Dual-frequency piezoelectric micromachined ultrasound transducer based on polarization switching in ferroelectric thin film

Byung Chul Lee (bclee@kist.re.kr)  
Korea Institute of Science and Technology (KIST)  
https://orcid.org/0000-0002-7702-716X

Jin Soo Park  
Korea Institute of Science and Technology (KIST)

Soo Young Jung  
Korea Institute of Science and Technology (KIST)

Dong Hun Kim  
Korea Institute of Science and Technology (KIST)

Jung Ho Park  
Korea University

Ho Won Jang  
Seoul National University

Tae Geun Kim  
Korea University

Seung-Hyub Baek  
Korea Institute of Science and Technology (KIST)

Article

Keywords: Dual frequency ultrasound, ferroelectric thin film, piezoelectric micromachined ultrasound transducer (PMUT), Polarization switching

Posted Date: April 11th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2714836/v1

License: ☒️  This work is licensed under a Creative Commons Attribution 4.0 International License.  
Read Full License

Version of Record: A version of this preprint was published at Microsystems & Nanoengineering on October 2nd, 2023. See the published version at https://doi.org/10.1038/s41378-023-00595-z.
Abstract

Dual-frequency ultrasound has advantages over conventional ultrasound, which operates at a specific frequency band, due to its additional frequency response. Moreover, a tunable frequency from a single transducer enables sonographers to achieve ultrasound images with a large detection area and high resolution. This facilitates the availability of more advanced techniques that require low- and high frequency ultrasound simultaneously such as harmonic imaging and image-guided therapy. In this article, we present a novel method for dual-frequency ultrasound generation from a ferroelectric piezoelectric micromachined ultrasound transducer (PMUT). Uniformly designed transducer arrays can be used for both deep low-resolution imaging and shallow high-resolution imaging. To switch the ultrasound frequency, the only requirement is to tune a DC bias for controlling the polarization state of the ferroelectric film. Flextensional vibration of the PMUT’s membrane strongly depends on the polarization state, producing low- and high-frequency ultrasound from a single excitation frequency. This strategy for dual-frequency ultrasound dispenses with the requirement for either multi-electrode configurations or hetero-designed elements, which are integrated into an array. Consequently, this technique significantly reduces the design complexity of transducer arrays and their associated driving circuits.

Highlights

- Dual-frequency ultrasound can be generated from a single excitation frequency by simply tuning an applied DC bias on a ferroelectric thin film-based PMUT.
- An approach based on polarization control of ferroelectric film dispenses with the requirement for multi-electrode configuration or the integration of hetero-designed elements for dual-frequency ultrasound, resulting in reduced design complexity.
- Dual-frequency ultrasound results in tunable penetration depth and spatial resolution in ultrasound images.

1 Introduction

Multi-frequency ultrasound devices provide many benefits and are used extensively in medical clinical applications, such as multi-scale imaging, harmonic contrast agent imaging, and image-guided high-intensity focused ultrasound (HIFU)\(^1,2\). They are especially suitable for biomedical ultrasound imaging, as the sonographer can carefully select a frequency to tune the penetration depth and spatial resolution. This ability to achieve both good penetration depth and high resolution provides a comprehensive understanding of the full anatomic information of the target, helping the clinicians’ diagnosis\(^3\). Compared to conventional ultrasound, which operates within a predefined frequency band, dual-frequency ultrasound is capable of effectively enhancing the contrast of the produced image. Moreover, non-linear oscillations of microbubbles, which are used as a contrast agent for angiography under exposure to dual-frequency ultrasound, reduce the threshold value\(^4\) for acoustic cavitation and generate additional frequency responses, such as harmonics, sub-harmonics, and ultra-harmonics\(^5,6\). By extracting harmonic
signals from the backscattered echo, it is possible to isolate the non-linear response of microbubbles from that of human soft tissue, resulting in improved images for vascular remodeling.\(^7\)

