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A Mini Review of Ultrasound Limiter Devices

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***Abstract*—This paper provides a brief review of limiter devices for ultrasound systems. The limiter devices are very important to affect the performances of the ultrasound transducers, transmitters, and receivers which are one of the most critical components of the ultrasound systems. Each different limiter device has its own characteristics such as insertion loss, bandwidth, electrical impedances, total harmonic distortion, and input-referred noise. Therefore, this review paper could provide how to design proper limiter devices for various ultrasound systems.**

Keywords—limiter device; transmitter; receiver; ultrasound system

I. INTRODUCTION

The most widely used medical imaging are X-ray, computed tomography (CT), positron emission tomography (PET), optical, single photon emission computer tomography (SPECT), magnetic resonance imaging (MRI), and ultrasound [1-10]. The X-ray, CT, SPECT, and PET are invasive imaging methods [9]. The optical, MRI, and ultrasound are non-invasive imaging methods [11-16]. Compared to MRI, ultrasound is relatively cheap imaging methods such that it can be used as portable and mobile instruments [17]. The penetration depth of the ultrasound imaging is much larger than that of the optical imaging [14, 18-22].

Among the medical imaging systems, ultrasound systems have offered the certain characteristics such as non-invasive, cost-effective, and non-ionized parameters [23-27]. The ultrasound systems have been used for a variety of applications such as non-destructive testing, sound navigation ranging, parking sensors, ultrasonic cleaning, surgical, energy harvesting technologies, body stimulator, treatment, intravascular imaging, small animal imaging, photoacoustic imaging, and touch sensors of mobile phones [28-39]. Especially, medical ultrasound systems have been used a variety of applications such as treatment sources, cell sorting, ultrasound imaging, acoustic tweezer, acoustic radiation force imaging, and photoacoustic imaging [40]. Recently, the photoacoustic imaging systems have been widely studied such that they have moved to the clinical machines [41, 42]. Higher frequency (> 15 MHz) ultrasound imaging could provide higher axial and lateral image resolutions than lower frequency (< 15 MHz) ultrasound imaging. However, the penetration depth of the ultrasound signals depends on the frequency of the ultrasound transducers. Therefore, higher frequency ultrasound imaging has lower penetration depth than lower frequency ultrasound imaging.

Compared to photoacoustic imaging systems, the ultrasound systems are composed of the transmitters, receivers, protection devices, and ultrasound transducers [43-47]. Each component can affect the performances of the ultrasound systems [48-51]. Therefore, proper design of the components is very important to obtain proper performances for different characteristics such as sensitivities, resolutions, and depth of focus [52-55]. Due to trade-off between each performance, each component needs to be used for different purposes [25, 56-58]. Section II describes the overview of ultrasound systems and architectures of protection devices. Section III is the conclusion of the paper.

II. MATERIALS AND METHODS

A. *Overview of Ultrasound Systems*

The typical ultrasound systems including the ultrasound array transducers are briefly described in Fig. 1 [25, 59-61]. The arrows describe the flow of the electrical signals in the ultrasound systems. Computer controls the beamformer [62]. The transmitting and receiving beamformer controls other components except the ultrasound array transducers [63]. For photoacoustic systems, the transmitter parts are replaced by the light sources such as laser or light emitting diodes.

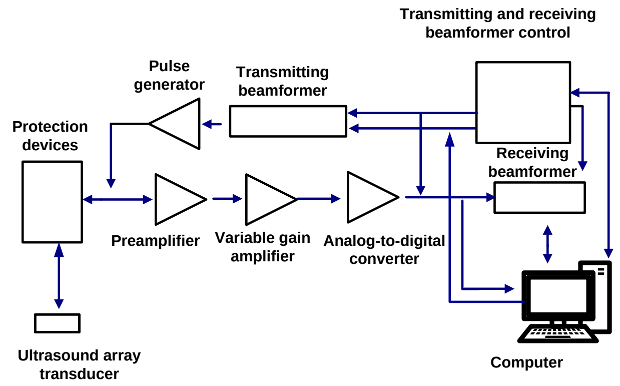

Fig. 1. *Ultrasound System Block.*

The computer sends the commands to the transmitting beamformer controller and then, transmitting beamformer sends the electronic pulse signals [64]. The pulse signals are amplified by the power amplifiers or pulse generators through the protection devices [65, 66]. The received echo signals from the ultrasound array transducers pass through the protection devices [67, 68]. The preamplifier, variable gain amplifier, and time-gain compensation amplifier amplifies the echo signals [69]. The analog to digital converter convert the analog echo signals into the digital echo signals [70, 71]. Through receiving beamformer, these signals are processed to display the image in the computer [72, 73]. As shown in Fig. 1, the protection devices are located between the power amplifiers, pulse generators, preamplifiers and ultrasound array transducers. Thus, we can conclude the limiter devices can affect the whole performances of the ultrasound systems.

