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5.8 GHz 4-Channel Beamforming Tx IC for Microwave Power Transfer

JAEKYUNG SHIN[1], JONGSEOK BAE[2], HYUNGMO KOO[1], SOONCHEOL BAE[1], JONGYUN NA[1], HANSIK OH[1], (Graduate Student Member, IEEE), HYUNGJIN JEON[1], HOSEOK JUNG[1], YOUNG CHAN CHOI[1], SEUNGMIN WOO[1], CHAN MI SONG[1], KEUM CHEOL HWANG[1], (Senior Member, IEEE), KANG-YOON LEE[1], (Senior Member, IEEE), AND YOUNGOO YANG[1], (Senior Member, IEEE)

[1]Department of Electrical and Computer Engineering, Sungkyunkwan University, Suwon 16419, South Korea
[2]Qualcomm Korea RFFE, Seoul 06060, South Korea

Corresponding author: Youngoo Yang (yang09@skku.edu)

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ABSTRACT The microwave power transfer (MPT) system requires a massive Tx array for building a focused radio wave to efficiently transfer power to the Rx. Beamforming IC is one of the core elements for the massive Tx array. This paper presents a 5.8 GHz 4-channel beamforming Tx IC based on a CMOS process. The beamforming Tx IC includes a resistive 4-way power splitter, 5-bit differential phase shifters, drive amplifiers, and power amplifiers. Each channel is designed to transmit a power of no less than 100 mW. To verify the Tx IC, a 16-channel beamforming Tx module based on 16 patch antennas and four 4-channel Tx ICs was designed. The module also includes a PLL, a frequency doubler, and a 4-way Wilkinson power divider. MPT experiments to verify the beamforming IC and module were carried out using the implemented 16-channel Tx module at 5.8 GHz. Received power levels of 13 dBm and 2.1 dBm were achieved at distances of 0.4 and 1.4 m, respectively. The results are almost similar to the values acquired from the calculation using the Friis equation.

INDEX TERMS Microwave power transfer, massive Tx array, beamforming, complementary metal-oxide-semiconductor (CMOS), Tx IC.

I. INTRODUCTION

Various devices for mobile, wearable, or wireless sensors of Internet of Things (IoT) have been developed and used in various ways for our life. Since one of the most important features of these devices is mobility, charging the battery of the device is very important issue for the convenience of the users. To improve the convenience of charging, wireless charging methods have been studied in a few ways [1]–[4]. Wireless charging methods based on magnetic induction or electro-magnetic (EM) resonance have been widely adopted for mobile or wearable devices due to capability of high power transfer and high power transfer efficiency [5]–[8]. However, the methods based on magnetic induction or EM resonance require very tight alignment in a very short distance between the Tx and the Rx. Within a few meters for the charging distance, MPT technology based on EM-wave radiation as an alternative method has been emerging to charge relatively low power-consuming devices [9]–[16].

MPT systems are generally designed to operate in the Industry-Science-Medical (ISM) bands. However, the path loss for the transmission distance becomes inherently large in such a high frequency band [17]. The path loss can be reduced by using a high-gain Tx and Rx antennas which can be achieved using a massive antenna array. Using the massive Tx antenna array, the beam can be formed and dynamically steered to more efficiently transmit power to an arbitrary position of the Rx, or to the Rx with mobility in the range [18]–[20].

To form and steer the radiated beam from the Tx antenna array, the phase of the radiated signal from each Tx element should be adjusted for optimum power transfer. Hence, each Tx element should include a phase shifter, a power amplifier,

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and an antenna. The overall Tx array consists of a number of Tx elements and some extra components, such as a signal generator, multi-way power dividers, drive amplifiers, dc power management circuits, digital control circuits, and so on.

Several beamforming methods for far-field and/or near-field MPT applications have been reported [21]–[32]. For far-field applications, the retrodirective method has been popularly used by utilizing a pilot signal that is transmitted from the Rx, to estimate the channel condition between the Tx and Rx for beamforming [21]–[28]. In particular for near-field applications, the retroreflective method has also been adopted by utilizing a pilot signal transmitted from the Rx to directly acquire the optimum phase of the signal for each Tx element [29]–[32]. Since both retrodirective and retroreflective methods require a pilot Tx in the Rx and a pilot Rx in the Tx element, the systems utilizing these methods can be complex, and the Rx has additional power consumption arising from the pilot generation and transmitting circuits. To reduce the system complexity of the retrodirective or retroreflective methods, methods using a look-up table (LUT) were proposed [33], [34]. The phase sets for various Rx locations were predetermined, and stored in the LUT. The Tx should find the best phase set for the Tx array using a backscatter communication with the Rx [33], or an out-band communication using a Bluetooth Low Energy (BLE) between the Tx and Rx [34]. In [35], a beamforming Tx based on an orthogonal or pseudo-orthogonal masks was proposed for near-field MPT. It is also able to have a simple structure, due to having no pilot Tx and Rx.

So far, many beamforming Tx modules for MPT applications have been reported [29]–[33]. A 4-channel retroreflective beamforming Tx for 2.08 GHz was reported in [29]. Each channel has an output power of 0.25 W. Using an Rx at a distance of 0.5 m, a received power of 14 mW was obtained. A 8-channel retroreflective Tx module for 2.125 GHz was reported in [30]. Each channel has an output power of 0.175 W. Using an Rx at a distance of 0.5 m, a received power of 7 mW was obtained. A 16-channel retroreflective beamforming Tx for 2.45 GHz was reported in [31]. Each channel has an output power of 0.016 W. Using an Rx at a distance of 1 m, a received power of 11 mW was obtained. A 64-channel retroreflective beamforming Tx module for 5.2 GHz with a size of as large as $27.2 \times 27.2 \times 28\ cm^3$ was reported in [32]. Each channel has an output power of 0.5 W. Using an Rx at a distance of 1 m, a received power of 446 mW was obtained. A 16-channel LUT-based beamforming Tx for 5.8 GHz far-field MPT was reported in [33]. The output power for a channel is about 0.079 W. Using an Rx at a distance of 0.5 m, a received power of 7 mW was obtained. Since the most previous Tx modules were based on commercial off-the-shelf (COTS) components, they could be complex and bulky.