Traditional single-frequency operating devices cannot meet the requirements of these applications. Accordingly, multi-frequency (especially dual-frequency) transducers have been proposed as a promising solution. The conventional approach to achieving dual-frequency ultrasound devices is to integrate the high- and low-frequency operating elements in either a vertical or horizontal configuration.\(^9\) In a bi-layered stack, each element is fabricated with a different thickness to determine the frequency band, then they are sequentially bonded with one underneath the other. However, if both layers in this vertically stacked structure are fabricated from high-property piezoelectric materials (such as Pb(Zr, Ti)O\(_3\) (PZT) and Pb(Mg\(_{1/3}\)Nb\(_{2/3}\))O\(_3\)–PbTiO\(_3\) (PMN-PT)), there are significant coupling issues between the two layers that can generate aliasing echoes, which shift the resonant frequencies of both layers. To prevent this phenomenon, a frequency-selective anti-matching layer must be placed between the top and bottom layers to provide isolation.\(^9–11\) Moreover, acoustic matching for both the low and high frequencies is difficult to optimize\(^12\), and fabrication becomes more difficult as the transducer dimensions are scaled down. One alternative solution is the interleaved array, which is referred to as a horizontal stack, where the low-frequency elements are laterally positioned on both sides of a central high-frequency element.\(^8\) Here, the even-numbered elements are used for the transmission of ultrasound and the odd-numbered elements are used for reception. This technique does not require an anti-matching layer and dispenses with having to modify the initial performance of the subarray. However, these horizontally arranged elements cause overlapping of the transmission and receiving beams and increase the footprint compared to regular array designs.\(^1\)

The inherent manufacturing challenges with stacked arrays have inspired developers to investigate micro-electromechanical systems (MEMS)-based devices, such as capacitive micromachined ultrasound transducers (CMUTs) and piezoelectric micromachined ultrasound transducers (PMUTs). These microfabrication techniques enable the monolithic integration of each designed sub-array with different frequency bands and unique flexural vibration of the membranes, instigating studies on realizing multi-frequency ultrasound operation based on uniform element transducer arrays.\(^13–15\) In MUTs, a well-known approach for achieving multi-frequency ultrasound is excitation at their fundamental and harmonic modes.\(^19–22\) Hence, it is possible to generate low- and high-frequency ultrasound from a single element by patterning its driving electrodes into several segments and activating different modes with an electrical frequency-switchable control unit. To manage the required frequency bands and optimize the corresponding vibrational modes, the design principle of patterned electrodes and their driving method have been explored. For example, Wang et al. presented individual five-electrode configurations in a single rectangular membrane PMUT.\(^22\) By activating different electrode sets, the synthesized in-phase motion part enabled the PMUT to vibrate in the 1st, 3rd, and 5th modes, producing ultrasound at corresponding frequencies of 2.01, 3.19, and 5.84 MHz. Dual electrodes have also been employed in an annular form for circular membrane devices. For example, Wu et al. introduced two ring-type electrodes in a circular PMUT...
that was designed to operate in the (0,1) and (0,2) modes at 3.75 and 18 MHz, respectively. Here, by optimizing the design parameters (including the electrode's width and position), vibrational crosstalk between the two resonant modes of the diaphragm could be eliminated. These design strategies successfully extended the available frequency band of a single device, indicating the potential for advanced biomedical imaging. Although this is a promising method for achieving multi-band frequencies from harmonic modes, the number of interconnections for patterned electrodes needs to be considered. As the number of elements increases to achieve better performance, the challenge of individually addressing the elements derived from massive interconnections becomes inevitable.

This paper reports a novel and simple method for generating dual-frequency ultrasound from a uniformly designed PMUT array. The presented method is established on a polarization state that is dependent on the vibrational motion of a ferroelectric PMUT, which only requires a single membrane and a driving electrode to cover the separated dual frequency bands. Moreover, by tuning the polarization state of the ferroelectric film using DC bias, the two types of driving modes can be switched. These modes make the ferroelectric PMUT emit low-frequency (5 MHz) and high-frequency (10 MHz) ultrasound from a single excitation frequency of 5 MHz. The first section of the paper presents the concepts of dual frequency generation in a ferroelectric PMUT and demonstrates the interrelationship between the vibrational motion of the PMUT and the polarization state of the ferroelectric film. From this PMUT behaviour, we propose a method of generating dual-frequency ultrasound from a single device by adjusting the DC bias. To prove the concept, a ferroelectric Pb(Mg\(_{1/3}\)Nb\(_{2/3}\))O\(_3\)-PbZrO\(_3\)-PbTiO\(_3\) (PMN-PZT) thin-film-based PMUT array is manufactured using microfabrication techniques. Subsequently, sufficient driving conditions for each mode (low and high frequency) are investigated by measuring the acoustic pressure in a fluid under varying DC biases and AC amplitudes. In terms of potential use as a future biomedical imaging device, safe conditions for the self-heating PMUT and potential skin burns were investigated. Furthermore, the zoom-in and zoom-out capabilities of the frequency-tunable PMUT are presented through B-mode imaging of wire phantoms.

