Positioning-Free Resonant Wireless Power Transmission Sheet With Staggered Repeater Coil Array (SRCA)

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(Invited Paper)

***Abstract*—A magnetically resonant wireless power transmission sheet (WPTS) on a printed circuit board is developed. WPTS wirelessly supplies the power to electronic devices including the wearable wireless healthcare devices anywhere on the sheet with high efficiency. In order to increase a power transmission efficiency degraded by a misalignment of a receiver coil, a transmitter coil array and a proposed staggered repeater coil array (SRCA) are stacked in WPTS. One transmitter coil closest to the receiver coil and the surrounding four repeater coils are selectively activated based on the result of a position detection of the receiver coil. By adding SRCA to the transmitter coil array, the measured power transmission efficiency at the worst-case misalignment increases from 4.8% to 64% at a distance of 15 mm between the transmitter and receiver coils with a diameter of 40 mm. The measured results are verified by electromagnetic simulations.**

***Index Terms*—Magnetic resonance, power transmission, repeaters, wireless communication.**

I. Introduction

AMBIENT or ubiquitous charging of electronic devices such as smartphones is increasingly needed because the smartphone requires a frequent charging due to the increased power consumption. A wireless power transmission sheet (WPTS) [1]–[4] with a transmitter (TX) coil array and a selective activation of a TX coil based on the position detection of a receiver (RX) coil is one of the possible solutions for the ubiquitous charging. The WPTS embedded in a bed or clothes also enables the ubiquitous charging of wearable wireless healthcare devices. A wireless power transmission distance of the sheet, however, is short (e.g., 4 mm distance at 10% efficiency [1]) because an electromagnetic induction is used in the sheet. In order to increase the distance, a magnetic resonance [5] instead of the electromagnetic induction is used in this letter. In the newly developed magnetically resonant WPTS on a printed circuit board (PCB), however, wireless power transmission efficiency degradation due to a misalignment of the RX coil is still large even if the magnetic resonance is used. In order to keep a high efficiency regardless of the misalignment, a staggered repeater coil array (SRCA) is proposed in this letter [6]. By using a WPTS with an SRCA, a positioning of the RX coil is not required, thereby enabling the ubiquitous charging.

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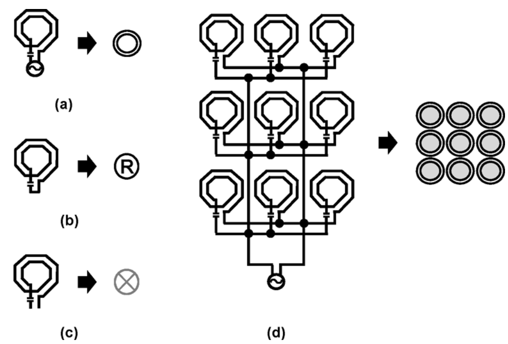


Fig. 1. Four types of coils used in coil arrays in Fig. 2. (a) Transmitter coil (TXC). (b) Repeater coil (RepC). (c) Open coil. (d) Nine transmitter coils (9 TXCs).

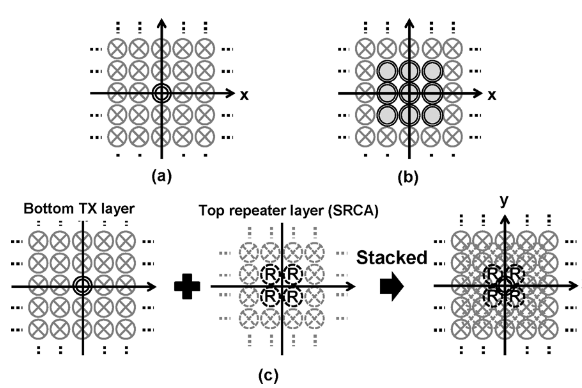


Fig. 2. Three different coil arrays. (a) Conventional 1-TXC scheme [1], [3], [4]. (b) 9-TXC scheme [2]. (c) Proposed stacked 1 TXC +4 RepC scheme.

II. Resonant Wireless Power Transmission Sheet With SRCA

A WPTS has transmitter coil arrays. In a WPTS, the target size is 1–2 m^2, and the target thickness is less than 1 mm. In a WPTS, a transmitter coil is selectively activated based on the position detection [1]–[4] of RX coil. The purpose of this letter is to propose the best configuration of the coil array that achieves the highest wireless power transmission efficiency at the worst

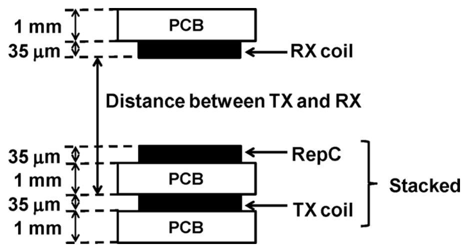


Fig. 3. Thickness of the coil arrays.