To make the massive Tx array less complex, less expensive, and smaller, multi-channel Tx IC is essential. The Tx IC should include a power splitter, integrated phase shifters, drive amplifiers, power amplifiers, and digital control circuits. Then, the module can be designed using multiple number of these Tx ICs in cheaper and more compact way. There have been no many previous works about the Tx IC specialized for MPT applications. A beamforming Tx IC that works at 8.5-10 GHz was reported [36]. However, it only has a single Tx channel and an output power of merely 14 mW. A 4-channel Tx IC was reported for the 7.9-9.6 GHz band [37]. It also has a low output power of 13 mW per channel. It could be still difficult to use these ICs because additional power amplifier is required to obtain sufficient output power for MPT applications. A 16-channel Tx IC for MPT at the 10 GHz band was reported [35]. It includes a frequency synthesizer, a clock multiplying unit based on a phase-locked loop (PLL) for phase shifting of the signal, and stacked power amplifiers. Each channel has an output power of 50 mW. Using a Tx array with 16×25 channels using 25 Tx ICs and an Rx with 64 antennas, a received power of 0.2 W (dc) was reported at a distance of 1 m.

In this paper, a simple 4-channel beamforming Tx IC using a 130 nm bulk CMOS process is proposed for the 5.8 GHz MPT application. The beamforming Tx IC includes a resistive 4-way power splitter, 5-bit differential phase shifters, drive amplifiers, power amplifiers, and digital control circuits based on a serial peripheral interface (SPI). Each channel is designed to transmit a power of no less than 100 mW which is much higher than those reported by the previous works [35]–[37]. A very compact 16-channel beamforming Tx module using four 4-channel Tx ICs and 16 patch antennas were designed and implemented. Experiments for MPT were carried out using an adaptive sequential searching algorithm [38]. The results are summarized, and compared to the previous works.

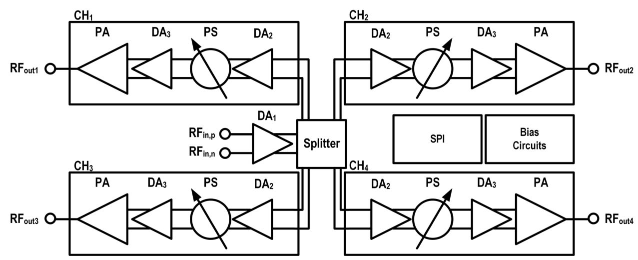


FIGURE 1. Block diagram of the 4-channel beamforming Tx IC.

II. 4-CHANNEL TX IC

A. DESIGN

Structure and design of the 4-channel Tx IC is presented in this section. Fig. 1 shows a block diagram of the 4-channel beamforming Tx IC. The Tx IC includes a resistive 4-way power splitter, an SPI for digital control, bias circuits, 5-bit differential phase shifters, drive amplifiers, and power amplifiers. The signal input to the Tx IC is amplified by DA_1 (the first drive amplifier), and is split into each Tx channel by the resistive 4-way power splitter. To compensate for the losses of the resistive 4-way power splitter and a phase shifter of each channel, two DAs (DA_2 and DA_3) are deployed in each channel before and after the phase shifter. After DA_3, a power amplifier (PA) comes as the final stage of each Tx. Using the digital control circuit based on SPI, phases of the phase shifters and bias conditions of the amplifiers can be controlled.

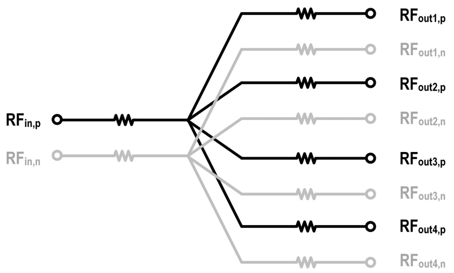


FIGURE 2. **Schematic of the resistive 4-way power splitter.**

Fig. 2 shows a schematic of the resistive 4-way power splitter. The resistive 4-way power splitter has a differential structure to split the input signal, and supply it to each Tx channel. Though it could have larger loss due to the resistors, it has significantly smaller size compared to the conventional Wilkinson power divider based on quarter-wave transmission lines. All the resistors used in the power splitter are 30 Ω. The resistive power splitter has a size of as small as $160 \times 180\ \mu m^2$, and showed a simulated insertion loss of no larger than 12.1 dB, and a simulated return loss of no less than 50 dB. Isolation characteristics between any two of the output ports were designed to be no less than 11.5 dB.

