A Programmable Pulser-Receiver Circuit for Single Transducer Medical Ultrasound System

Hyun Tae Park[1] and Ji Yong Um[a]
[1] Navcours Co., Ltd.
[a] Department of Medical IT Convergence Engineering, Kumoh National Institute of Technology
E-mail : jyum@kumoh.ac.kr

***Abstract* - This work presents a proof-of-concept pulser-receiver circuit for a single-transducer-based medical ultrasound system. The proposed circuit consists of a high-voltage pulser and a preamplifier. The pulser can generate an arbitrary pulse waveforms by adjusting external digital control signals. Also, the proposed pulser can drive a transducer with a capacitive load of several nF at a frequency up to 10 MHz by using a single-stack output stage. To reduce an active area, the return-to-ground path of pulser is reused as a transmit/receive switch during an echo-acquisition period. The mid-band gain of preamplifier can be adjusted, and the achieved maximum gain is 45 dB. The input-referred noise voltage of preamplifier is 5.1 μVrms at the maximum gain condition. The proposed ultrasonic pulser-receiver circuit was fabricated in a 180-nm BCD process. The pulser operates at supply voltages of ±10 V, and the preamplifier operates at supply voltages of ±0.9 V. The active area of fabricated chip is 1.09 mm^2.**

***Keywords*—Medical Ultrasound System, Preamplifier, Ultrasonic Pulser, Single Transducer**

I. INTRODUCTION

A medical ultrasound system interrogates a human body by using backscattered ultrasound waves. That is, after transmitting ultrasound waves into biological tissue, the medical ultrasound system acquires ultrasonic echo signals, so that it can reconstruct a change of acoustic impedance of medium along scan lines.

There are several results of integrated circuits to achieve interfaces with various ultrasonic transducers [1-8]. Most of these works deal with integrated circuits which can be attached to an ultrasonic transducer array. In most cases, these attachable chips need to reduce an overall data rate between a chip and an imaging system by using a real-time beamforming or a multiplexing scheme. However, the mostly adopted data-rate-reduction methods can increase a complexity of circuit and overall cost. In addition, a low

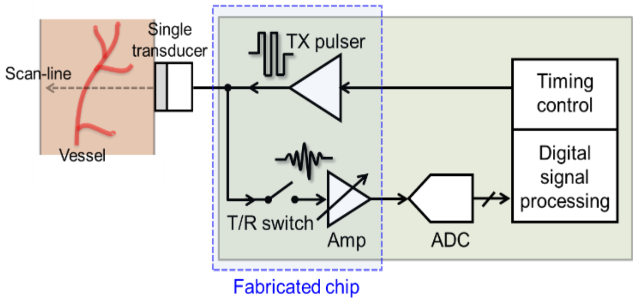


Fig. 1. Block diagram of single-transducer-based ultrasound system

yield of transducer elements can degrade the performance of ultrasonic sensor module. Correspondingly, a countermeasure circuit or methodology is necessary to mitigate the yield problem of transducer elements [7].

A medical ultrasound system can also be implemented using a single ultrasonic transducer. Compared to an array-based ultrasound system, a single-element ultrasound system has a relatively low complexity of signal processing and circuit structure. However, the single transducer ultrasound system cannot reconstruct an ultrasound image unless a mechanical scanning is used. In addition, the single transducer ultrasound system typically performs a reconstruction of amplitude-mode waveforms or Doppler signal processing for a single scan line [9-11]. Most single transducer ultrasound systems utilize commercial discrete chips to implement sensor interfaces and signal processing parts. These ultrasound systems have a relatively large circuit board and consume relatively large power.

In this work, we propose a pulser-receiver circuit for a single transducer-based medical ultrasound system. Fig. 1 presents a block diagram of integrated circuit dedicated to a single-transducer ultrasound system. As shown in Fig. 1, the proposed circuit corresponds to a sensor interface in a block diagram, and it is implemented as a chip for the purpose of proof-of-concept. It is required to control a number of cycles and a shape of ultrasonic pulse depending on a purpose of signal processing. The proposed ultrasonic pulser can reconfigure the number of cycles and the shape of the pulses by using digital control signals. In addition, in order to drive an ultrasonic transducer generating a relatively high acoustic pressure, the proposed ultrasonic pulser can drive a capacitive load of several nF at the maximum frequency of 10 MHz. Besides, in order to save an active area, the return-to-ground path of the ultrasonic pulser is reused as a

---

a. Corresponding author; jyum@kumoh.ac.kr

Manuscript Received Jun. 16, 2021, Revised Aug. 31, 2021, Accepted Aug. 31, 2021

transmit/receive (T/R) switch during the ultrasonic echo-signal acquisition period. A preamplifier is designed to amplify ultrasonic echo signals. The preamplifier has a closed-loop structure using capacitors, and the mid-band voltage gain can be adjusted using digital control signals.