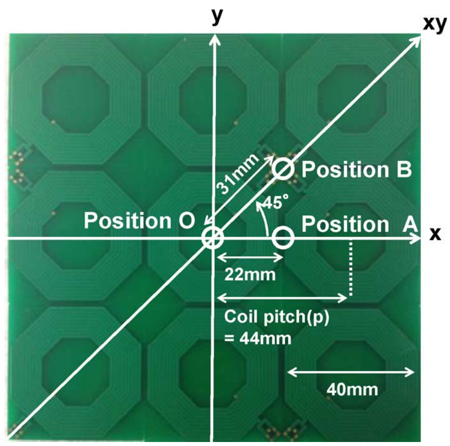


Fig. 4. Photograph of 3 × 3 coil array fabricated on PCB.

TABLE I
SUMMARY OF COIL FOR MAGNETIC RESONANCE

Parameters	Value
Diameter	40mm
Coil pitch (p)	44mm
Number of turns	9
Line width	1mm
Line spacing	0.1mm
Thickness of metal	35µm
Thickness of PCB	1mm
Inductance	3.42µH
Chip capacitor	39pF (TXC, RepC) 33~39pF (Receiver coil)
Frequency	13.8~16.2MHz

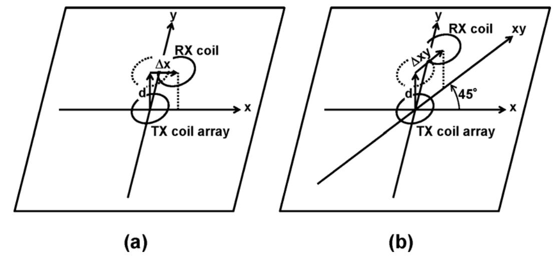


Fig. 5. Definition of distance (d) and misalignment (a) Δx and (b) Δxy.

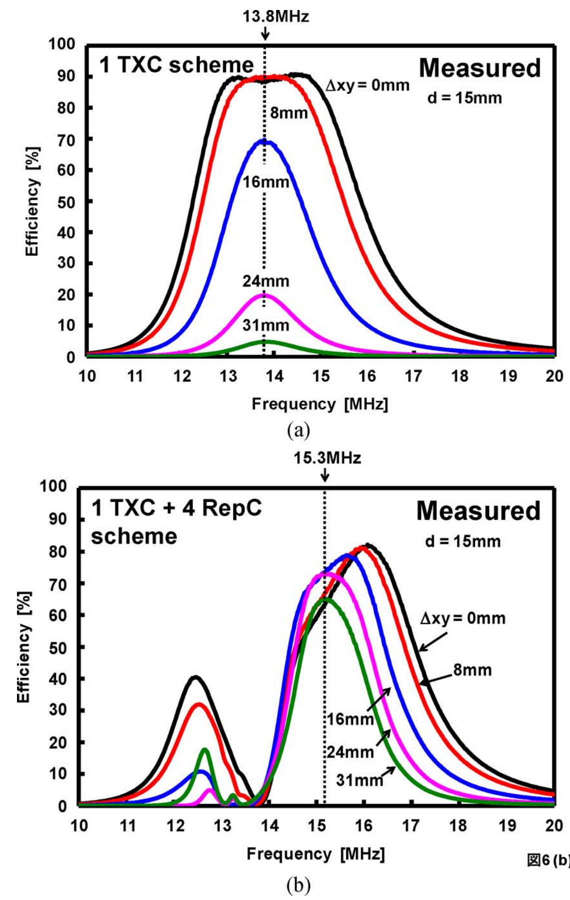


Fig. 6. Measured frequency dependence of efficiency. (a) Conventional 1-TXC scheme. (b) Proposed stacked 1 TXC +4 RepC scheme.

misalignment condition of RX coil. In order to find the best configuration, the efficiency of three different coil arrays are compared.

Fig. 1 shows three types of coils used in the coil arrays. Marks for the three types of coils are defined. The transmitter coil (TXC) in Fig. 1(a) is a power feeding coil. The repeater coil (RepC) in Fig. 1(b) is a short coil to extend the wireless power transmission distance [7]. The open coil in Fig. 1(c) is a nonactivated and unused coil. The nine transmitter coils (9 TXC's) in Fig. 1(d) are nine coils sharing a single power source.