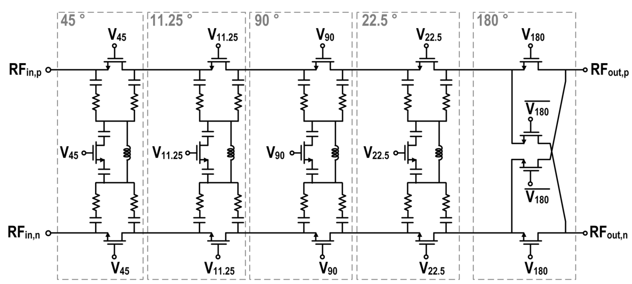


FIGURE 3. **Schematic of the 5-bit differential phase shifter.**

Fig. 3 shows a schematic of the 5-bit differential phase shifter. Each phase shifting block was designed with a switched filter structure except the 180° block. Since there is only one series switch in the signal path of each block, it can have low insertion loss. Except for the 180° block, which is simply based on cross switching for the + and − paths, all other blocks, such as 11.25°, 22.5°, 45°, and 90° blocks, consist of 3 switches. For the reference state, all 3 switches should be turned on, so that the parallel resonance circuit at the center provides very high impedance. Then, the signal can pass through the switches on the + and − signal paths with no phase shift. For the phase shifting state, all 3 switches should be turned off. Due to the virtual ground at the midpoint of the

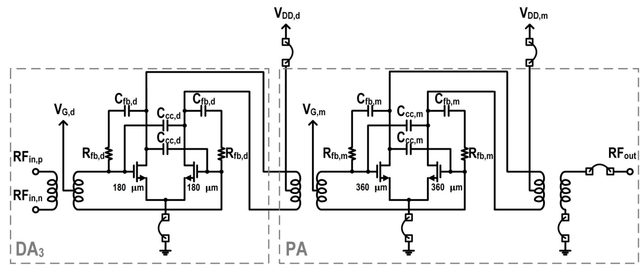


FIGURE 4. **Schematic of the DA_3 and PA as a two-stage amplifier.**

inductor, a high-pass C-L-C network can be formed to shift the phase from the reference phase. The values of the C-L-C network should be optimized to have the given phase shift value for each block. For the simulated results, both S_{11} and S_{22} were obtained as no larger than -8 dB, S_{21} was obtained as about −10 dB, and the rms phase error was just 1.2°.

Fig. 4 shows a schematic of DA_3 and PA as a differential two-stage amplifier. The gate widths of DA_1, -2 and -3 are the same as 360 μm, while PA has a twice larger gate width of 720 μm. All amplifiers have a gate length of 0.35 μm for a V_{DD} of 3.3 V using a 130 nm bulk CMOS process. To improve the stability and power gain, neutralization of the feedback capacitor was conducted using cross-coupled capacitors (CCCs) for both DA and PA. At the output of the PA, an on-chip transformer as a balun is deployed to convert the differential signal to a single-ended for interconnection with an antenna. The output transformer has a loss of 1.5 dB. For the simulation results of this two-stage amplifier, S_{11} of no larger than −30 dB, S_{21} of about 27 dB, and PAE of 27% at 20.7 dBm of the output power were achieved.

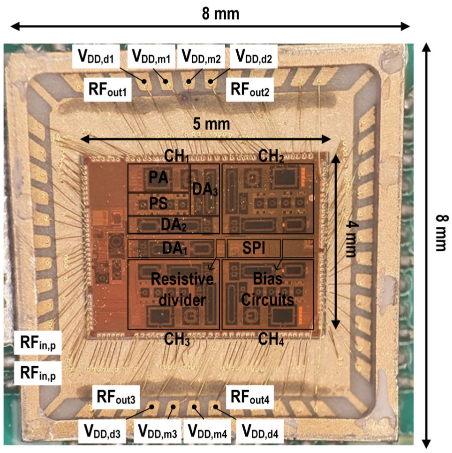
B. IMPLEMENTATION AND MEASUREMENT RESULTS

The 4-channel beamforming Tx IC described in the previous sub-section was implemented using TSMC's 130 nm bulk CMOS process. Fig. 5 shows the photographs of the implemented 4-channel beamforming Tx IC in (a) and the evaluation board for the Tx IC in (b). The Tx IC has a size of $5 \times 4\ mm^2$, and is packaged using an $8 \times 8\ mm^2$ QFN.

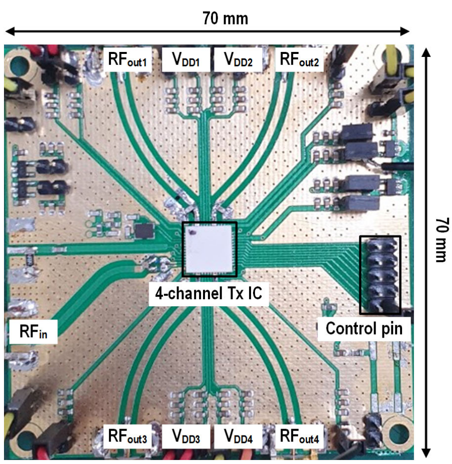
Fig. 6 shows the measured performances of each channel for the Tx IC according to the phase control at 5.8 GHz: (a) small-signal gain and (b) phase shift. The measured small-signal gain is in the range of from 22 to 26 dB, while the measured phase shift spreads evenly from 0° to 360° using 5 control bits. Fig. 7 shows the measured performances of the channel #1 in the Tx IC for the frequency range of 5.5-5.9 GHz. Fig. 7(a) shows the peak output power which is distributed in the range of 16-20 dBm and the power consumption of about 33 dBm. The peak output power at the 5.8 GHz reaches to about 20 dBm as shown. Fig. 7(b) shows the measured small-signal gain of the channel #1 according to the phase control for each frequency point. For the frequency of 5.5-5.9 GHz, the small-signal gain spreads from 17 to 26 dB for the overall phase control angles. Fig. 7(c) shows the phase shift characteristics of the channel #1 according to the

TABLE 1. Performance comparison of the proposed 4-channel beamforming Tx IC to the previous works.