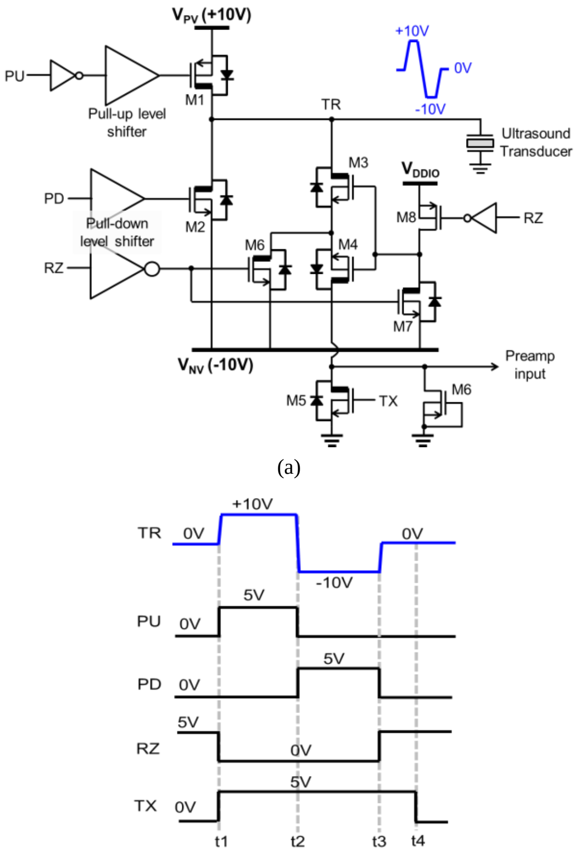
This paper is organized as follows. Section II describes a circuit diagram of ultrasonic pulser-receiver. Section III and Section IV present the measurement results and conclusions, respectively.

II. CIRCUIT DESIGN

In this work, the proposed ultrasonic pulser-receiver circuit repeatedly acquires ultrasonic echo signals from a single scan line. TABLE I summarizes the requirements and countermeasures for the proposed ultrasonic pulser-receiver circuit. To detect relatively small blood vessels on a scan line, this work uses a commercial ultrasound transducer with a center frequency of 10 MHz. Since the utilized transducer generates a relatively higher acoustic pressure than an element of typical transducer array, it has a capacitance of several nF. By considering the load condition and required ultrasonic center frequency of pulser, a number of transistor stack in the output stage of pulser is minimized. Also, to achieve a reasonable active area, a reconfigurable topology is adopted in a pulser. In case of noise performance of preamplifier, operational regions of transistors in preamplifier are optimized to suppress a thermal noise level.

TABLE I. Requirements of proposed pulser-receiver circuit

Requirement	Countermeasure
Large capacitive load (several nF) at center frequency up to 10 MHz	Minimum transistor stack in output-stage of pulser
Small active area	Reconfigurable topology of pulser
Low noise performance of preamplifier	Optimization of operational region of transistors



(a)

(b)

Fig. 2. High-voltage ultrasonic pulser; (a) schematic (b) timing diagram

A. High-Voltage Ultrasonic Pulser

A circuit diagram of the proposed high-voltage ultrasonic pulser is presented in Fig. 2(a). A transistor with a diode between drain terminal and source terminal corresponds to a lateral double-diffused metal oxide silicon (DMOS) transistor. Four supply voltages including V_{PV} (+10V), V_{NV} (-10V), V_{DDIO} (5V) and GND (0V) are utilized in this work. The transistors M1 and M2 act as a pull-up path and a pull-down path, respectively. As mentioned above, in a capacitive load condition of several nF, it is necessary to perform a pull-up or pull-down operation during a half period of the target center frequency. Considering the margin of the transition time of pulser output, it is designed such that the half period of 10 MHz equals to five times of time constant of output stage of pulser.

