problems arise because of multiple input ports. First, considerable effort is required to make circuits match each other. Second, as many power sources as

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the number of input ports are required. However, this worsens the transmission efficiency.

In this study, we propose an omnidirectional resonator in the x-y plane that feeds on a single port. The transmitter coils are located orthogonally and radiate in the x-y plane.

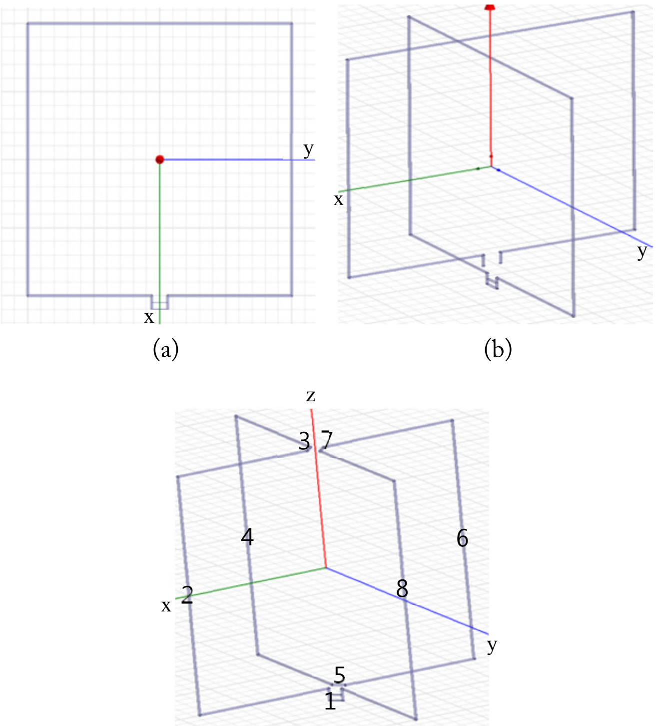
II. STRUCTURE FOR OMNIDIRECTIONAL RESONATOR IN THE X-Y PLANE

Fig. 1(a) shows a single closed loop coil placed in the x-y plane; it can radiate in only one direction. Fig. 1(b) shows two single closed loop coils that are crossed orthogonally; it can radiate omnidirectionally but has two ports. Fig. 1(c) shows the structure of the proposed single closed loop coil.

The proposed coil is similar to that shown in Fig. 1(b). It mainly differs in that the x-, y-, and z-axes are used when winding the coil. First, we start at point 1. The coils formed along 1-2-3, 3-4-5, and 5-6-7 are placed on the x-z, y-z, and x-z planes, respectively. Finally, point 7 placed on the y-z plane returns to point 1 through point 8. Therefore, the proposed transmitter coil forms a crisscross structure with a single port and can radiate omnidirectionally.

When the current is applied to the input port, it flows along the coil as shown in Fig. 2. Next, according to Ampere's law, magnetic field vectors are of two types.

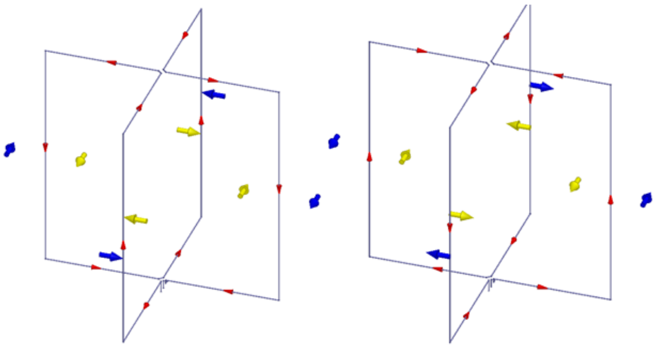
Some (blue arrows) are generated outside the resonator and others (yellow arrows), inside the resonator. Some of those formed outside radiate along the +x, -x, +y, and –y axes. The others formed inside combine with each other. The others that are synthesized (green arrows) radiate diagonally along the x-y axis, as shown in Fig. 3. Therefore, the receiver can receive power omnidirectionally in the x-y plane.