Ref.	Process technology	Freq. (GHz)	Signal generation	Tx channel per chip	Phase step (°)	P_{OUT} (mW/channel)	P_{DC} (mW)	Phase control	PA structure	Size (mm^2)
[35]	65 nm CMOS	10	On-chip PLL	16	11.25	50	-	LO phase shifting	4-stacked, differential	-
[36]	0.18 μm CMOS	8.5-10	Off-chip PLL	1	5.625	14	640	RF phase shifting	2-stacked, single-ended	4.4×2.9
[37]	0.13 μm CMOS	7.9-9.6	Off-chip PLL	4	22.5	13	870	RF phase shifting	2-stacked, differential	2.9×3.0
This work	0.13 μm CMOS	5.6-5.8	Off-chip PLL	4	11.25	100	2000 (500/channel)	RF phase shifting	Common-source, differential	5.0×4.0

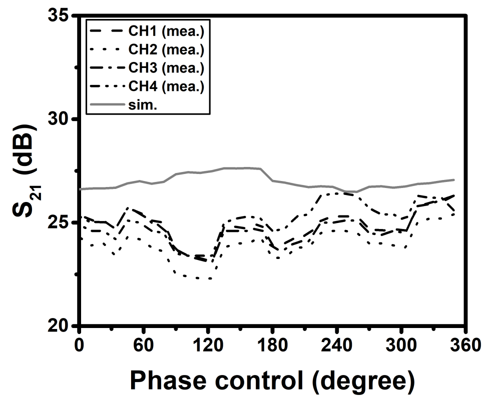


(a)

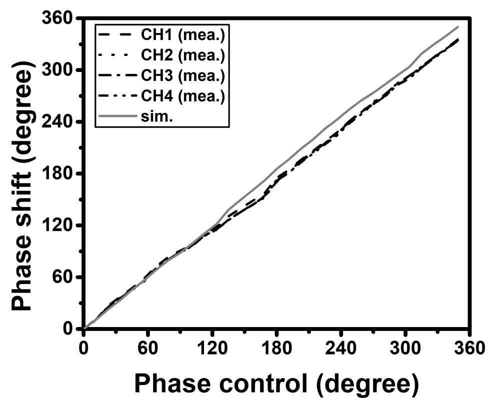


(b)

FIGURE 5. Photographs of the implemented 4-channel beamforming Tx IC (a), its evaluation board (b).



(a)



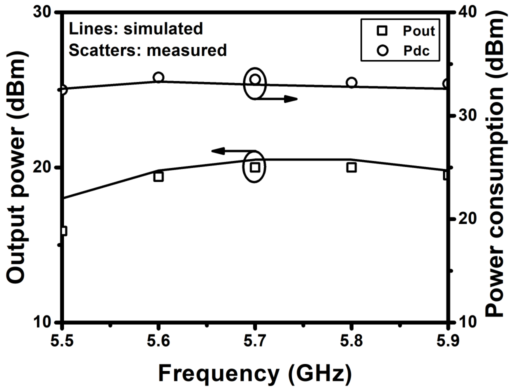
(b)

FIGURE 6. Measured and simulated performances of each channel for the Tx IC at 5.8 GHz according to the phase control: (a) small signal gain (S_{21}), (b) phase shift.

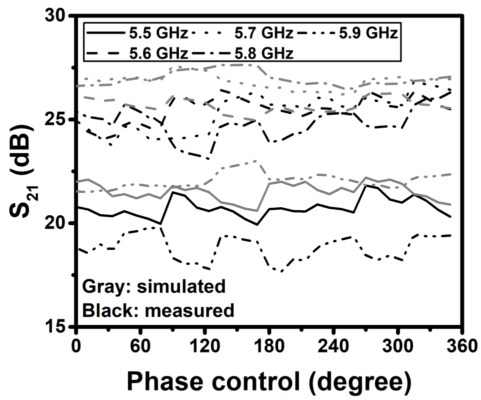
phase control. The measured performances of the proposed 4-channel beamforming Tx IC are summarized and compared to the previous works in Table 1. The Tx IC in this work exhibited the highest output power of about 100 mW per channel. It also has relatively small chip size in spite of having relatively low operation frequency of 5.8 GHz and having 4 channels per chip.

III. 16-CHANNEL TX MODULE AND BEAMFORMING EXPERIMENTS

Using four 4-channel Tx ICs, a Tx module that has 16 channels was implemented, and was evaluated for the MPT performances. Its structure is shown in Fig. 8. It has four 4-channel Tx ICs, 16 patch antennas, a 4-way Wilkinson power divider, a PLL to synthesize the 2.9 GHz signal, and a frequency



(a)



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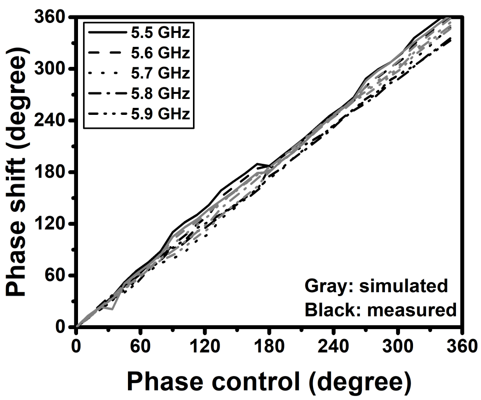


(c)

FIGURE 7. Measured and simulated performances of a channel in the Tx IC for the frequency range of 5.5-5.9 GHz: (a) peak output power and power consumption, (b) small signal gain (S_{21}), (c) phase shift.

doubler to make the 5.8 GHz input signal. The Tx module is controlled by Labview in a PC which runs the beamforming algorithm. MPT experiments were carried out with an Rx with one patch antenna and a 2-D sequential searching algorithm [38].