$$\frac{T_C}{2} = 5 \cdot R_{ON} \cdot C \qquad (1)$$

,where T_C, R_{ON}, and C correspond to a period of ultrasonic center frequency, an ON resistance of pull-up/down transistor, and a capacitance of ultrasonic transducer, respectively. When the capacitance C of the target transducer is assumed to be 2.5 nF, the required R_{ON} value of (1) is 4 Ω. Correspondingly, it is necessary to determine the size of pull-up/down transistors to have a resistance value of several Ohms.

In this work, the maximum gate-source voltage of utilized DMOS transistors is limited to 5V. Therefore, it is necessary to control the gate-source voltage of DMOS to ensure the reliability of transistor. The proposed pulser circuit uses a zener-diode-based level shifter circuit of [3] and does not use additional external DC voltages for level-shifting operation.

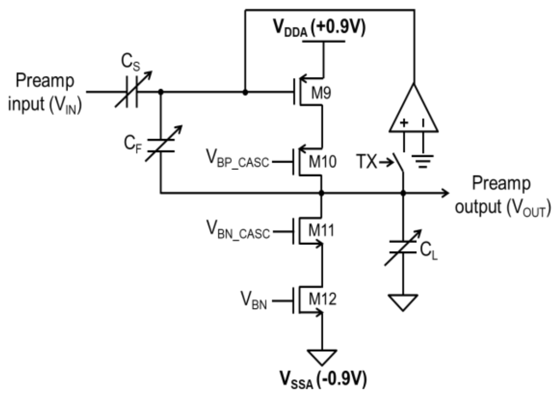


Fig. 3. Schematic of preamplifier

A return-to-ground path is implemented with a series connection of transistors M3, M4, and M5. The transistors of M3 and M4 in the return-to-ground path are as a form of back-to-back connection. Transistor M5 is turned on only when the output of the pulser is driven to 0V. During an echo-acquisition period, the transistor M5 is turned off, because the output of the pulser must be a floating state. Transistors M3 and M4 of the return-to-ground path maintain the turn-on state during the echo-acquisition period and act as a T/R switch. Therefore, the ultrasonic pulser in this work has a reconfigurable topology which embeds a T/R switch, thereby reducing an active area of overall circuit.

A timing diagram of the ultrasonic pulser is presented in Fig. 2 (b). The proposed pulser uses four digital control signals. A shape of the pulser output can be reconfigured using control signals. As a result, a unipolar or a bipolar pulse can be generated. In addition, when control signals are properly prepared, an arbitrary chirp pulse or a coded pulse can also be generated. Then, the proposed pulser can be used for applications such as coded excitation [10, 11].

B. Preamplifier

A schematic of preamplifier of pulser-receiver circuit is presented in Fig. 3. It uses a basic single-ended cascode amplifier and adjusts a voltage gain using an input capacitor C_S and a feedback capacitor C_F. Considering an input equivalent noise of amplifier, the operating region of input transistor M9 is set to subthreshold region, and the current source transistor M12 is set to strong inversion [12]. Cascode transistors M10 and M11 do not significantly affect noise performance. Since the DC operating point of input transistor primarily affects the noise performance of amplifier, the aspect ratio *W/L* of transistor M9 is set large enough. In addition, in order to separately optimize the DC operating points of gate of transistor M9 and the output of amplifier, a feedback scheme using an auxiliary amplifier is adopted. In an ultrasound system of this work, the ultrasound-transmission period and the echo-acquisition period are repeated. Therefore, a feedback circuit repeatedly sets the gate voltage of input transistor M9 so that the operating point of amplifier output becomes the middle voltage of supply rails during the ultrasound transmission period.