(a) (b)

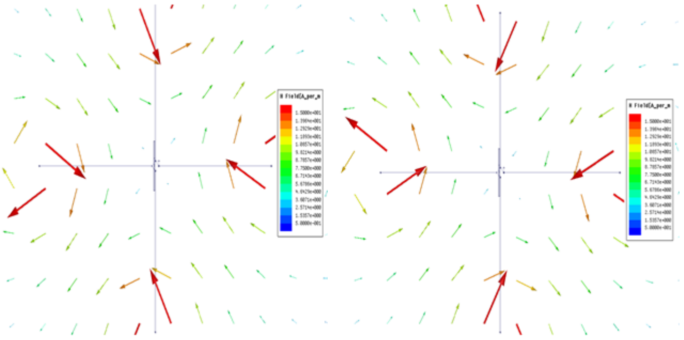
(c)

Fig. 1. Several types of resonators. (a) Single closed loop coil, (b) two single closed, and (c) proposed single closed loop coil.



(a) (b)

Fig. 2. Magnetic field vector in each half-operating period.



(a) (b)

Fig. 3. Simulation results of magnetic field vector in each half-operating period shown in top view.

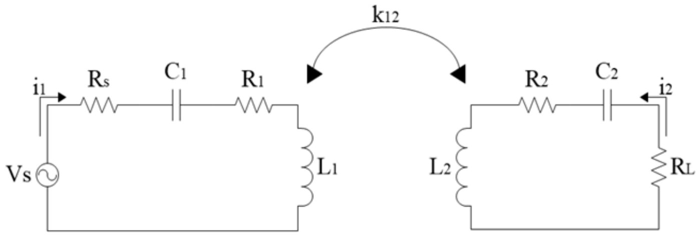


Fig. 4. Circuit model of magnetic resonant system.

III. ANALYSIS OF MAGNETIC RESONANT COUPLING SYSTEM

The WPT system has a strongly coupled magnetic field between the transmitter and each receiver [6-9]. Fig. 4 shows the equivalent circuit of the transmitter and the receiver coils. The coupling coefficient (k_{12}) can be expressed as follows:

$$k_{12} = \frac{M_{12}}{\sqrt{L_1 L_2}} \tag{1}$$

L_1 and L_2 denote the self-inductance of each coil, M_{12} denotes the mutual inductance, and k_{12} denotes the strength of magnetic coupling between the transmitter and the receiver.

$$\begin{bmatrix} V_s \\ 0 \end{bmatrix} = \begin{bmatrix} Z_1 & j\omega M_{12} \\ j\omega M_{12} & Z_2 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \tag{2}$$

Eq. (2) is a node equation of the circuit model shown in Fig. 4. Z_1 and Z_2 denote the impedances of each circuit and can be calculated by Eq. (3).

$$Z_1 = R_s + R_1 + j\left(\omega L_1 - \frac{1}{\omega C_1}\right), \quad Z_2 = R_L + R_2 + j\left(\omega L_2 - \frac{1}{\omega C_2}\right) \tag{3}$$

By using Eqs. (2) and (3), we can obtain the load voltage as follows.

$$V_L = -i_2 \cdot R_L = \left(\frac{V_S\cdot(j\omega M_{12})}{Z_1 Z_2 + \omega^2 M_{12}^2}\right) \cdot R_L \tag{4}$$

The transmitted power can be quantified using the S-parameter. S_{21} and η are acquired by the electric components of the circuit model as shown in Eq. (5).

$$S_{21} = 2\frac{V_L}{V_S}\left(\frac{R_S}{R_L}\right)^{1/2}, \quad \eta = \frac{|S_{21}|^2}{(1-|S_{11}|^2)} \times 100\ (\%) \tag{5}$$

IV. EXPERIMENT

The transmitter size is 200 × 200 × 200 mm^3 and has a wound of 5 turns into a helix. The receiver size is 200 × 200 mm^2 and has a wound of 5 turns into a helical loop coil.

The distance between the transmitter and the receiver ranges from 50 to 350 mm. The step size is 50 mm, as shown in Fig. 5.

Fig. 5. Transmitter and receiver at 200 mm at 0°.