### 2 Concepts Of Dual Frequency Generation In Ferroelectric Pmut

The proposed approach for generating dual-frequency ultrasound was established from the unique vibration mode of a PMUT, which strongly depends on the polarization state of its ferroelectric film. Unlike the proposed technique, conventional driving methods, in which the transducer uses either a non-ferroelectric film (such as aluminium nitride (AlN)) or strongly polarized ferroelectric film), the transducer operates below the coercive voltage (the voltage required to induce domain reversal). Here, driving with a large bipolar signal above the coercive voltage results in the membrane vibrating at a frequency that is desynchronized from the input voltage.

Figure 1a and b present the general polarization and strain curves for ferroelectric materials as a function of input voltage. In ferroelectrics such as PZT, PMN-PT, and PMN-PZT, a single driving cycle at a voltage level above the coercive voltage results in two electromechanical displacement cycles of the
membrane. At segment A → B (red lines in Fig. 1a and b), where the film is not yet polar and has started to be polarized in the thickness direction, the electromechanical-induced stress is contractive in the transverse direction, forcing the membrane to flex upwards. In contrast, as the polarization decreases with a negative sign of the derivative of the voltage (B → D), the membrane attempts to switch the direction of motion. Even at segment C → D, where the voltage polarity is opposed to the remaining polarization in the film, tensile stress forces the membrane to move down strongly. This series of movements occurs for both signs of the bipolar cycle (A → D and D → G). Consequently, the periodical reversal of polarization during every excitation cycle causes two cycles of flextensional vibration in the membrane, resulting in the output transmit frequency being twice that of the frequency of the input voltage ($f_{\text{out}} = 2 f_{\text{in}}$). Conversely, in the cases of unipolar (yellow line) or semi-bipolar (orange line) driving, unidirectional stress occurs in cycles due to the consistent orientation of polarization. This results in a vibrational frequency ($f_{\text{out}} = f_{\text{in}}$) of the PMUT that is synchronized with the driving voltage.

Dual frequency ultrasound transmission using DC bias is proposed based on the non-linear vibrational behaviour of PMUTs, which is derived from polarization hysteresis. For the low-frequency ($f_{\text{out}} = f_{\text{in}}$) emissions, a large DC bias is also applied to ensure the ferroelectric film is strongly poled and domain reversal can be restrained during the driving cycles (Fig. 1c). Conversely, to generate high frequency ($f_{\text{out}} = 2 f_{\text{in}}$) ultrasound, the PMUT is driven by large bipolar swings at levels above the coercive voltage without any bias (or with a weak DC bias), allowing easy domain switching (Fig. 1d). In both modes of operation, only a single driving frequency ($f_{\text{in}}$) is required.

3 Materials And Methods

3.1 Fabrication of ferroelectric PMN-PZT PMUT

A simplified fabrication process flow of the PMUT is presented in Fig. 2a. The fabrication process started by sequentially growing three buffer layers: yttria-stabilized zirconia (YSZ), cerium oxide (CeO$_2$), and La$_{0.67}$Sr$_{0.33}$MnO$_3$ (LSMO). These were grown on a 5-µm-thick device layer of silicon on an insulator (SOI) wafer using pulsed laser deposition (PLD). This oxide heterostructure had bridged perovskite ferroelectric film and Si with structural similarities (symmetry and lattice parameters), enabling the growth of a film with high crystalline quality. The laser energy density for deposition was set to 1.5 J/cm$^2$ and each layer was grown to the following thicknesses at 750 °C: 50 nm (YSZ), 50 nm (CeO$_2$), and 75 nm (LSMO). The last buffer layer (LSMO), which has high electrical conductivity, acted as the ground electrode of the PMUT.