B. Fundamental Theory of Limiter Device

The protection device are composed of expander and limiter circuits [61]. The expander circuits are used to reduce the small ring down of the output signals of the pulse generator or power amplifiers because the ring down signals generated from the transmitters could generate the ring down of the electrical signals generated by ultrasound transducers [74]. The ring down of the signals reduces the axial resolution of the ultrasound systems. The limiter circuits are used to minimize the signal loss of the electrical signals generated by ultrasound transducers while they are also used to block the high voltage pulse signals generated from the pulse generators or power amplifiers when the ultrasound systems have one-side mode which shares the same paths between the transmission and reception [75]. The limiter devices have passive and active types. The passive limiter devices does not have external control powers to change the impedances of the devices. The active limiter devices have the external control powers. Next chapter will describe the design of the limiter devices.

C. Limiter Device Architecture

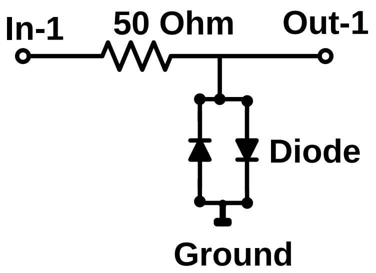

Fig. 2. *Resistor circuit.*

Fig. 2 shows the resistor circuit. In-1 and Out-1 are the input and output ports of the resistor circuit. Therefore, high voltage pulse signals go into the limiter and reduce pulse signals to avoid going into the preamplifier. The resistor circuit is most fundamental limiter device so it has been widely used and very easy to be implemented [76]. The resistor circuit is composed of a series 50-Ω resistor and parallel dual-side diode connected to ground port [77]. A 50-Ω resistor is used because the ultrasound transducer is originally designed to have 50-Ω impedance at center frequency [78]. The dual-side diode has different polarity such that positive and negative pulse signals could go to the ground via parallel dual-side diode [79]. Therefore, the preamplifier could be avoided from the high voltage pulse signals.

However, this circuit could reduce the bandwidth of the limiter devices such that insertion loss at high frequency operation could be increased [80]. Therefore, it is not suitable for high frequency ultrasound system. A 50-Ω resistor could increase input referred noise at high frequency operation [81-83]. As a result of that, the resistor circuit is not suitable for high frequency ultrasound systems. However, they can be useful for portable ultrasound systems because of limited hardware capacity.

Fig. 3 shows the bridge circuit which is widely used in the ultrasound commercial machines. In-2 and Out-2 are the input and output ports of the bridge circuit. The typical bridge circuit is composed of a bridge diode architecture and parallel dual-side diode connected to ground port with two capacitors and external control power units connected to beamformer controller. As shown in Fig. 3, the bridge diode is controlled by external control power. Thus, they have low impedances when echo signals are received but high impedances when pulse signals are received [84]. The external control powers need to be controlled by the transmitting/receiving beamformer controller to distinguish the transmission and reception periods [85]. Otherwise, the pulse and echo signals could be merged. Thus, it generates mixed pulse and echo signals, thus possibly breaking the ultrasound systems.

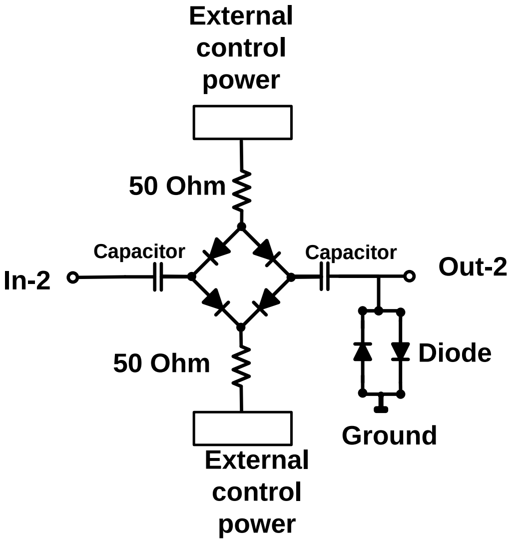

Fig. 3. *Bridge circuit.*

Additionally, external noise signals could go into the bridge diodes and reach into the ultrasound transducers or preamplifiers. Therefore, it could increase the input referred noises of the ultrasound systems. Otherwise, the regulated power supply needs to be used for bridge circuit. As a result of that, this method could increase the size of the ultrasound systems. However, the external control power units are useful to reduce the ring down generated from the ultrasound transducers [86]. The external control power units generate the opposite signals to block the input signals into the preamplifier. Longer ring down can deteriorate the axial resolution of the ultrasound systems.