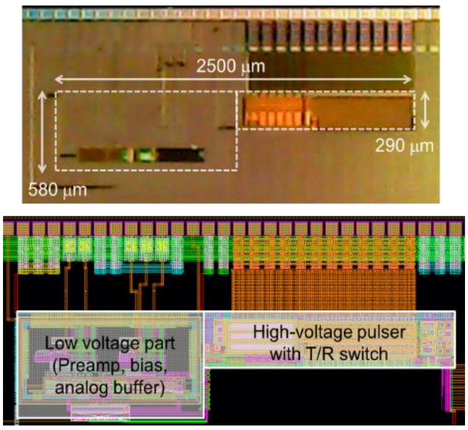


Fig. 4. Chip micrograph and layout

The gate voltage of input transistor (M9) can be drifted when an echo acquisition period is relatively long. So, the utilized feedback-amplifier-based biasing scheme should be verified by considering the maximum time duration of echo acquisition period, the leakage current, and gate capacitance of input transistor. Considering the leaky-corner simulation condition such as a FF corner at temperature of 85°C, the equivalent leakage current at the gate node of input transistor is 41.8 fA with the gate capacitance of 955 fF including parasitic capacitance due to layout. The duration of echo acquisition period is primarily determined by the imaging depth of ultrasound application. Considering the speed of sound of 1540 m/s and the maximum imaging depth of 15 cm, the feasible time duration of echo acquisition period can be around 195 μs. Then, the resultant drift of gate voltage of input transistor corresponds to 8.7 μV, which results in a drift of preamplifier output of 7 mV by considering the open-loop gain of preamplifier. Hence, the overall voltage drift due to floated-state due to feedback-amplifier-based biasing scheme is relatively small, and the preamplifier does not lose its DC operating point.

A bias current and a load capacitance can be adjusted to adapt to the center frequency of the utilized transducer. Also, an adjustment of load capacitance can enhance a noise performance by optimizing bandwidth of amplifier [12].

