A 6.78 MHz Wireless Power Transfer System Enabling Perpendicular Wireless Powering with Efficiency Increase from 0.02 % to 48.2 % by Adaptive Magnetic Field Adder IC Integrating Shared Coupling Coefficient Sensor

Hao Qiu, Toru Sai, and Makoto Takamiya
The University of Tokyo, Tokyo, Japan
hqiu@iis.u-tokyo.ac.jp

Abstract

To achieve a misalignment-free wireless power transfer (WPT), an IC for an adaptive magnetic field adder (AMFA), where the magnetic fields from multiple transmitter (TX) coils are adaptively added based on the coupling coefficient (k) between each TX coil and the receiver (RX) coil, is realized for the first time. A 6.78 MHz AMFA IC fabricated in 1.8 V, 180 nm CMOS integrating four power amplifiers (PAs) and shared k sensor increases the perpendicular WPT efficiency from 0.02 % to 48.2 % with the load power of 458 mW.

Introduction

Similar to the beamforming technique of the radio wave for 5G MIMO systems, an AMFA [1-3] that can add the magnetic fields from a TX coil array with the amplitude and phase control based on k between each TX coil and the RX coil is an emerging trend for a misalignment-free WPT. In the worst case, the RX coil can be perpendicular to the TX coil array plane, as shown in Fig. 1. Without any control in the TX coil array in Fig. 2 (b), the power transferred to the RX coil can be zero. Compared with the single TX coil in Fig. 2 (a), AMFA in Fig. 2 (c) can achieve a high WPT efficiency. All previous works [2-3] on AMFA, however, are implemented with discrete components. Those systems are bulky and costly. In addition, a vector network analyzer (VNA) is used to measure k in [2] and no k sensor is implemented in [3]. In order to achieve a $n \times n$ TX coil array, n^2 PAs are required, which is not practical. To solve the problems, in this paper, an AMFA IC integrating four PAs and the k sensor is realized for the first time. The proposed shared circuit topology reduces the die area to reduce the cost.

Adaptive Magnetic Field Adder IC

Fig. 3 shows a block diagram of 6.78 MHz WPT system. Four TX coils out of a 4 × 4 coil array are driven by four AMFA ICs (TX1 to TX4). Four differential class D PAs, the k sensor, and digital controllers are integrated on the AMFA IC. The PAs are adaptively controlled by digital signals from the top controller, which calculates the optimal amplitude and phase for each TX coil [1] based on the output from k sensors integrated on AMFA ICs. The amplitude of PA is digitally controlled by the phase difference between two half-bridges (HBs) [4]. Fig. 4 compares the AMFA ICs with and without the proposed shared topology. By sharing k sensors and HBs, the number of k sensors and HBs are reduced by 75 % and 38 %, respectively, thereby reducing the die area. Due to the shared HB, however, only one PA out of four PAs can be activated. The restriction is solved by the proposed alternate TX coil array shown in Fig. 5, in which one IC is connected to four TX coils. For different positions of the RX coil, four nearest 2 × 2 TX coils can be adaptively activated by four AMFA ICs. For example, when the RX coil is within the dashed region in case 1, TX coils 1A, 2A, 3A, and 4A are driven by TX1, TX2, TX3, and TX4, respectively. Fig. 6 shows two modes of the AMFA IC. In WPT mode in Fig. 6 (a), two HBs are activated and the duty ratio (D) of 6.78 MHz input is 50 %. In k sensing mode in Fig. 6 (b), one HB and the k sensor are activated, and we propose to use D of 2%. Fig. 7 shows an operation principle of the proposed k sensor. In Fig. 7 (a), at the resonant frequency, R is the equivalent resistance of the RX side seen from the TX side. Since R is a pure resistance [5], rather than using a VNA [2] or a gain & phase detector that is impossible for integration, we used a simple transimpedance amplifier (TIA) in Fig. 7 (a) for k sensor implementation. According to Eq. (2) in Fig. 7 (a), k can be calculated by measuring V_{OUT}. Figs. 7 (b) and (c) show the reason why D of 2 % is proposed in the k sensor. At D of 15 %, V_{OUT} waveform is distorted, because TIA operates beyond the linear region due to the large input current to TIA. D smaller than 10% can be used for the k sensor at R = 10 Ω. Fig. 7 (c) shows the design window of D for different R. In this work, we selected D = 2% for the wide range of k sensor.