Fig. 2 shows the three different coil arrays compared in this letter. In the conventional 1-TXC scheme [1], [3], [4] in Fig. 2(a), one TXC closest to the RX coil is activated based on the result of a position detection of the RX coil, and all the other coils are open. In the 9-TXC scheme [2] in Fig. 2(b), nine TXCs are activated. In the proposed stacked 1 TXC +4 RepC scheme in Fig. 2(c), a bottom TX layer and a top repeater layer are stacked, and one TXC in the bottom TX layer and the surrounding four RepC's in the top repeater layer are activated. The repeater layer is called SRCA because the centers of the TX coils and the centers of the repeater coils are staggered with each other. Fig. 3 shows thickness of the coils of the setup.

Fig. 4 shows a photograph of the 3 × 3 coil array fabricated on FR4 PCB. The diameter of the octagonal coil is 40 mm, and the coil pitch (p) is 44 mm. "Position O," "Position A," and "Position B" of the RX coil are defined to evaluate the efficiency at the misalignment conditions. Table I summarizes the coil for the magnetic resonance. The number of turns of the coil is nine, and the thickness of the metal is 35 μm. Chip capacitors are used to resonate the coil for the magnetic resonance.

III. EXPERIMENTAL RESULTS

In order to compare the three different coil arrays in Fig. 2, the dependence of the efficiency on the frequency, the distance, and the misalignment are measured. One TX coil is driven. The

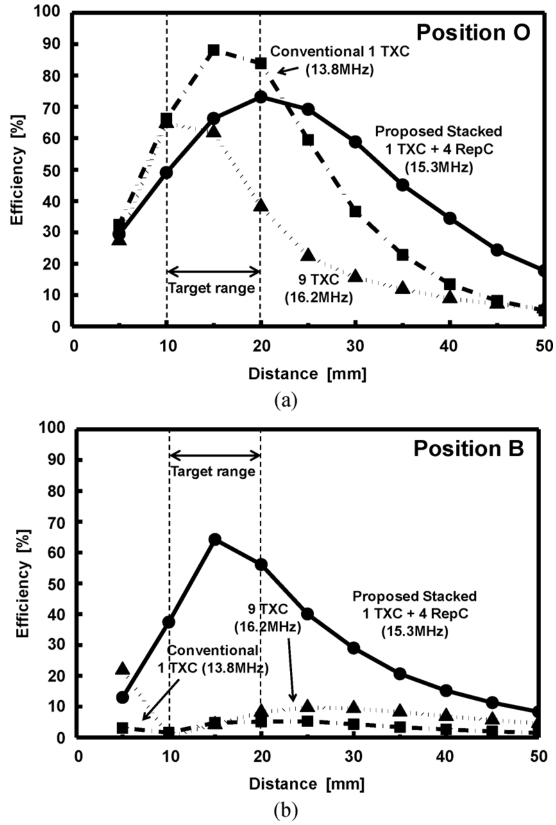


Fig. 7. Measured distance dependence of WPT efficiency in three different coil arrays. (a) Position O. (b) Position B.

coils are matched to 50 Ω. S_{21} is measured with the VNA and converted into the efficiency. Fig. 5 shows a definition of the distance and the misalignment. The distance is defined as d. The misalignment on the x-axis and xy-axis are defined as Δx and Δxy, respectively.

Fig. 6 shows a measured frequency dependence of the efficiency. Fig. 6(a) and (b) shows the conventional 1-TXC scheme and the proposed stacked 1 TXC +4 RepC scheme, respectively. d is 15 mm, and Δxy is varied. The frequency that achieves the highest efficiency at the worst misalignment condition of $\Delta xy = 31$ mm (Position B) is used in the following measurements for each of the three different coil arrays.

Fig. 7 shows a measured distance dependence of the efficiency in the three different coil arrays. Fig. 7(a) and (b) shows the efficiency at Position O and Position B, respectively. The target d in this letter is 10–20 mm. At Position O, the conventional 1-TXC scheme achieves the highest efficiency at $d =$ 15–20 mm. In contrast, at Position B, the proposed stacked 1 TXC +4 RepC scheme achieves the highest efficiency at $d >$ 5 mm. The 15-mm distance that achieves the highest efficiency in the proposed stacked 1 TXC +4 RepC scheme at Position B is used in the following measurements.