Fig. 4 shows the MOSFET circuit. As shown in the MOSFET circuit which is composed of several series n-channel MOSFET and parallel dual-side diode are supposed to be connected to ground port. In-3 and Out-3 are the input and output ports of the MOSFET circuit.

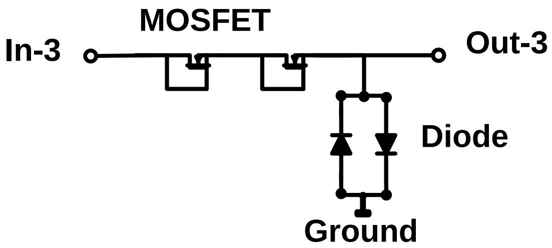

Fig. 4. *MOSFET circuit.*

The metal-oxide-MOSFET circuit has series MOSFET and parallel dual-side diode connected to ground port. The MOSFET device itself has low impedances such that it provides low insertions loss with low input referred noise [77]. The bandwidth depends on the MOSFET device which has some burden to reduce the high volte pulse [87, 88]. However, the MOSFET circuit is useful for high frequency ultrasound systems due to low impedances of the MOSFET devices [77, 86, 89].

D. Evaluation method of limiter devices

The passive limiter devices are resistor and MOSFET circuits and active limiter device is bridge circuit. The limiter circuits need to be used to block high voltage pulse signals generated from pulse generators or power amplifiers controlled by beamformer. However, each different limiter circuit has its own advantages and disadvantages for insertion loss, bandwidth, electrical impedances, total harmonic distortions, and input referred noise. Therefore, circuit or system designer need to be considered for these kinds of characteristics to optimize the ultrasound system performances. Therefore, several performance parameters need to be measured before integration with ultrasound transducers.

To evaluate the performances of the limiter circuits, several performances need to be measured. The insertion loss can be obtained by the output signal with limiter devices and the output signal without limiter devices. The insertion loss performances need to be measured with respect to the different voltage and frequency ranges. The bandwidth can be estimated from the insertion loss versus frequency. Wide bandwidth is desirable since the ultrasound transducer devices are wide band devices. The total harmonic distortion can be calculated by several harmonic distortion amplitudes and fundamental signal amplitudes [90]. Lower total harmonic distortions are highly desirable for ultrasound harmonic imaging. Input referred noise of the passive type limiter can be directly obtained by the insertion loss of the limiter. The input referred noise of the active type limiter need to be tested using spectrum analyzer or noise analyzer instruments. The electrical impedances of the limiter devices could be easily measured using impedance analyzer machines.

Finally, the pulse-echo evaluation method needs to be obtained since the pulse-echo evaluation system is a kind of basic ultrasound machine. Using the pulse-echo evaluation method, the performance of insertion loss, total harmonic distortions, and bandwidths of the ultrasound transducers or other electronic components like limiter devices could be estimated. In addition, ultrasound biomicroscopy is another method to obtain the ultrasound image. Therefore, axial and later resolutions of the ultrasound components could be evaluated.

III. Conclusion

Among the medical imaging systems, ultrasound systems are cost-effective, non-ionized, and non-invasive. Therefore, ultrasound systems have been widely used for a variety of applications such as photoacoustic, treatment, cell sorting, and imaging systems. In the ultrasound systems, the limiter devices are located between the ultrasound transducers, pulse generators, and preamplifiers. The limiter devices are composed of the expander and limiters. The performances of the limiters are crucial for entire ultrasound systems. Therefore, the limiter devices are reviewed for proper ultrasound system design.

Each limiter device has its own characteristics such as insertion loss, bandwidths, total harmonic distortions, electrical impedances, and input referred noises. To obtain the performances of the ultrasound systems such as sensitivity, image resolution, and focal depth, proper limiter devices need to be considered with ultrasound array transducers. The limiter devices are resistor, bridge, and MOSFET type devices. Among the limiter devices, the resistor device is very simple circuit such that it is useful for array transducer for low frequency operation. The MOSFET device is useful for high frequency operation because the device has low impedance. For low-frequency ultrasound array systems with high sensitivity, resistor device is preferable. The ultrasound systems which has long ring down is preferable to use bridge circuit because external control power units can reduce the ring down, thus improving the axial resolution of the ultrasound systems. For high frequency ultrasound single systems with low sensitivity, the MOSFET device is desirable because of low insertion loss at high frequency operation.