After deposition of the buffer layers, (001) oriented ferroelectric PMN-PZT film was grown by sputtering with a 3:1 ratio of Ar and O$_2$ gases at 600 °C (Fig. 2a( )). On the grown 1 µm thick PMN-PZT film, which is displayed in the cross-sectional SEM image of the PMUT (Fig. 2c), a bi-layer of Ti/Au (30 nm/ 200 nm) was deposited using sputtering and then patterned via lift-off (Fig. 2a( )). Subsequently, 70 µm diameter circles were patterned on the handle silicon layer of the SOI wafer using lithography and then etched
using deep-reactive ion etching to define the PMUT’s membrane (Fig. 2a()). Figure 2b displays an optical top-view of the 1-dimensional (1D) PMUT array with circular cells. The PMUT array consisted of 16 elements that could be driven individually and 8 cells within each element that were electrically linked together, resulting in simultaneous excitation of all the cells in each element. Finally, for electrical access to the grounded LSMO layer, the PMN-PZT layer on the edge of the PMUT chip was physically peeled off and conductive silver paste was applied (Fig. 2a()

3.2 Electrical characterization of PMN-PZT film

The hysteresis (polarization vs. voltage) loops of (001) oriented ferroelectric PMN-PZT thin film on PMUT were characterized at room temperature (25 °C) using a ferroelectric test system (Precision Premier, Radiant Technologies). Here, a cyclical bipolar voltage ranging from 2 to 80 V\(_{\text{pp}}\) was applied to the PMN-PZT film at 1 mHz, which was the lowest sweeping frequency in the measurement system. Each loop was obtained after five sampling cycles to average out the noise.

3.3 Acoustic characterization of PMUT

The acoustic pressure output of the ferroelectric PMUT was measured in a liquid environment (soybean oil) with the following characteristics: sound speed \(c = 1466 \text{ m} \cdot \text{s}^{-1}\) at room temperature\(^{35}\) and mass density = 917 kg\(\cdot\)m\(^{-3}\)[\(^{36}\)]. This vegetable oil is widely used as a coupling media in acoustic imaging studies as it has similar acoustic properties to human tissue and good electrical insulation characteristics\(^{37}\). In the experiments, the PMUT was wire bonded to a ceramic pin grid array and electrically connected to the driving system using a customized printed circuit board. The transducer was driven by sinusoidal pulses of up to 80 V\(_{\text{pp}}\), which were generated by a function generator (33500B, Keysight) and magnified by an RF amplifier (325LA, Electronics & Innovation) in sequence. To investigate the effect of DC bias on the output pressure of the PMUT, a bias voltage ranging from −20 to +20 V was applied together using a power supply (E36234A, Keysight) and a bias network (5575A Bias Tee, Picosecond). As a function of the DC bias and the magnitude of the AC pulses, the output pressure generated from the PMUT was measured using a calibrated hydrophone (HGL-0200, ONDA) at a distance of 4.5 mm from the PMUT’s surface, as displayed in Fig. 2d. The one-way travel time of the ultrasound was approximately 3 µs. The recorded acoustic signals were then decomposed to their frequency components using a fast Fourier transform (FFT). In the diverse driving conditions of the results, the correlation between polarization dynamics in the ferroelectric film and the PMUT output pressure was comprehensively examined and the best conditions for dual-frequency ultrasound generation were derived from the frequency response of the transmitted ultrasound.

3.4 Thermal dissipation measurement

In the high-frequency ultrasound operation mode, over-coercive voltage driving can cause self-heating problems associated with electrical losses of the ferroelectrics\(^{38,39}\). Moreover, repetitive switching polarization during excitation can induce dielectric losses, which are derived from the domain wall moving\(^{40}\). In turn, this loss results in heat dissipation of the ferroelectric film that is deposited within the
transducer itself, restricting its practical use as a biomedical imaging transducer due to the possibility of burning the skin. Accordingly, the thermal dissipation from the PMUT was investigated under a range of tone-burst operating conditions. With an established best condition of DC bias for high-frequency ultrasound, the PMUT was driven by 10 cycles of a large AC swing (80 \( V_{pp} \)), which was sufficient to fully switch the polarization orientation. The temperature increases at duty cycles from 1–20% were observed by capturing thermographic images of the oil-immersed PMUT using an infrared camera (FLIR A325sc, FLIR systems). In each case, the corresponding pulse repetition frequency (PRF) was set to 5, 25, 50, and 100 kHz.

### 3.4 Ultrasound imaging with PMUT

The ultrasound imaging performance of the PMUT was assessed in both modes of operation by obtaining B-mode images of wire phantoms using an ultrasound research platform (Vantage 64, Verasonics). Here, 6 copper wires with a diameter of 100 \( \mu m \) were equally spaced at 2 mm and distributed at depths of 4 to 14 mm from the PMUT surface. In the imaging setup, all elements in the 1-D array were used for transmission and reception the ultrasound signals. The transmitted wave steered from −20° to +20° in sequential 31 transmit events by adding a gradual delay to the firing time in each element. During the receiving events, backscattered ultrasound echoes from the plane wave emitting at different steer angles were recorded, processed, and beamformed in parallel by implementing synthetic dynamic focus to reconstruct the image\(^{41}\). This coherent plane-wave compound (CPWC) technique offers a higher SNR of the image compared to synthetic aperture imaging (SAI) due to the large array gain during transmission. Furthermore, CPWC provides a high frame rate with the same quality as conventional multifocal B-mode imaging\(^{42,43}\).