Fig. 8 shows a measured misalignment dependence of the efficiency in the 3 different coil arrays. Fig. 8(a) and (b) shows Δx and Δxy dependence, respectively. The horizontal axis is normalized by p. d is 15 mm. As Δx or Δxy increases, the efficiency decreases except for the proposed stacked 1 TXC +4 RepC scheme. Therefore, Position O ($\Delta x = 0$ in Fig. 8(a) and $\Delta xy = 0$ in Fig. 8(b)) are the best-case misalignments, while Position A [$\Delta x/p = 0.5$ in Fig. 8(a)] and Position B

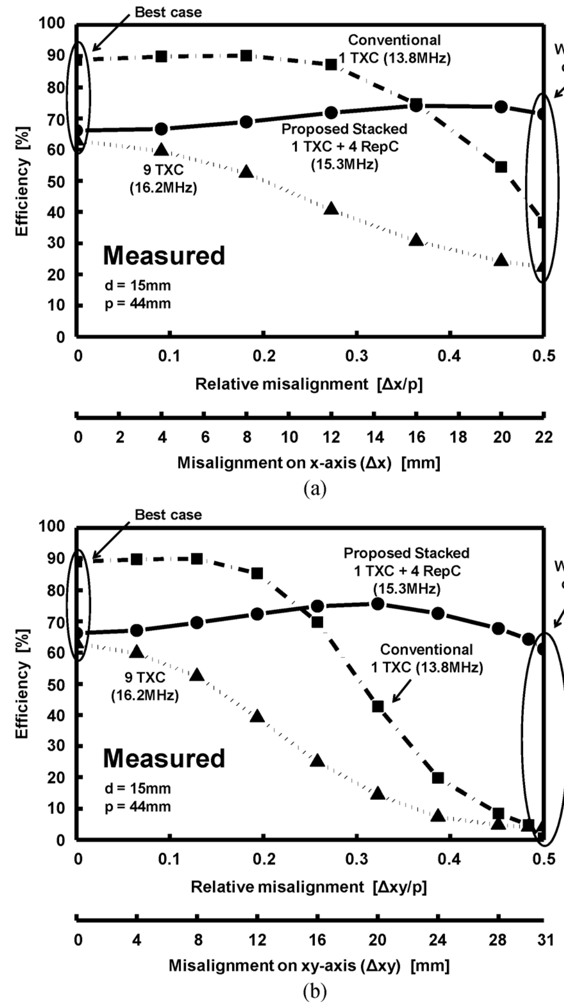


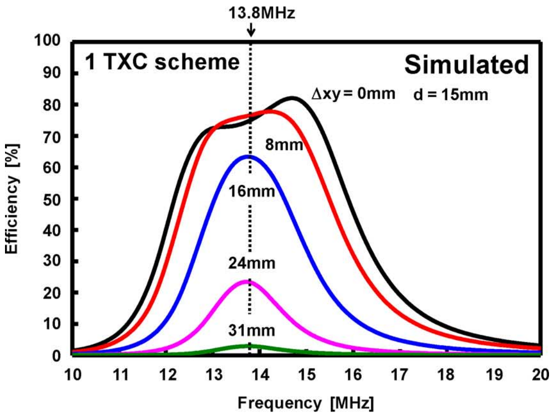
Fig. 8. Measured misalignment dependence of WPT efficiency in three different coil arrays. (a) Δx dependence. (b) Δxy dependence.

TABLE II
SUMMARY OF FREQUENCY AND WPT EFFICIENCY

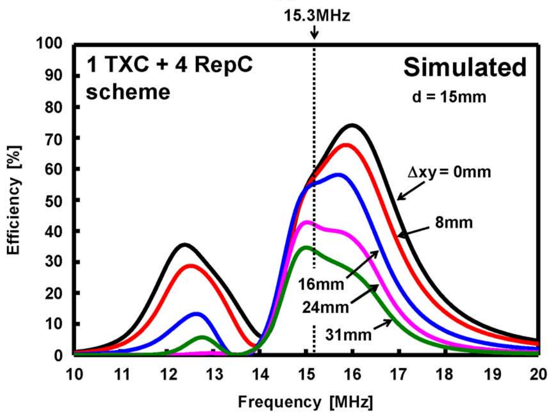
Scheme	Frequency (MHz)	Efficiency		
		Position of RX coil		
		O (Best case)	A (Δx=p) (Worst case)	B (Δxy=√2p) (Worst case)
1 TXC (Conventional)	13.8	89%	37%	4.8%
9 TXC	16.2	63%	22%	4.2%
Stacked 1 TXC + 4 RrepC (Proposed)	15.3	66%	71%	64%

[$\Delta xy/\sqrt{2}p = 0.5$ in Fig. 8(b)] are the worst-case misalignment. The efficiency of the proposed stacked 1 TXC +4 RepC scheme is more than 64% at any misalignment.