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REFERENCES

[1] W. R. Hendee and E. R. Ritenour, *Medical Imaging Physics*. Hoboken, NJ, USA: John Wiley & Sons, 2003.

[2] H. Choi, J. M. Ryu, and J. H. Kim, "Tolerance Analysis of Focus-adjustable Head-mounted Displays," *Curr. Op. Photon*, vol. 1, no. 5, pp. 474-490, 2017.

[3] P. Strojnik and P. H. Peckham, *The Biomedical Engineering Handbook*. Boca Raton, FL, USA: CRC Press, 2000.

[4] H. Choi, J. Ryu, and C. Yoon, "Development of novel adjustable focus head mount display for concurrent image-guided treatment applications," *Comput. Assisted Surg.*, vol. 22, no. sup1, pp. 163-169, 2017.

[5] H. Choi, S. Kim, J. Kim, and J.-M. Ryu, "Development of an Omnidirectional Optical System Based Photoacoustic Instrumentation," *J. Med. Imaging Health Inf.*, vol. 8, no. 1, pp. 20-27, 2018.

[6] M. Cho, K.-t. Lim, H. Kim, J.-y. Yeom, J. Kim, C. Lee, H. Choi, and G. Cho, "A design of a valid signal selecting and position decoding ASIC for PET using silicon photomultipliers," *J. Instrum.*, vol. 12, no. 01, p. C01089, 2017.

[7] H. Riaz, J. Park, H. Choi, H. Kim, and J. Kim, "Deep and Densely Connected Networks for Classification of Diabetic Retinopathy," *Diagnostics*, vol. 10, no. 1, p. 24, 2020.

[8] M. N. Ullah, C. Park, E. Pratiwi, C. Kim, H. Choi, and J.-Y. Yeom, "A new positron-gamma discriminating phoswich detector based on wavelength discrimination (WLD)," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 946, p. 162631, 2019.

[9] M. Ullah, E. Pratiwi, J. Park, K. Lee, H. Choi, and J. Yeom, "Wavelength discrimination (WLD) TOF-PET detector with DOI information," *Phys. Med. Biol.*, vol. 65, no. 5, p. 055003, 2019.

[10] S. Chee, J. Ryu, and H. Choi, "New Optical Design Method of Floating Type Collimator for Microscopic Camera Inspection," *Applied Sciences*, vol. 11, no. 13, p. 6203, 2021.

[11] P. Beard, "Biomedical photoacoustic imaging," *Interface Focus*, vol. 1, no. 4, pp. 602-631, 2011.

[12] H. Choi, J. Ryu, and J.-Y. Yeom, "A Cost-effective Light Emitting Diode-acoustic System for Preclinical Ocular Applications," *Curr. Op. Photon*, vol. 2, no. 1, pp. 59-68, 2018.

[13] H. Choi and J. Ryu, "Design of Wide Angle and Large Aperture Optical System with Inner Focus for Compact System Camera Applications," *Appl. Sci.*, vol. 10, no. 1, p. 179, 2019.

[14] K. M. Kim, S.-H. Choe, J.-M. Ryu, and H. Choi, "Computation of Analytical Zoom Locus Using Padé Approximation," *Mathematics*, vol. 8, no. 4, p. 581, 2020.

[15] S. H. Seo, J. M. Ryu, and H. Choi, "Focus-Adjustable Head Mounted Display with Off-Axis System," *Applied Sciences*, vol. 10, no. 21, p. 7931, 2020.

[16] H. Choi, S.-w. Choe, and J. Ryu, "Optical Design of a Novel Collimator System with a Variable Virtual-Object Distance for an Inspection Instrument of Mobile Phone Camera Optics," *Applied Sciences*, vol. 11, no. 8, p. 3350, 2021.

[17] H. Choi, C. Yoon, and S.-H. Shin, "Development of a Novel Image Compression Algorithm for Point-of-Care Ultrasound Applications," *J. Med. Imaging Health Inf.*, vol. 8, no. 7, pp. 1526-1531, 2018.

[18] S.-H. Shin, W. Sok Yoo, and H. Choi, "Development of modified RSA algorithm using fixed mersenne prime numbers for medical ultrasound imaging instrumentation," *Comput. Assisted Surg.*, pp. 1-6, 08/14 2019.