### 4 Results And Discussion

#### 4.1 DC bias effects on ultrasound frequency

The grown PMN-PZT film had almost symmetrical polarization characteristics with respect to the zero voltage axis. Figure 3a displays the hysteresis curve of the No.5 element in the PMUT array. Here, the measured coercive voltages where polarization reversal occurred were \(-2.3\) and \(+2.5\) \( V \) under negative and positive biases, respectively. The remanent polarization was \( \pm 17 \mu C/cm^2 \). To demonstrate the dependency of ultrasound frequency on the polarization state of the ferroelectric film, the ultrasound output signals from the PMUT were investigated under three different bias points, which represented the PMN-PZT’s polarization. Figure 3c–e presents the output ultrasound signals at 20 \( V \) (strongly poled in an upward direction), 10 \( V \) (weakly poled), and \(-2.3\) \( V \) (not polarized with negative coercive bias). Under these biases, the driving pulse was identically set to 5 MHz (5 cycles) and an AC.

Fig. 3c–e presents the output ultrasound signals at 20 \( V \) (strongly poled in an upward direction), 10 \( V \) (weakly poled), and \(-2.3\) \( V \) (not polarized with negative coercive bias). Under these biases, the driving pulse was identically set to 5 MHz (5 cycles) and an AC voltage magnitude of 30 \( V_{pp} \). In the strongly
poled state with high bias (Fig. 3c), the unipolar driving did not switch the polarization direction during the excitation cycles. The unidirectional induced piezoelectric stress resulted in synchronized vibrational motion of the membrane and an emitted ultrasound frequency identical to the driving signal (5 MHz).

As the polarization was weakened by reducing the bias, polarization reversal during the negative half-driving cycle started to switch the direction of the piezoelectric stress and caused the PMUT to vibrate faster. Consequently, the accelerated vibration of the PMUT resulted in second-harmonic ultrasound generation with a frequency that was double the driving signal (10 MHz), as displayed in Fig. 3d. When the bias point reached the coercive voltage (~2.3 V), the polarization was easily reversed by bipolar excitation, resulting in maximized harmonic ultrasound components (Fig. 3e). This frequency shift was also exhibited in the upward sweeping bias, except for at the coercive voltage. If the ferroelectric film was strongly poled in the downward direction with a negative bias, the PMUT emitted a 5 MHz ultrasound signal. As the polarization weakened due to the upward sweeping bias, high-frequency (10 MHz) ultrasound became intensive and maximized at a positive coercive voltage of 2.5 V. These characteristics resulted in an inverse butterfly-shaped loop for the relationship between DC bias and 10 MHz ultrasound components (blue solid line in Fig. 3b). The low-frequency ultrasound (5 MHz) manifested the other way round, presenting as a butterfly-shaped loop (red solid line in Fig. 3b). This minimized at the coercive biases (~2.3 and +2.5 V) and started to increase with the high bias voltage in both directions. In conclusion, the PMUT’s driving modes for low- and high-frequency ultrasound could be easily switched by tuning the DC bias. For low-frequency ultrasound, a high bias, which made the ferroelectric strongly poled, was required (red dashed area in Fig. 3b). Conversely, a low bias near the coercive voltages was necessary to obtain high-frequency ultrasound (blue dashed area in Fig. 3b).

4.2 AC swing for high-frequency ultrasound

In addition to coercive biasing, for high-frequency ultrasound generation, the PMUT should be driven with a large bipolar signal that can fully induce ferroelectric domain switching. This concept is demonstrated in Fig. 4, which displays the transmit pressure from the PMUT (Fig. 4a) and polarization hysteresis (Fig. 4b) under varying driving voltages. As presented in the grey dashed area of Fig. 4a, the small AC swing below 6 V<sub>pp</sub> was unable to force the PMUT to vibrate sufficiently, resulting in the emitted pressure being too small to detect. Under small excitations, polarization in the PMN-PZT film did not exhibit hysteresis, resulting in no domain switching. However, above this threshold value of 6 V<sub>pp</sub>, the transmit pressure rapidly increased due to significant hysteresis, resulting in sufficient domain switching (blue dashed area of Fig. 4a). At voltage levels above 60 V<sub>pp</sub>, the polarization of the PMN-PZT started to saturate, resulting in constant piezoelectricity. Under these large swings, the PMUT exhibited a linear relationship between the driving voltage and output pressure (red dashed area of Fig. 4a).