Fig. 9 shows the geometry of the antenna element for the Tx array and the Rx. A grooved rectangular patch is

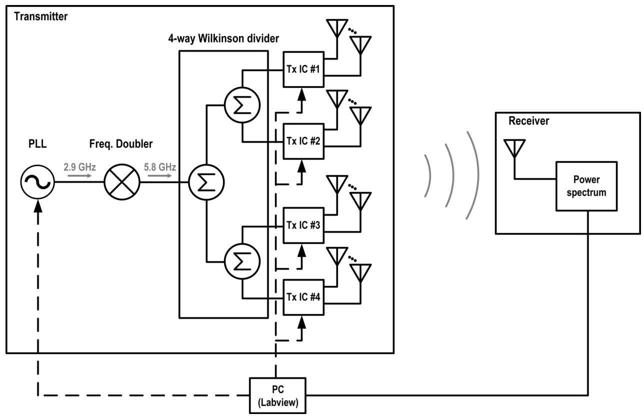


FIGURE 8. Block diagram of the 16-channel beamforming module.

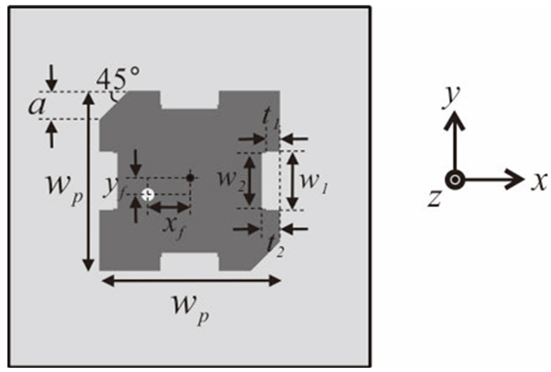


FIGURE 9. Antenna element for the Tx and Rx.

implemented on an RO4350B substrate with a thickness of 1.52 mm, a dielectric constant of 3.5, and a loss tangent of 0.0037. Using truncated patterns for its four sides and the feed point location ($x_f = -3$ mm, $y_f = -1$ mm), the right-handed circular polarization (RHCP) is obtained. The dimensions of this patch element were optimized with w_p of 13 mm, w_1 of 4.2 mm, w_2 of 4 mm, t_1 of 1 mm, t_2 of 1.3 mm, and a of 2.1 mm. The simulated bandwidth to have a reflection coefficient of no larger than -10 dB for the patch antenna was from 5.55 to 5.88 GHz. Fig. 10 shows the simulated radiation patterns for xz-plane in (a) and yz-plane in (a) at a frequency of 5.8 GHz. In the broadside direction, the RHCP gain is as high as about 6.11 dBic, while the LHCP gain is very low. The patches for the overall 16 Tx channels were implemented on a board and has a spacing of 26 mm (0.5 λ_0) between the adjacent patches. Then, the overall gain of the 4 $\times$ 4 antenna array can be expected to be about 16.56 dBic.

Fig. 11 shows the photographs of the implemented 16-channel beamforming Tx module for its front side view in (a) and for its rear side view in (b). The size of the module is 140 $\times$ 120 mm^2 due to using a 4-layer RO4350B ($\epsilon = 3.5$) PCB whose height is as thin as 2.1 mm. Antenna was implemented on the front side of the module, while all other circuits, such as a PLL, a frequency doubler, 2-way Wilkinson dividers for 4-way power splitting, and four Tx ICs, are deployed on the rear side of the module.

TABLE 2. Performance comparison to the previous works.

Ref.	Beamforming method	Freq. (GHz)	Tx configuration	# of Tx elements	P_{OUT} (W/element)	P_{OUT} (W)	# of Rx antennas	P_R (mW)	Distance (m)	Size (mm^3)
[29]	Retroreflective	2.08	COTS	4	0.25	1	1	14 (RF)	0.5	-
[30]	Retroreflective	2.125	COTS	8	0.175	1.4	1	7 (RF)	0.5	-
[31]	Retroreflective	2.45	COTS	16	0.016	0.25	3	11 (RF)	1	-
[32]	Retroreflective	5.2	COTS	64	0.5	32	1	8-446 (RF)	1-4	272×272×280
[33]	LUT	5.8	COTS	16	0.079	1.3	16	7 (RF)	0.5	-
[35]	Orthogonal mask	10	Twenty five 16-channel Tx ICs	400	0.05	20	64	20-2000 (dc)	1-3	-
This work	2-D sequential searching	5.8	Four 4-channel Tx ICs	16	0.1	1.6	1	1.6-20 (RF)	0.4-1.4	140×120×2.1

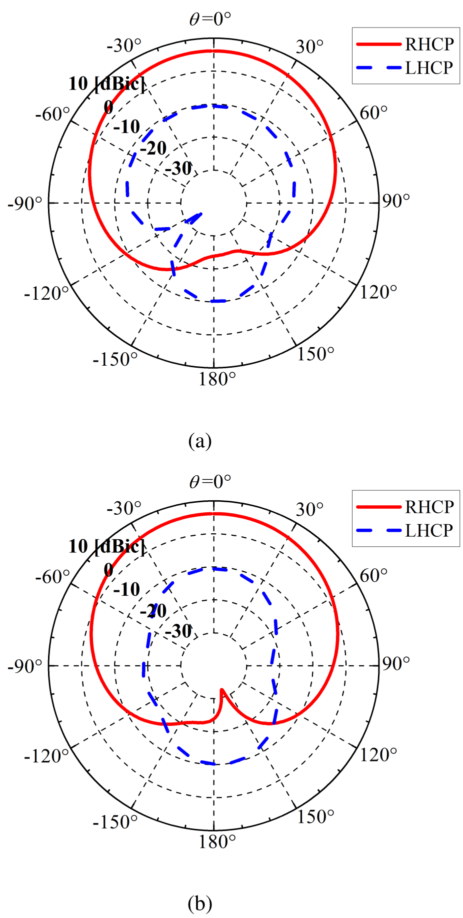


FIGURE 10. Simulated radiation patterns of the antenna element at 5.8 GHz: (a) *xz*-plane, (b) *yz*-plane.