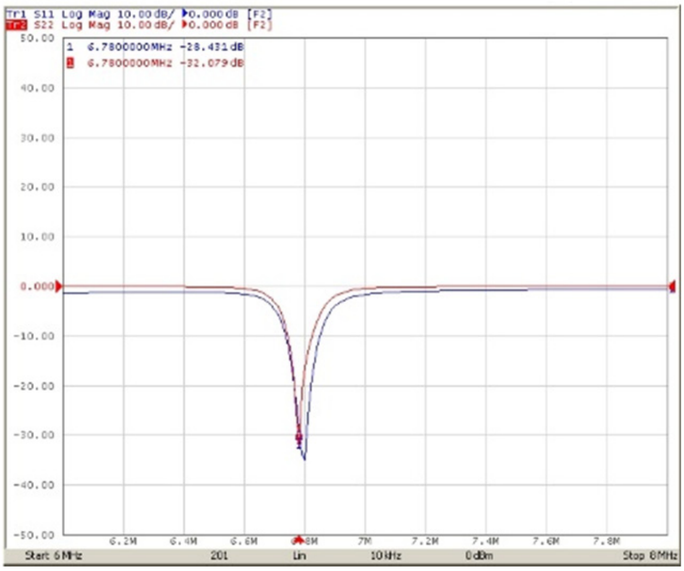
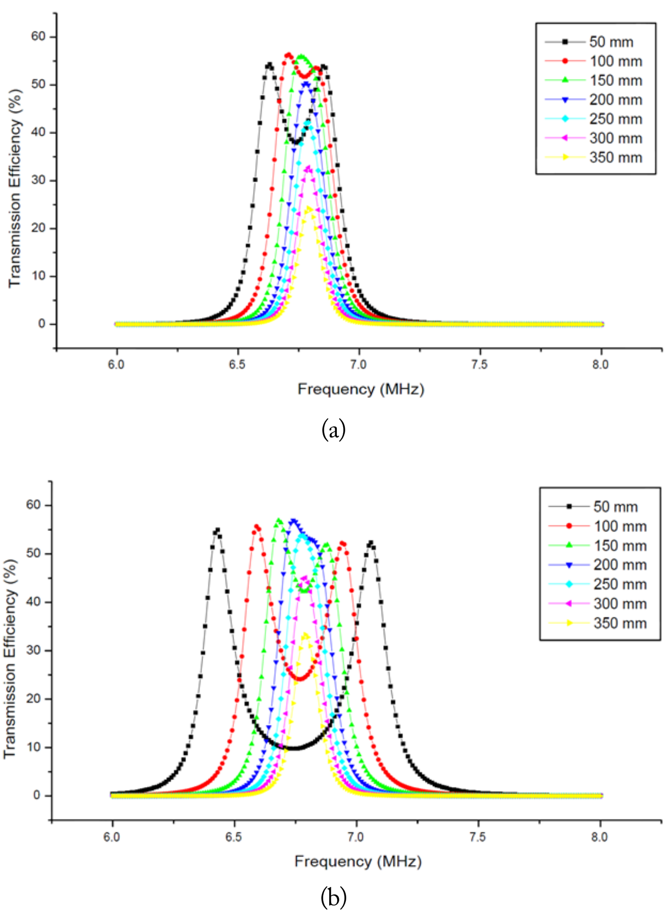


Fig. 6. Measured reflection coefficient at 200 mm at 0°.



(a)

(b)

Fig. 7. Measured transmission efficiency. (a) 0° and (b) 45°.

The S-parameter is measured at each position (from 0° to 315°).

The value of each reflection coefficient is −28.431 dB (S_{11})

Table 1. Measured S_{21} and TE at 200 mm

	0°	45°	90°	135°	180°	225°	270°	315°
S_{21} (dB)	−2.96	−2.65	−2.83	−2.66	−3.12	−2.62	−3.05	−2.65
TE (%)	50.58	54.33	52.12	54.2	48.75	54.7	49.55	54.33

TE = transmission efficiency.

Table 2. Comparison of omnidirectional resonators

	Kim and Seo [9]	This study
Frequency (MHz)	6.78	6.78
No. of ports	Two	One
TE @ 200 mm (%)	38.00–42.63	48.75–54.70

TE = transmission efficiency.

and −32.079 dB (S_{22}), as shown in Fig. 6. It shows that the transmitter and the receiver are strongly coupled.

Fig. 7 shows the occurrence of the split effect. It occurs within 150 mm at 0° and 200 mm at 45°. At 0°, the maximum transmission efficiency is 55.29% at 150 mm. At 45°, it is 54.33% at 200 mm.

V. CONCLUSION

This study proposed an omnidirectional resonator in the x-y plane using a crisscross structure. The omnidirectional magnetic vectors are generated by the current in the coils. It enables the receiver to receive uniform power at any angle in the x-y plane. Tables 1 and 2 show the transmission efficiency is approximately 50% at a distance of 200 mm with the proposed resonator.

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