[19] H. Choi, J.-Y. Jo, and J.-M. Ryu, "A Novel Focal Length Measurement Method for Center-Obstructed Omni-Directional Reflective Optical Systems," *Appl. Sci.*, vol. 9, no. 11, p. 2350, 2019.

[20] K. You and H. Choi, "Inter-Stage Output Voltage Amplitude Improvement Circuit Integrated with Class-B Transmit Voltage Amplifier for Mobile Ultrasound Machines," *Sensors*, vol. 20, no. 21, p. 6244, 2020.

[21] M. N. Ullah, Y. Park, G. B. Kim, C. Kim, C. Park, H. Choi, and J.-Y. Yeom, "Simultaneous Acquisition of Ultrasound and Gamma Signals with a Single-Channel Readout," *Sensors*, vol. 21, no. 4, p. 1048, 2021.

[22] R. B. A. Zawawi, H. Choi, and J. Kim, "High-PSRR Wide-Range Supply-Independent CMOS Voltage Reference for Retinal Prosthetic Systems," *Electronics*, vol. 9, no. 12, p. 2028, 2020.

[23] C. R. Hill, J. C. Bamber, and G. t. Haar, *Physical Principles of Medical Ultrasonics*. Hoboken, NJ, USA: Wiley Online Library, 2004.

[24] S.-W. Choe, K. Park, C. Park, J. Ryu, and H. Choi, "Combinational light emitting diode-high frequency focused ultrasound treatment for HeLa cell," *Comput. Assisted Surg.*, vol. 22, no. S1, pp. 79-85, 2017.

[25] K. You, S.-H. Kim, and H. Choi, "A Class-J Power Amplifier Implementation for Ultrasound Device Applications," *Sensors*, vol. 20, no. 8, p. 2273, 2020.

[26] K. Kim and H. Choi, "Novel Bandwidth Expander Supported Power Amplifier for Wideband Ultrasound Transducer Devices," *Sensors*, vol. 21, no. 7, p. 2356, 2021.

[27] K. Kim and H. Choi, "High-efficiency high-voltage class F amplifier for high-frequency wireless ultrasound systems," *PLOS ONE*, vol. 16, no. 3, p. e0249034, 2021.

[28] H. Choi, X. Li, S.-T. Lau, C. Hu, Q. Zhou, and K. K. Shung, "Development of Integrated Preamplifier for High-Frequency Ultrasonic

Transducers and Low-Power Handheld Receiver," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 58, no. 12, pp. 2646-2658, 2011.

[29] Q. Weibao, Y. Yanyan, T. Fu Keung, and S. Lei, "A multifunctional, reconfigurable pulse generator for high-frequency ultrasound imaging," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 59, no. 7, pp. 1558-1567, 2012.

[30] B. Zhu, Y. Zhu, J. Yang, J. Ou-Yang, X. Yang, Y. Li, and W. Wei, "New potassium sodium niobate single crystal with thickness-independent high-performance for photoacoustic angiography of atherosclerotic lesion," *Sci. Rep.*, vol. 6, p. 39679, 2016.

[31] H. Choi, H. Jung, and K. K. Shung, "Power Amplifier Linearizer for High Frequency Medical Ultrasound Applications," *J. Med. Biol. Eng.*, pp. 1-10, 2015.

[32] T. Zhang, J. Ou-Yang, X. Yang, W. Wei, and B. Zhu, "High Performance KNN-Based Single Crystal Thick Film for Ultrasound Application," *Electron. Mater. Lett.*, vol. 15, no. 1, pp. 1-6, 2019.

[33] H. Choi, M. Kim, T. Cumins, J. Hwang, and K. Shung, "Power MOSFET-diode-based limiter for high frequency ultrasound systems," *Ultrason. Imaging*, vol. 37, no. 1, pp. NP1-NP1, 2015.

[34] B. Zhu, J. Xu, Y. Li, T. Wang, K. Xiong, C. Lee, X. Yang, M. Shiiba, S. Takeuchi, and Q. Zhou, "Micro-particle manipulation by single beam acoustic tweezers based on hydrothermal PZT thick film," *AIP Adv.*, vol. 6, no. 3, p. 035102, 2016.

[35] H. Choi, J. Ryu, and J. Kim, "A Novel Fisheye-Lens-Based Photoacoustic System," *Sensors*, vol. 16, no. 12, p. 2185, 2016.

[36] S.-H. Shin, W.-S. Yoo, and H. Choi, "Development of Public Key Cryptographic Algorithm Using Matrix Pattern for Tele-Ultrasound Applications," *Mathematics*, vol. 7, no. 8, p. 752, 2019.