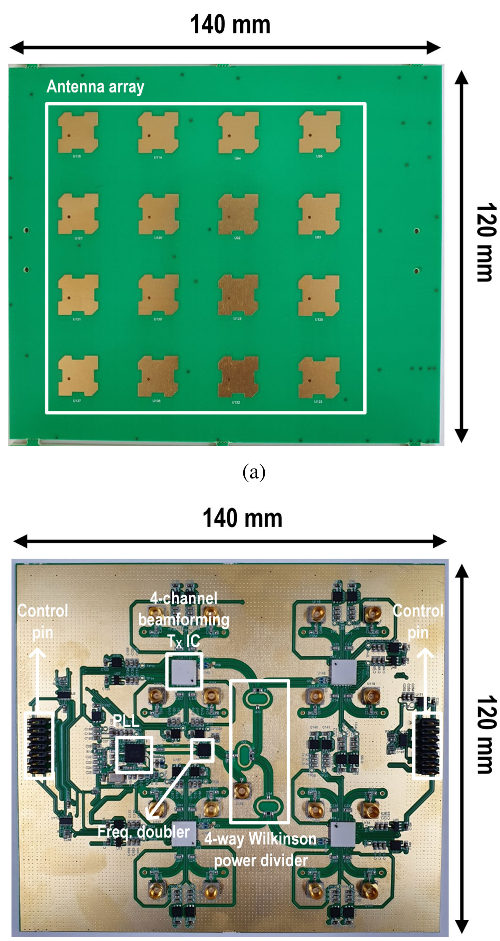
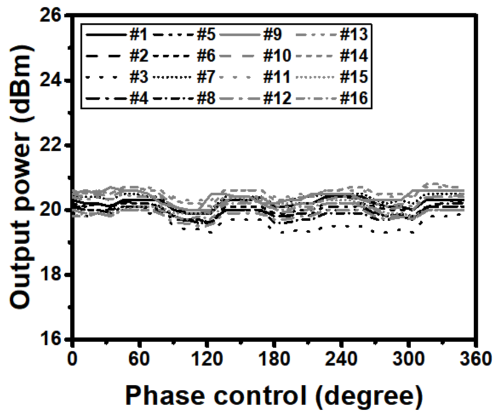
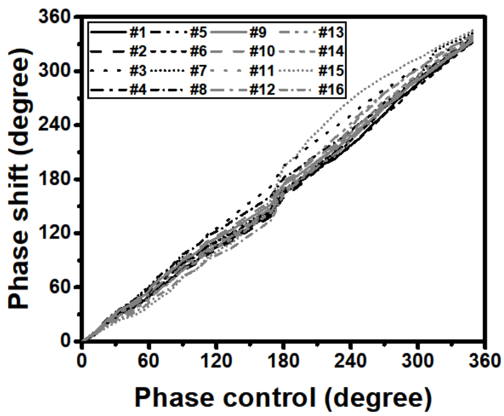


FIGURE 11. Photographs of the implemented 16-channel beamforming Tx module: (a) front view, (b) rear view.

Fig. 12 shows the output performances of the implemented 16-channel beamforming module according to the phase control at 5.8 GHz: output power in (a) and phase shift in (b). For all the 16 channels, output power levels of about 20 dBm were obtained for the entire phase control angles. Fig. 13 shows an experimental setup for MPT. The Rx has the same patch antenna that was designed for the Tx element. The received power is measured, and is used to find the optimum phase set for the Tx elements using the sequential searching algorithm which was realized using Labview in the PC.



(a)



(b)

FIGURE 12. Output performances according to the phase control of the 16-channel beamforming Tx module at 5.8 GHz: (a) output power, (b) phase shift.

Since each channel transmits about 0.1 W, the overall 16 channel can transmit total power of about 1.6 W. Fig. 14 represents the measured and calculated received RF power levels at the Rx. As shown, the measured and calculated power levels match very well. Received RF power levels are in the range of 13-2.1 dBm at the distance of 0.4-1.4 m.

In Table 2, the performances of this work are summarized and compared to the previous works for short- and mid-range MPT. The Tx modules presented in [29]–[33] are based on COTS components, whereas the Tx module proposed in this work has a simple structure with the 4-channel Tx ICs and just a few additional COTS components, such as a PLL and a frequency doubler. For [35], the Tx module has overall 400 Tx channels, and transmits a power of 0.05 W per channel. It also has an Rx that has 64 antennas. Since, the Tx module in this work has 16 Tx channels and the Rx has only one antenna, the received power is relatively low compared to that of [35]. However, since the Tx IC in this work transmits a high out power of 0.1 W per channel, received power can be easily increased by increasing the number of Tx channels using more Tx ICs.