Experimental Results

Fig. 8 shows a die micrograph of AMFA IC fabricated in 1.8 V, 180 nm CMOS. The die size is 2.6 mm × 2.7 mm. Fig. 9 shows the measured power efficiency and output power of the PA with a 4-bit control at the supply voltage of 1.8 V. The peak power efficiency reaches 74 % with an output power of 145 mW. All TX and RX coils are 10-turn flexible PCB coils with the outer diameter of 50 mm. Fig. 10 (a) shows the measurement setup corresponding to Fig. 5 (a). The RX coil is in perpendicular to the TX coil array plane. In Figs. 10 (b) to (f), the proposed WPT system is measured, when the vertical RX coil move to x-axis direction. For each position of the RX coil, firstly, the TX chips work in k sensing mode. Fig. 10 (b) shows the measured k between each TX coil and the RX coil. Then the optimal current amplitude and phase in each TX coil are calculated and the TX chips work in WPT mode. Figs. 10 (c) and (d) show the measured current amplitudes and phases, respectively. The measured system efficiency and load power are shown in Figs. 10 (e) and (f), respectively. Three TX control methods shown in Figs. 2 (a) to (c) are compared. At x = 0 mm, the proposed AMFA increases the WPT efficiency from 0.02 % to 48.2 % with the load power of 458 mW. Table I shows a comparison table with the conventional AMFA. This work achieves the AMFA IC integrating four PAs and the k sensor for the first time.

Acknowledgment

This work was partially supported by JST ERATO Grant Number JPMJER1501, Japan. We would like to thank Dr. Yang Jiang from University of Macau for his discussions.

References

[1] G. Yang *et al.*, *IEEE Trans. Signal Process.*, pp. 2860-2874, 2017.
[2] B. Zhao *et al.*, *IEEE Trans. Power Elec.*, pp. 7130-7139, 2017.
[3] B. H. Waters *et al.*, *IEEE Trans. Power Elec.*, pp. 6298-6309, 2015.
[4] M. K. Kazimierczuk, RF Power Amplifiers, Wiley, 2015.
[5] H. Qiu *et al.*, *IEEE Southern Power Elec. Conf.*, pp. 830-835, 2019.

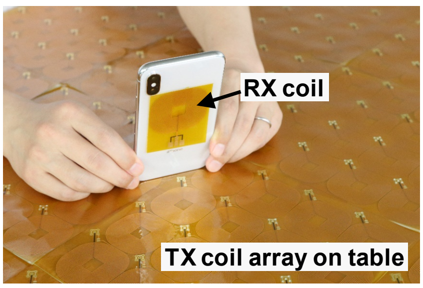

Fig. 1. Application scenario of perpendicular WPT.

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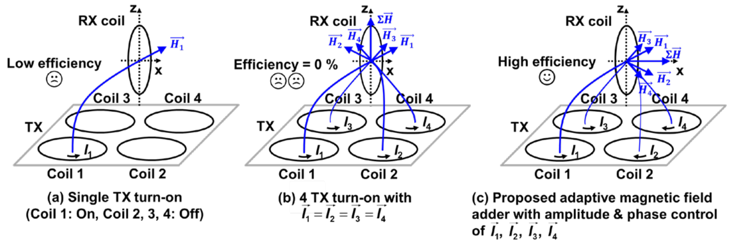


Fig. 2. Three control methods for perpendicular WPT.