Table II summarizes the frequency and the efficiency at Position O, Position A, and Position B in the three different coil arrays. Compared to the conventional 1-TXC scheme, the efficiency of the proposed stacked 1 TXC +4 RepC scheme increases from 37% to 71% at Position A, and from 4.8% to 64% at Position B. The increase of the efficiency at the worst-case misalignment by adding SRCA is very important because the end-product performance of WPTS is determined by the worst (= minimum) efficiency.

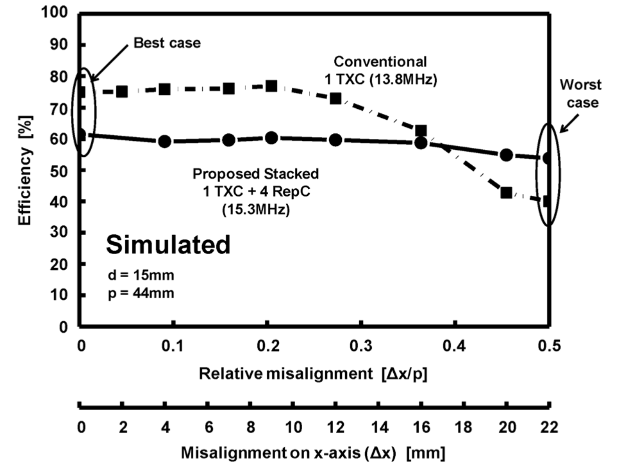


(a)

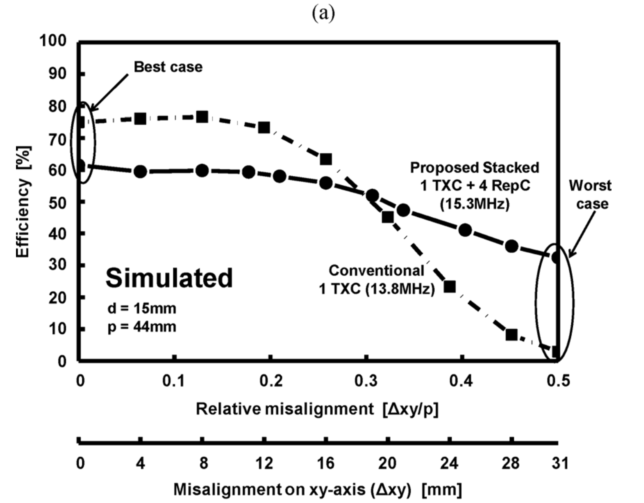


(b)

Fig. 9. Simulated frequency dependence of efficiency. (a) Conventional 1-TXC scheme. (b) Proposed stacked 1 TXC +4 RepC scheme.



(a)



(b)

Fig. 10. Simulated misalignment dependence of WPT efficiency in two different coil arrays. (a) Δx dependence. (b) Δxy dependence.

IV. Verification With Electromagnetic Simulations

In order to validate the measured results, 2.5-dimensional electromagnetic simulations are performed with Momentum (Agilent). Fig. 9 shows a simulated frequency dependence of the efficiency, which corresponds to the measured results in Fig. 6. Fig. 9(a) and (b) shows the conventional 1-TXC scheme and the proposed stacked 1 TXC +4 RepC scheme, respectively. The simulated frequency dependence in Fig. 9 correlates with the measured results in Fig. 6.

Fig. 10 shows a simulated misalignment dependence of the efficiency in the conventional 1-TXC scheme and the proposed stacked 1 TXC +4 RepC scheme, which corresponds to the measured results in Fig. 8. Fig. 10(a) and (b) shows Δx and Δxy dependence, respectively. The simulated misalignment dependence in Fig. 10 correlates with the measured results in Fig. 8, and the maximum simulation error is 47%.

V. Conclusion

SRCA is proposed to enable the positioning-free WPTS for the ubiquitous charging of the electronic devices including the wearable wireless healthcare devices. By stacking SRCA and the transmitter coil array, the measured efficiency at the worst-case misalignment condition increases from 4.8% to 64% at 15 mm distance. The improvement of the worst (= minimum) efficiency is very important because the end-product performance of WPTS is determined by the worst efficiency, regardless of the reduction of the efficiency of the best case due to the absorbed power by the repeater coils. The electromagnetic simulations prove the validity of the measurements.

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