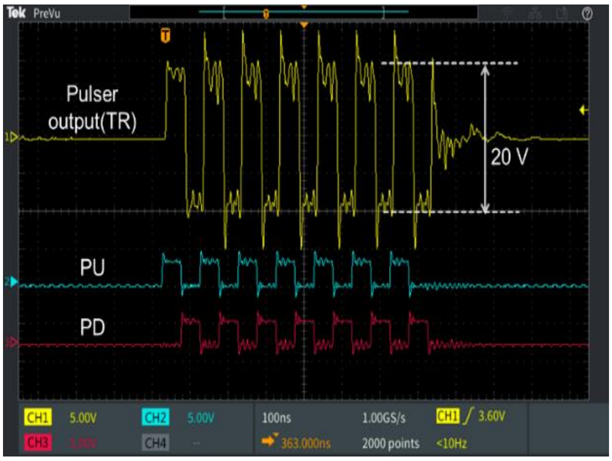


Fig. 5. Measured waveforms of ultrasonic pulser

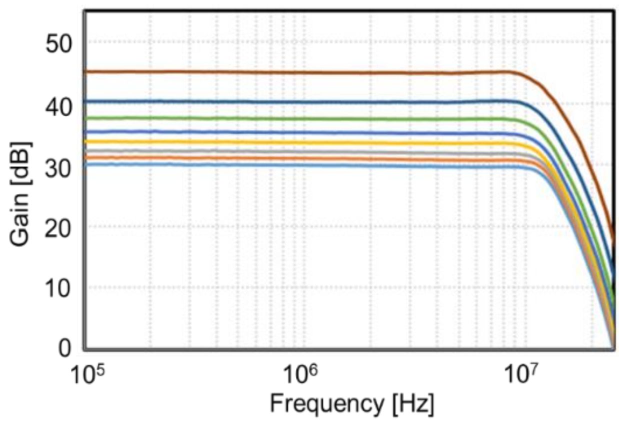
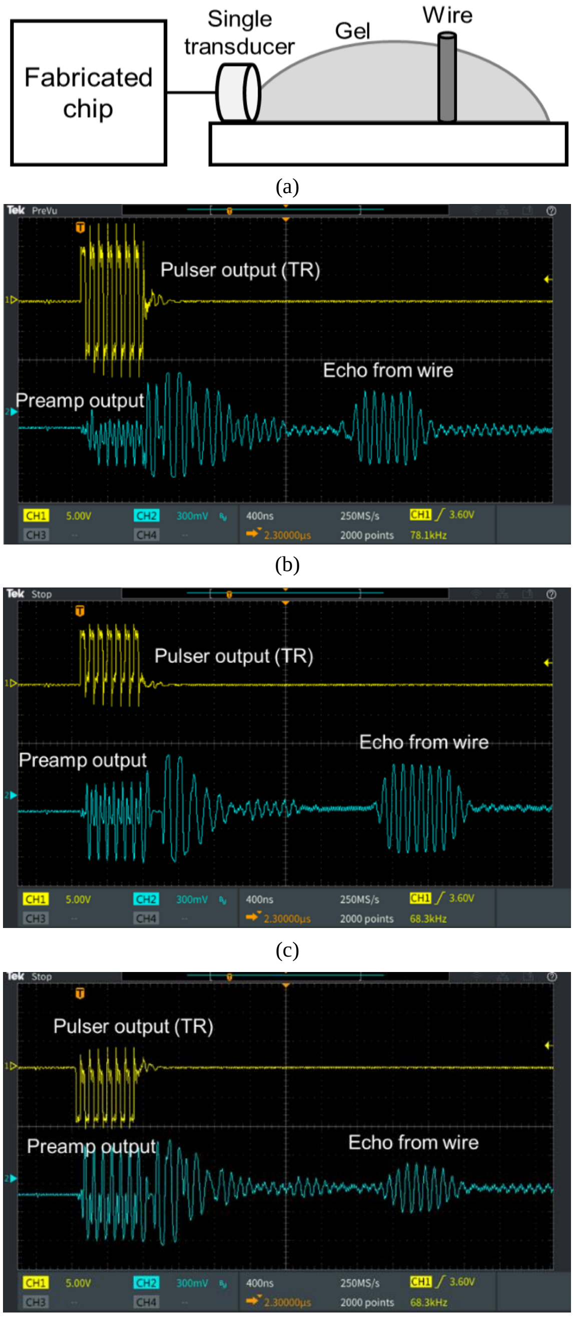


Fig. 6. Measured frequency response of preamplifier

III. IMPLEMENTATION RESULTS

The proposed pulser-receiver circuit was fabricated in TSMC 180-nm BCD process. A chip micrograph along with layout is shown in Fig. 4, and an active area of fabricated chip is 1.09 mm^2. The implemented pulser uses ±10 V and 5 V as supply voltages. The ultrasonic pulser circuit consumes a power of 25 mW under conditions of a center frequency of 10 MHz, a capacitive load of 2.5 nF, and pulse repetition frequency of 100 kHz. The measured waveforms to illustrate a basic operation of pulser are presented in Fig. 5. The implemented pulser can perform pull-up and pull-down operations depending on control signals of *PU* and *PD*.



(a) (b) (c) (d)

Fig. 7. Measured waveforms ultrasonic pulser and preamplifier for a wire phantom; (a) a wire phantom (b) bipolar-pulse condition (c) positive unipolar-pulse condition (d) negative unipolar-pulse condition

The implemented preamplifier uses supply voltages of ± 0.9 V. As shown in Fig. 6, the measured voltage gain ranges from 30 dB to 45 dB, and the bandwidth at the maximum voltage gain is 12 MHz. The measured output equivalent noise of preamplifier under the maximum voltage-gain condition is 912 μV, then the input equivalent noise voltage corresponds to 5.1 μVrms. At conditions of the maximum bandwidth and voltage gain, the preamplifier dissipates 3.6 mW.

To verify the performance of ultrasonic pulser-receiver circuit, we utilized a wire phantom shown in Fig. 7(a). An ultrasonic gel was used as the medium of ultrasound, and the distance between the transducer and the wire was set to around 0.25 cm. The oscilloscope waveforms of Fig. 7 show the output of ultrasonic pulser and the output of preamplifier. By adjusting the control signals of pulser, a bipolar pulse and a positive/negative unipolar pulse are generated. It can be seen that the intended pulse shape with seven periods is successfully generated.

After the pulser transmits an ultrasonic signal, a ring-down phenomenon occurs for around 1.2 μs. The measurement condition for preamplifier is the maximum gain and bandwidth. As shown in the oscilloscope waveforms of Fig. 7, an ultrasonic echo reflected from the wire phantom is amplified by preamplifier, and it can be confirmed that the ultrasonic echo is acquired at the time corresponding to the distance between the transducer and the wire phantom.