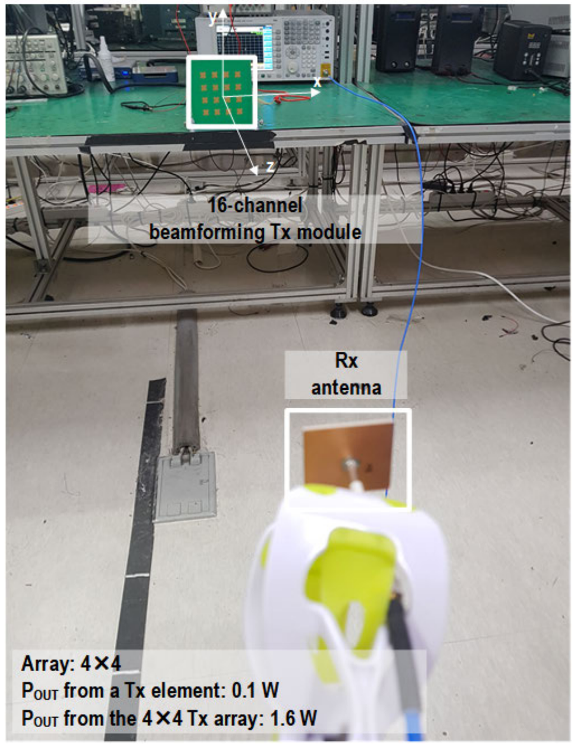


FIGURE 13. Experimental setup for the 16-channel beamforming Tx array.

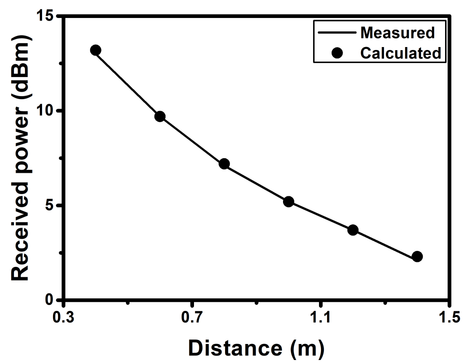


FIGURE 14. Measured and calculated received RF power levels at the Rx.

IV. CONCLUSION

In this paper, a 4-channel beamforming Tx IC is proposed for the Tx module of the 5.8 GHz MPT system for charging mobile/wearable devices or various wireless sensors. The proposed beamforming Tx IC is composed of a 4-way resistive power splitter, 5-bit digital controlled phase shifters, drive amplifiers, and power amplifiers. It has 4 transmitting channels, and each channel can transmit a signal that has an output power of no less than 100 mW. The Tx IC was designed and fabricated using TSMC's 130 nm bulk CMOS process.

In order to verify the performances of the beamforming Tx IC, a 16-channel beamforming Tx module for MPT was designed using 16 patch antennas on the front side of the module, a PLL to generate a 2.9 GHz signal, a frequency doubler to make a 5.8 GHz signal, a 4-way Wilkinson divider, and four beamforming Tx ICs. The Tx module was implemented using a 4-layer RO4350B PCB. Experiments were carried out using the implemented 16-channel Tx module and an Rx having the same patch antenna that is used for the Tx element. By adjusting the phases of the Tx elements using the 2-D sequential searching algorithm for the beamforming, received RF power levels of 13 and 2.1 dBm were obtained at the distances of 0.4 and 1.4 m, respectively. The results are almost similar to the values acquired from the calculation using the Friis equation.

If the number of channels were increased with more Tx ICs and antennas, greater distance or higher received power could be achieved using a still compact and planar Tx module. The proposed 4-channel Tx IC was proved for its performances to be applied for the massive Tx array for MPT. It could make the MPT systems more compact and cheaper compared to the systems based on the COTS components.

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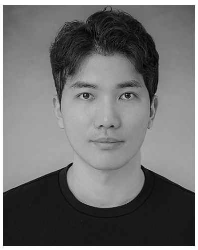
JAEKYUNG SHIN was born in Seoul, South Korea, in 1993. He received the B.S. degree from the Department of Electronic and Electrical Engineering, Korea Aerospace University, Goyang, South Korea, in 2018. He is currently pursuing the Ph.D. degree with the Department of Electrical and Computer Engineering, Sungkyunkwan University, Suwon, South Korea.

His current research interests include the design of RF/mm-wave power amplifiers, efficiency enhancement techniques, broadband techniques, and microwave power transmission.



JONGSEOK BAE was born in Suwon, South Korea, in 1987. He received the B.S. degree in electronic engineering from Chungnam University, Daejeon, South Korea, in 2014, and the Ph.D. degree from the Department of Electrical and Computer Engineering, Sungkyunkwan University, Suwon, in 2020.

Since 2020, he has been with the Department of Electrical and Computer Engineering, Sungkyunkwan University, where he designed power amplifiers. Since 2021, he has been with Qualcomm Korea RFFE, Seoul, South Korea, where he is currently a Senior Engineer. His research interests include the design of RF/mm-wave power amplifiers, RF and analog integrated circuits, and microwave power transfer.

HYUNGMO KOO was born in Seoul, South Korea, in 1992. He received the B.S. degree from the Department of Electronic and Electrical Engineering, Sungkyunkwan University, Suwon, South Korea, in 2016, where he is currently pursuing the Ph.D. degree with the Department of Electrical and Computer Engineering.

His current research interests include the design of RF power amplifiers, efficiency enhancement techniques, transceiver arrays, microwave power transmission, and passive circuits optimisations.

SOONCHEOL BAE was born in Daegu, South Korea, in 1995. He received the B.S. degree from the Department of Electronic and Electrical Engineering, Sungkyunkwan University, Suwon, South Korea, in 2019, where he is currently pursuing the M.S. degree with the Department of Electrical and Computer Engineering.