[37] H. Choi, J.-M. Ryu, and S.-w. Choe, "A novel therapeutic instrument using an ultrasound-light-emitting diode with an adjustable telephoto lens for suppression of tumor cell proliferation," *Measurement*, vol. 147, p. 106865, 2019.

[38] J. Kim, K. Kim, S.-H. Choe, and H. Choi, "Development of an Accurate Resonant Frequency Controlled Wire Ultrasound Surgical Instrument," *Sensors*, vol. 20, no. 11, p. 3059, 2020.

[39] J. Kim, K. You, S.-H. Choe, and H. Choi, "Wireless Ultrasound Surgical System with Enhanced Power and Amplitude Performances," *Sensors*, vol. 20, no. 15, p. 4165, 2020.

[40] U. Jung and H. Choi, "Active echo signals and image optimization techniques via software filter correction of ultrasound system," *Applied Acoustics*, vol. 188, p. 108519, 2022.

[41] W. Xia, M. Kuniyil Ajith Singh, E. Maneas, N. Sato, Y. Shigeta, T. Agano, S. Ourselin, S. J West, and A. E Desjardins, "Handheld real-time LED-based photoacoustic and ultrasound imaging system for accurate visualization of clinical metal needles and superficial vasculature to guide minimally invasive procedures," *Sensors*, vol. 18, no. 5, p. 1394, 2018.

[42] S.-H. Shin and H. Choi, "Image Formation Technique Using Advanced Matrix Pattern in Fourier Transform for Medical Ultrasound Machine," *J. Med. Imaging. Health. Inf.*, vol. 9, no. 9, pp. 1950-1954, 2019.

[43] H. Choi, M. Qian, M. G. Kim, H. Zheng, H. K. Choi, B. Zhang, and K. K. Shung, "Analog Wideband Receiver Architecture for High Frequency Ultrasound Instrumentation," *J. Med. Imaging Health Inf.*, vol. 6, no. 1, pp. 47-52, 2016.

[44] W. Qiu, Y. Yu, H. R. Chabok, C. Liu, F. K. Tsang, Q. Zhou, K. K. Shung, H. Zheng, and L. Sun, "A Flexible Annular-Array Imaging Platform for Micro-Ultrasound," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 60, no. 1, pp. 178-186, 2013.

[45] H. Choi and J.-M. Ryu, "Photo-Acoustic Applications Using a Highly Focused Macro Lens," *J. Med. Imaging Health Inf.*, vol. 7, no. 1, pp. 25-29, 2017.

[46] S.-w. Choe and H. Choi, "Suppression Technique of HeLa Cell Proliferation Using Ultrasonic Power Amplifiers Integrated with a Series-Diode Linearizer," *Sensors*, vol. 18, no. 12, p. 4248, 2018.

[47] H. Choi, Y. J. Ju, J. H. Jo, and J.-M. Ryu, "Chromatic aberration free reflective mirror-based optical system design for multispectral photoacoustic instruments," *Technol. Health Care*, vol. 27, no. S1, pp. 397-406, 2019.

[48] H. Choi, P. C. Woo, J.-Y. Yeom, and C. Yoon, "Power MOSFET Linearizer of a High-Voltage Power Amplifier for High-Frequency Pulse-Echo Instrumentation," *Sensors*, vol. 17, no. 4, p. 764, 2017.

[49] J. J. Jeong and H. Choi, "An impedance measurement system for piezoelectric array element transducers," *Measurement*, vol. 97, pp. 138-144, 2017.

[50] H. Choi and S.-w. Choe, "Therapeutic Effect Enhancement by Dual-bias High-voltage Circuit of Transmit Amplifier for Immersion Ultrasound Transducer Applications," *Sensors*, vol. 18, no. 12, p. 4210, 2018.

[51] H. Choi, J.-M. Ryu, and J.-Y. Yeom, "Development of a Double-Gauss Lens Based Setup for Optoacoustic Applications," *Sensors*, vol. 17, no. 3, p. 496, 2017.

[52] H. Choi, J. J. Jeong, and J. Kim, "Development of an Estimation Instrument of Acoustic Lens Properties for Medical Ultrasound Transducers," *J. Healthcare Eng.*, no. Sup1, p. 7, 2017.

[53] H. Choi and S.-w. Choe, "Acoustic Stimulation by Shunt-Diode Pre-Linearizer Using Very High Frequency Piezoelectric Transducer for Cancer Therapeutics," *Sensors*, vol. 19, no. 2, p. 357, 2019.