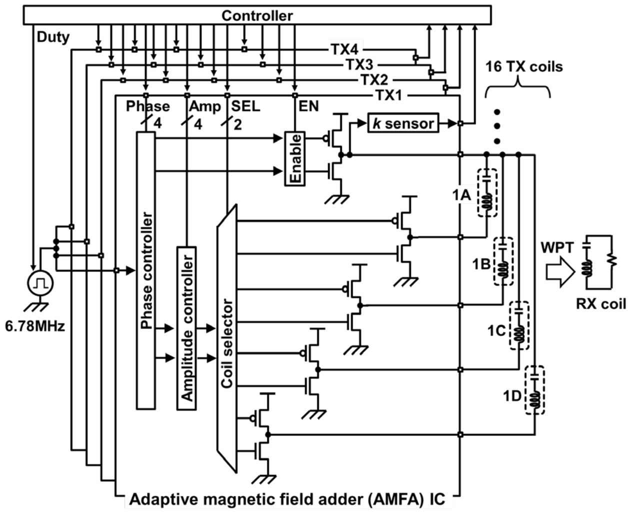
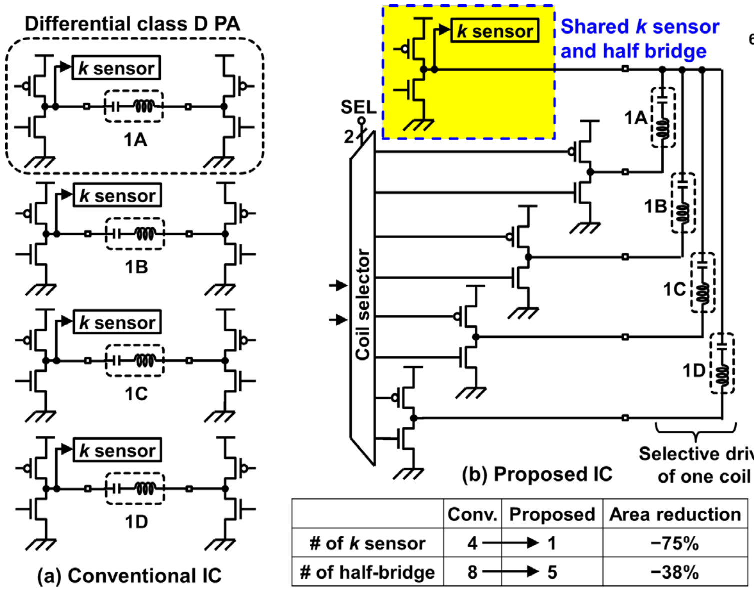


Fig. 3. Block diagram of 6.78 MHz wireless power transfer system.



	Conv.	Proposed	Area reduction
# of *k* sensor	4 → 1		−75%
# of half-bridge	8 → 5		−38%

(c) Comparison table

Fig. 4. Proposed shared topology in AMFA IC.

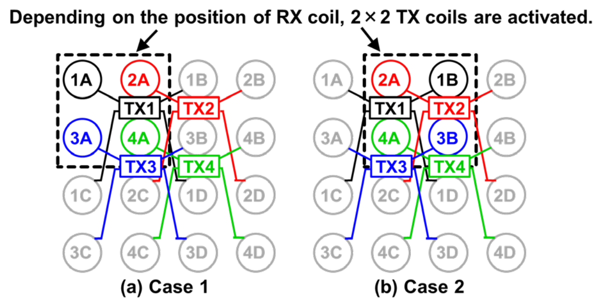


Fig. 5. Proposed 4×4 alternate TX coil array.

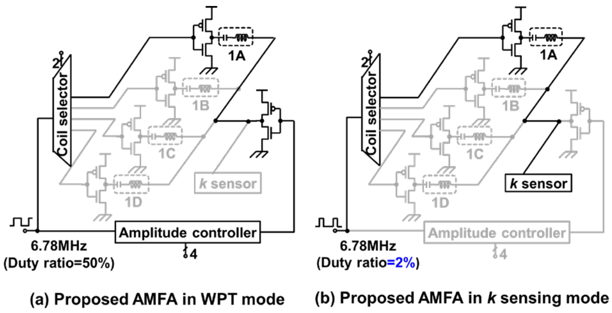
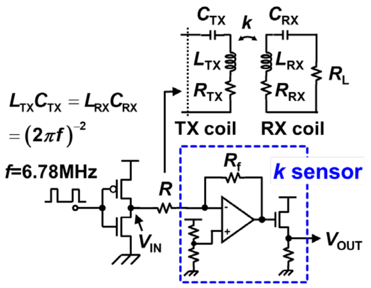


Fig. 6. Two modes of AMFA IC. (a) WPT mode. (b) *k* sensing mode.