His current research interests include the design of RF/mm-wave power amplifiers, RF and analog integrated circuits, and wireless power transfer.

JONGYUN NA was born in Seoul, South Korea, in 1994. He received the B.S. degree from the Department of Electronic and Electrical Engineering, Sungkyunkwan University, Suwon, South Korea, in 2020, where he is currently pursuing the M.S. degree with the Department of Electrical and Computer Engineering.

His current research interests include the design of RF power amplifiers, RF integrated circuits, efficiency enhancement techniques, linearization techniques, and wireless power transfer.

HANSIK OH (Graduate Student Member, IEEE) was born in Seoul, South Korea, in 1991. He received the B.S. degree from the Department of Electronic and Electrical Engineering, Sungkyunkwan University, Suwon, South Korea, in 2016, where he is currently pursuing the Ph.D. degree with the Department of Electrical and Computer Engineering.

His current research interests include the design of RF power amplifiers, RF integrated circuits, analog integrated circuits, efficiency enhancement techniques, and linearization techniques.

HYUNGJIN JEON was born in Mokpo, South Korea, in 1994. He received the B.S. degree from the Department of Electronic and Electrical Engineering, Sungkyunkwan University, Suwon, South Korea, in 2020, where he is currently pursuing the Ph.D. degree with the Department of Information and Communication Engineering.

His research interests include the design of RF/mm-wave power amplifiers, RF/analog integrated circuit, efficiency enhancement techniques, linearization techniques, broadband techniques, and wireless power transfer systems.

HOSEOK JUNG was born in Daegu, South Korea, in 1995. He received the B.S. degree from the Department of Electronic and Electrical Engineering, Sungkyunkwan University, Suwon, South Korea, in 2020, where he is currently pursuing the M.S. degree with the Department of Electrical and Computer Engineering.

His current research interests include the design of RF power amplifiers, RF integrated circuits, efficiency enhancement techniques, and linearization techniques.

YOUNG CHAN CHOI was born in Seoul, South Korea, in 1996. He received the B.S. degree from the Department of Electronic and Electrical Engineering, Sungkyunkwan University, Suwon, South Korea, in 2020, where he is currently pursuing the Ph.D. degree with the Department of Information and Communication Engineering.

His research interests include the design of RF/mm-wave power amplifiers, efficiency enhancement techniques, linearization techniques, broadband techniques, and mm-wave integrated circuits and systems.

SEUNGMIN WOO was born in Daegu, South Korea, in 1996. He received the B.S. degree from the Department of Electronic and Electrical Engineering, Sungkyunkwan University, Suwon, South Korea, in 2021, where he is currently pursuing the M.S. degree with the Department of Electrical and Computer Engineering.

His current research interests include the design of RF power amplifiers, broadband techniques, and MMICs.

CHAN MI SONG received the B.S. degree in electronics and electrical engineering from Dongguk University, Seoul, South Korea, in 2015, and the Ph.D. degree from the Department of Electrical and Computer Engineering, Sungkyunkwan University, Suwon, South Korea, in 2021.

Her research interests include optimisation of array antenna and microwave power transfer.

KEUM CHEOL HWANG (Senior Member, IEEE) received the B.S. degree in electronics engineering from Pusan National University, Busan, South Korea, in 2001, and the M.S. and Ph.D. degrees in electrical and electronic engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea, in 2003 and 2006, respectively. From 2006 to 2008, he was a Senior Research Engineer at Samsung Thales, Yongin, South Korea, where he was involved with the development of various antennas, including multiband fractal antennas for communication systems, Cassegrain reflector antenna, and slotted waveguide arrays for tracking radars. From 2008 to 2014, he was an Associate Professor with the Division of Electronics and Electrical Engineering, Dongguk University, Seoul, South Korea. In 2015, he joined the Department of Electronic and Electrical Engineering, Sungkyunkwan University, Suwon, South Korea, where he is currently an Associate Professor. His research interests include advanced electromagnetic scattering and radiation theory and applications, design of multi-band/broadband antennas and radar antennas, and optimisation algorithms for electromagnetic applications. He is a Life Member of KIEES and a member of IEICE.

KANG-YOON LEE (Senior Member, IEEE) received the B.S., M.S., and Ph.D. degrees from the School of Electrical Engineering, Seoul National University, Seoul, South Korea, in 1996, 1998, and 2003, respectively. From 2003 to 2005, he was with GCT Semiconductor Inc., San Jose, CA, USA, where he was a Manager of the Analog Division and worked on the design of CMOS frequency synthesizer for CDMA/PCS/PDC and single-chip CMOS RF chip sets for W-CDMA, WLAN, and PHS. From 2005 to 2011, he was with the Department of Electronics Engineering, Konkuk University, as an Associate Professor. Since 2012, he has been with the College of Information and Communication Engineering, Sungkyunkwan University, South Korea, where he is currently an Associate Professor. His research interests include implementation of power integrated circuits, CMOS RF transceiver, analog integrated circuits, and analog/digital mixed-mode VLSI system design.

YOUNGOO YANG (Senior Member, IEEE) was born in Hamyang, South Korea, in 1969. He received the Ph.D. degree in electrical and electronic engineering from the Pohang University of Science and Technology, Pohang, South Korea, in 2002. From 2002 to 2005, he was with Skyworks Solutions Inc., Newbury Park, CA, USA, where he designed power amplifiers for various cellular handsets. Since 2005, he has been with the School of Information and Communication Engineering, Sungkyunkwan University, Suwon, South Korea. His research interest includes RF power amplifiers.