TABLE II. Performance comparison of ultrasonic sensor interface

Parameter	This work	TCAS2'21 [4]	JSSC'20 [3]	JSSC'18 [1]	JSSC'13 [7]
Process	180-nm BCD	180-nm BCD	180-nm BCD	180-nm BCD	180-nm HV
Center frequency	10MHz @ 2.5nF	1MHz @ 1nF	9MHz @ 18pF	7.5MHz @ 1.2pF	3.3MHz @ 40pF
Programm-able pulser level	O	X	O	X	X
Programm-able gain and BW in RX	O	- (no RX)	- (no RX)	X	X
Supply voltage	±10V, ±0.9V, 5V,	1.2V, 5V	±30V, 5V, 1.8V	30V, 5V, 1.8V	30V, 3.3V
Pulse polarity	Unipolar, biopolar	Unipolar	Unipolar , bipolar	Unipolar	Unipolar
Max pulser level	3	7	3	2	3
Pulser type	Class D	Capacitive boosting	Class D	Class D	Charge sharing
Max output	$20V_{PP}$	$28.7V_{PP}$	$60V_{PP}$	$30V_{PP}$	$30V_{PP}$
Building blocks	Pulser, T/R SW, preamp	Pulser	Pulser, T/R SW, TX BF	Pulser, T/R SW, preamp	Pulser, T/R SW, preamp
Active area of one channel	1.09mm^2	1.65mm^2	0.17mm^2	0.023m m^2	0.33mm^2
Target transducer	Single-element disc type	Single-element pMUT	PZT array	PZT array	cMUT array

TABLE II presents a performance comparison of ultrasonic sensor interface circuits. Most of previous works have utilized a high-voltage-dedicated fabrication process. This work utilizes a relatively small active area to implement an interface with a transducer with a relatively large capacitive load of 2.5 nF at a high center frequency of 10 MHz. Compared to other works of TABLE II, this work can support programmable functions on both the pulser and the receiver. As a result, the programmable pulser-receiver circuit of this work can be applied to various medical ultrasound applications.

IV. CONCLUSION

This work proposes an ultrasonic pulser-receiver circuit for a single transducer and corresponds to a proof-of-concept chip design that verifies one of building blocks of medical-ultrasound system. The proposed pulser-receiver circuit consists of a high-voltage pulser and a preamplifier. A shape and a number of cycles of output waveform of pulser can be programmed with external digital control signals. As a result, the pulsar can generate a unipolar or a bipolar pulse, and it can also be applied to ultrasound systems that transmit arbitrary waveforms. The target transducer of the proposed pulser-receiver circuit is a commercial single-element transducer. Since the target transducer transmits a relatively high acoustic pressure, it has a relatively large capacitive load. In addition, since it is required for the target ultrasound system to detect small blood vessels located in a scan line, it is necessary to transmit the ultrasound signal at a high center frequency. By considering these requirements, this work reduces the ON resistance of the transistors in pull-up/down paths to a few ohms by minimizing a number of transistor stacks at the output stage of the pulser. Moreover, to accomplish a relatively small active area, the return-to-ground path of pulser is reused as a T/R switch. In case of preamplifier, it is generally required to have a low noise performance. In order to suppress the thermal noise level of preamplifier, this work optimizes the operating region of primary transistors of the preamplifier.

The proposed pulser-receiver circuit was fabricated in a 180-nm BCD process. It was verified that a shape and a number of cycles of output waveform of implemented pulser can be adjusted with control signals. Also, primary performances of preamplifier such as frequency response and noise performance were evaluated. Moreover, through the measurement using a wire phantom, it is illustrated that an arbitrary ultrasonic pulse can be transmitted and an ultrasonic echo can be acquired. Considering the above implementation results, it is expected that the proposed ultrasonic pulser-receiver circuit can be used as a building block in a single transducer-based medical ultrasound integrated circuit.

ACKNOWLEDGMENT

This work was supported by Basic Science Research Program through the National Research Foundation (NRF) of Korea funded by the Ministry of Education (2019R1I1A3A01060591) and the chip fabrication along with EDA tools were supported by the IC Design Education (IDEC) in Korea.

REFERENCES

[1] E. Kang *et al.*, “A reconfigurable ultrasound transceiver ASIC with 24 x 40 elements for 3-D carotid artery imaging,” *IEEE J. Solid-State Circuits*, vol. 53, no. 7, pp. 2065-2075, Jul. 2018.