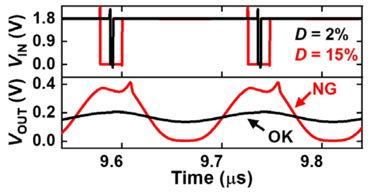


β: voltage gain of the source follower

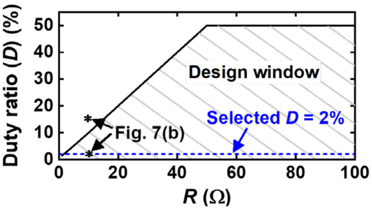
$$R = R_{TX} + \frac{(2\pi f k\sqrt{L_{TX}L_{RX}})^2}{R_{RX}+R_L} \quad (1)$$

$$k = \frac{\sqrt{(R_{RX}+R_L)(\beta R_f |V_{OUT}| / |V_{IN}| - R_{TX})}}{2\pi f \sqrt{L_{TX}L_{RX}}} \quad (2)$$

(a) Operation of *k* sensor



(b) Simulated waveforms at R=R_f=10Ω



(c) Design window at different *R*

Fig. 7. Operating principle of proposed *k* sensor.

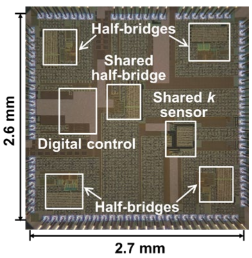


Fig. 8. Die micrograph.

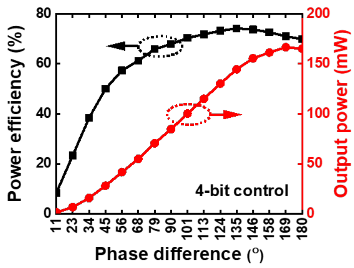


Fig. 9. Measured PA performance.

Table I Comparison with conventional AMFA.

		[2]	[3]	This work
Implementation		Discrete	Discrete	180nm CMOS
TX coil array control		Phase	Amplitude & Phase	Amplitude & Phase
Frequency		460MHz	13.56MHz	6.78MHz
Supply voltage		N/A	10V	1.8V
k sensor		Network analyzer	No	Integrated
Shared topology		No	No	Shared *k* sensor and half-bridge
TX ∥ RX	Load power	N/A	1.2W	55mW
	WPT efficiency	0.66%	43%	63%
	Distance*/TX size	7	1/2	1/2
TX ⊥ RX	Load power	N/A	N/A	458mW
	WPT efficiency	N/A	N/A	48.2%
	Distance*/TX size	N/A	N/A	1/2

* Distance between centers of TX and RX coils.

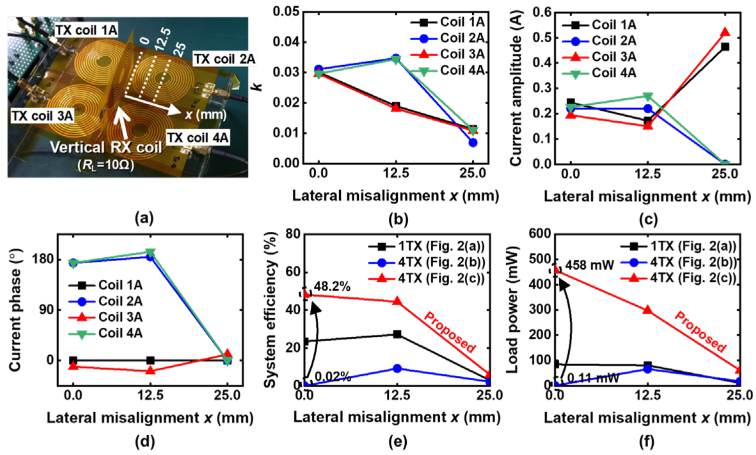


Fig. 10. (a) Measurement setup corresponding to Fig. 5(a).
(b)-(f) Measurement results of wireless power transfer system.