[54] H. Choi, S.-w. Choe, and J.-M. Ryu, "A Macro Lens-Based Optical System Design for Phototherapeutic Instrumentation," *Sensors*, vol. 19, no. 24, p. 5427, 2019.

[55] J. Yun, H. Choi, and J. Kim, "Low-noise wide-bandwidth DNA readout instrument for nanopore applications," *Electron. Lett.*, vol. 53, no. 11, pp. 706-708, 2017.

[56] H. Choi, J. Jo, J.-M. Ryu, and J.-Y. Yeom, "Ultrawide-angle optical system design for light-emitting-diode-based ophthalmology and dermatology applications," *Technol. Health Care*, vol. 27, no. S1, pp. 133-142, 2019.

[57] J. M. Daniels and R. A. Hoppmann, *Practical Point-of-care Medical Ultrasound*. New York, NJ, USA: Springer, 2016.

[58] H. Kang, H. Choi, and J. Kim, "Ambient Light Rejection Integrated Circuit for Autonomous Adaptation on a Sub-Retinal Prosthetic System," *Sensors*, vol. 21, no. 16, p. 5638, 2021.

[59] T.L.Szabo, *Diagnostic Ultrasound Imaging: Inside Out*. London, UK: Elsevier Academic Press, 2013.

[60] H. Choi, "Stacked Transistor Bias Circuit of Class-B Amplifier for Portable Ultrasound Systems," *Sensors*, vol. 19, no. 23, p. 5252, 2019.

[61] K. You and H. Choi, "Wide Bandwidth Class-S Power Amplifiers for Ultrasonic Devices," *Sensors*, vol. 20, no. 1, p. 290, 2020.

[62] K. Kim and H. Choi, "A New Approach to Power Efficiency Improvement of Ultrasonic Transmitters via a Dynamic Bias Technique," *Sensors*, vol. 21, no. 8, p. 2795, 2021.

[63] J. Kim, K. S. Kim, and H. Choi, "Development of a low-cost six-axis alignment instrument for flexible 2D and 3D ultrasonic probes," (in eng), *Technol. Health Care*, vol. 29, no. S1, pp. 77-84, 2021.

[64] G. Li, W. Qiu, Z. Zhang, Q. Jiang, M. Su, R. Cai, Y. Li, F. Cai, Z. Deng, and D. Xu, "Noninvasive Ultrasonic Neuromodulation in Freely Moving Mice," *IEEE Trans. Biomed. Eng.*, vol. 66, no. 1, 2018.

[65] H. Choi, C. Park, J. Kim, and H. Jung, "Bias-Voltage Stabilizer for HVHF Amplifiers in VHF Pulse-Echo Measurement Systems," *Sensors*, vol. 17, no. 10, p. 2425, 2017.

[66] Z. He, "Optimization of acoustic emitted field of transducer array for ultrasound imaging," *Bio-Med. Mater. Eng.*, vol. 24, no. 1, p. 1201, 2014.

[67] H. Choi, "Class-C Linearized Amplifier for Portable Ultrasound Instruments," *Sensors*, vol. 19, no. 4, p. 898, 2019.

[68] Y. Ma, Y. Yang, Z. He, K. Yang, C. Sun, and Y. Wang, "Theoretical and practical solutions for high-order superdirectivity of circular sensor arrays," *IEEE Trans. Ind. Electron.*, vol. 60, no. 1, pp. 203-209, 2013.

[69] H. Choi, J.-Y. Yeom, and J.-M. Ryu, "Development of a Multiwavelength Visible-Range-Supported Opto–Ultrasound Instrument Using a Light-Emitting Diode and Ultrasound Transducer," *Sensors*, vol. 18, no. 10, p. 3324, 2018.

[70] P. Sun, Q. Zhou, B. Zhu, D. Wu, C. Hu, J. M. Cannata, J. Tian, P. Han, G. Wang, and K. K. Shung, "Design and fabrication of PIN-PMN-PT single-crystal high-frequency ultrasound transducers," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 56, no. 12, pp. 2760-2763, 2009.

[71] H. Choi, "Development of negative-group-delay circuit for high-frequency ultrasonic transducer applications," *Sens. Actuators, A*, vol. 299, p. 111616, 2019.

[72] Z. He, F. Zheng, Y. Ma, H. H. Kim, Q. Zhou, and K. K. Shung, "A sidelobe suppressing near-field beamforming approach for ultrasound array imaging," *J. Acoust. Soc. Am.*, vol. 137, no. 5, pp. 2785-2790, 2015.