[2] C. Chen *et al.*, “A pitch-matched front-end ASIC with integrated subarray beamforming ADC for miniature 3-D ultrasound probes,” *IEEE J. Solid-State Circuits*, vol. 53, no. 11, pp. 3050-3064, Nov. 2018.

[3] M. Tan *et al.*, “A 64-channel transmit beamformer with ±30-V bipolar high-voltage pulsers for catheter-based ultrasound probes,” *IEEE J. Solid-State Circuits*, vol. 55, no. 7, pp. 1796-1806, Jul. 2020.

[4] K.-J. Choi, H. G. Yeo, H. Choi, and D.-W. Jee, “A 28.7V modular supply multiplying pulser with 75.4% power reduction relativle to CV^2f,” *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 68, no. 3, pp. 858-862, Mar. 2021.

[5] M.-C. Chen *et al.*, “A pixel pitch-matched ultrasound receiver for 3-D photoacoustic imaging with integrated delta-sigma beamformer in 28-nm UTB FD-SOI,” *IEEE J. Solid-State Circuits*, vol. 52, no. 11, pp. 2843-2856, Nov. 2017.

[6] M. Tan et al., “A front-end ASIC with high-voltage transmit switching and receive digitization for 3-D forward-looking intravascular ultrasound imaging,” *IEEE J. Solid-State Circuits*, vol. 53, no. 8, pp. 2284-2297, Aug. 2018.

[7] K. Chen, H.-S. Lee, A. P. Chandrakasan, and C. G. Sodini, “Ultrasonic imaging transceiver design for CMUT:a three-level 30-Vpp pulse-shaping pulser with improved efficiency and a noise-optimized receiver,” *IEEE J. Solid-State Circuits*, vol. 48, no. 11, pp. 2734-2745, Nov. 2013.

[8] Y.-J. Kim *et al*., “A single-chip 64-channel ultrasound RX-beamformer including analog front-end and an LUT for non-uniform ADC-sample-clock generation,” *IEEE Trans. Biomed. Circuits Syst*., vol. 11, no. 1, pp. 87-97, Feb. 2017.

[9] A. K. Sahani *et al*., “An imageless ultrasound device to measure local and regional arterial stiffness,” *IEEE Trans. Biomed. Circuits Syst*., vol. 10, no. 1, pp. 200-208, Feb. 2016.

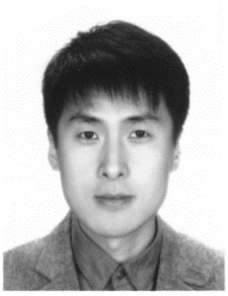
[10] W. Qui, Y. Yu, F. K. Tsang, and L. Sun, “A multifunctional, reconfigurable pulse generator for high-frequency ultrasound imaging,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 59, no. 7, pp. 1558-1567, Jul. 2012.

[11] J.-X. Wu *et al.*, “A novel bipolar pulse generator for high-frequency ultrasound system,” in *IEEE Ultrason. Symp. Proc.*, 2013, pp. 1571-1574.

[12] R. Schreier *et al*., “Design-oriented estimation of thermal noise in switched-capacitor circuits,” *IEEE Trans. Circuits Syst. I, Regular Papers*, vol. 52, no. 11, pp. 2358-2368, Nov. 2005.

Hyun Tae Park received the B.S. and M.S. degrees from Department of Electrical and Electronic Engineering, Hannam University, Daejeon, Korea in 2019 and 2021, respectively. Currently, he is an FPGA engineer in Navcours, Korea.

His research interests include circuit systems for ultrasound medical system and algorithm implementation in FPGA.



Ji Yong Um received the B.S., M.S. and Ph.D. degrees from Department of Electronic and Electrical Engineering, Pohang University of Science and Technology (POSTECH), Kyungbuk, Korea, in 2006, 2008 and 2013, respectively

From 2016 to 2021, he was an Assistant Professor in Hannam University, Daejeon, Korea. In 2021, he joined the faculty of Department of Medical IT Convergence Engineering in Kumoh National Institute of Technology, Kyungbuk, Korea, where he is currently an Assistant Professor. His research interests include mixed-signal circuit systems for biomedical ultrasound application.