[73] H. Choi, "Development of a Class-C Power Amplifier with Diode Expander Architecture for Point-of-Care Ultrasound Systems," *Micromachines*, vol. 10, no. 10, p. 697, 2019.

[74] H. Choi, C. Yoon, and J.-Y. Yeom, "A Wideband High-Voltage Power Amplifier Post-Linearizer for Medical Ultrasound Transducers," *Appl. Sci.*, vol. 7, no. 4, p. 354, 2017.

[75] H. Choi, "Prelinearized Class-B Power Amplifier for Piezoelectric Transducers and Portable Ultrasound Systems," *Sensors*, vol. 19, no. 2, p. 287, 2019.

[76] H. Choi, H.-C. Yang, and K. K. Shung, "Bipolar-power-transistor-based limiter for high frequency ultrasound imaging systems," *Ultrasonics*, vol. 54, no. 3, pp. 754-758, 2014.

[77] J. Camacho and C. Fritsch, "Protection circuits for ultrasound applications," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 55, no. 5, pp. 1160-1164, 2008.

[78] H. Choi and K. K. Shung, "Novel power MOSFET-based expander for high frequency ultrasound systems," *Ultrasonics*, vol. 54, no. 1, pp. 121-130, 1// 2014.

[79] H. Choi and K. K. Shung, "Protection circuits for very high frequency ultrasound systems," *J. Med. Syst.*, vol. 38, no. 4, p. 34, 2014.

[80] W. Qiu, X. Wang, Y. Chen, Q. Fu, M. Su, L. Zhang, J. Xia, J. Dai, Y. Zhang, and H. Zheng, "A Modulated Excitation Imaging System for Intravascular Ultrasound," *IEEE Trans. Biomed. Eng.*, vol. 64, no. 8, pp. 1935-1942, 2016.

[81] R. B. A. Zawawi, W. H. Abbasi, S.-H. Kim, H. Choi, and J. Kim, "Wide-Supply-Voltage-Range CMOS Bandgap Reference for In Vivo Wireless Power Telemetry," *Energies*, vol. 13, no. 11, p. 2986, 2020.

[82] J. Kim, K. You, and H. Choi, "Post-Voltage-Boost Circuit-Supported Single-Ended Class-B Amplifier for Piezoelectric Transducer Applications," *Sensors*, vol. 20, no. 18, p. 5412, 2020.

[83] J. Cheon, D. Lee, and H. Choi, "A CMOS Image Sensor with a Novel Passive Pixel Array and High

Precision Current Amplifier for a Compact Digital X-ray Detector," *J. Med. Imaging. Health. Inf.*, vol. 10, no. 11, pp. 2745-2753, 2020.

[84] J. S. Suri, C. Kathuria, R.-F. Chang, F. Molinar, and A. Fenster, *Advances in Diagnostic and Therapeutic Ultrasound Imaging*. Norwood, MA, USA: Artech House, 2008.

[85] W. Qiu, J. Zhou, Y. Chen, M. Su, G. Li, H. Zhao, X. Gu, D. Meng, C. Wang, Y. Xiao, K. H. Lam, J. Dai, and H. Zheng, "A Portable Ultrasound System for Non-Invasive Ultrasonic Neuro-Stimulation," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 25, no. 12, pp. 2509-2515, 2017.

[86] H. Jung, R. Wodnicki, H. G. Lim, C. W. Yoon, B. J. Kang, C. Yoon, C. Lee, J. Y. Hwang, H. H. Kim, and H. Choi, "CMOS High-Voltage Analog 1–64 Multiplexer/Demultiplexer for Integrated Ultrasound Guided Breast Needle Biopsy," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 65, no. 8, pp. 1334-1345, 2018.

[87] J. Kim, J. Ko, H. Choi, and H. Kim, "Printed Circuit Board Defect Detection Using Deep Learning via A Skip-Connected Convolutional Autoencoder," *Sensors*, vol. 21, no. 15, p. 4968, 2021.

[88] R. B. A. Zawawi, H. Choi, and J. Kim, "High PSRR Wide Supply Range Dual-Voltage Reference Circuit for Bio-Implantable Applications," *Electronics*, vol. 10, no. 16, p. 2024, 2021.

[89] H. Choi and K. K. Shung, "Crossed SMPS MOSFET-based protection circuit for high frequency ultrasound transceivers and transducers," *Biomed. Eng. Online*, vol. 13, no. 1, p. 76, 2014.

[90] H. Choi, J. Park, W. Lim, and Y.-M. Yang, "Active-beacon-based driver sound separation system for autonomous vehicle applications," *Appl. Acoust.*, vol. 171, p. 107549, 2021.