4.3 Heat dissipation during over-coercive driving mode

The aim of this study was to evaluate the self-heating characteristics of PMN-PZT PMUT under an over-coercive driving mode to achieve high-frequency ultrasound generation. The periodical domain wall
motion resulted in dielectric losses on each excitation cycle and heat dissipation from the driven PMUT. The duty cycle, which is an excitation parameter, was mainly investigated to obtain safe driving conditions, to avoid self-heating and predictable thermal injuries when used for biomedical imaging transducers. In the experiments, the PMUT was driven at a large AC voltage of 80 Vpp and −2.3 V coercive biasing, which was an established condition from the preceding experiments. As demonstrated in the thermal infrared images of an oil-immersed PMUT with an oil height of 1 mm (captured at 120 s after firing the PMUT), the temperature of the PMUT drastically increased with increasing duty cycles due to insufficient cooling time. For the 20% duty cycle (the highest value in the experiments), the temperature increased to 49 °C and became saturated. This temperature indicated that a duty cycle above 20% would either restrict medical usage (due to potential skin burns) or require safe time limits (approximately 19 s below 35 °C). The temperature increase could be alleviated by increasing the oil (acoustic media) height. When the oil height was increased to 7 mm, the temperature saturated to 42 °C, which was 17% lower than when the height was 1 mm. This result was due to the heat dispersion of the surrounding oil. In addition, the safe usage time was extended to approximately 25 s below 35 °C. Additionally, the saturated temperatures did not exceed 35 °C in either case at duty cycles of 1%, 5%, and 10%, suggesting that it could be used without any safety concerns. Typically, pulse-echo imaging schemes prefer low-duty cycles, except for special cases such as fast doppler imaging that needs to detect high-velocity blood flows without aliasing because short pulse duration and low pulse repetition frequency (PRF) results in enhanced axial resolution and large imaging depth.

4.4 Ultrasound imaging

With ultrasound imaging, the penetration depth and spatial resolution strongly depend on the ultrasound wave's frequency. Compared to low-frequency pulses, high-frequency pulses yield a narrow beamwidth and a resultant improved spatial resolution at the expense of a shallow depth of penetration due to high attenuation. Figure 6a displays a 30 dB compressed grayscale ultrasound image of wire phantoms obtained by 5 MHz ultrasound, and Fig. 6b displays an image from a 10 MHz ultrasound signal. As demonstrated in the images, the higher frequency (10 MHz) produced enhanced lateral resolution and reduced imaging depth compared to the image obtained using 5 MHz ultrasound. The measured full-width half maximum on the lateral axis of the 4 mm located wire was estimated as 141 µm in the 10 MHz ultrasound image, which was 21% smaller than that of the 5 MHz image (179 µm), as shown in Fig. 6c. However, the wire at 14 mm depth in the 10 MHz ultrasound image could not be found clearly rapidly decreasing signal to noise ratio (SNR). In contrast, the SNR of the 14 mm wire in the 5 MHz image was 6.64 dB and remained distinguishable.

There was no significant difference in axial resolution (the capability of resolving two reflectors along the beam's path) between images. This is because the pulse duration of high-frequency ultrasound generated from the over-coercive mode of the PMUT was comparable to that of low-frequency ultrasound. When the PMUT was subjected to over-coercive driving, the membrane vibrated in twice as many cycles compared...
to when operating in normal driving mode for low frequencies. The axial resolution in ultrasound imaging is determined by the total pulse duration (µsec), which is a product of the period (nsec) and number of cycles (#).

**Conclusions**

This paper presented a novel method for dual-frequency ultrasound generation in ferroelectric PMUTs using a single excitation frequency (5 MHz). The ferroelectric PMUT exhibited a shift in output ultrasound frequency under varying DC biases and resultant polarization states of the ferroelectric film. At a high DC bias (positive or negative polarity), the ferroelectric film was strongly poled and direction switching did not occur during excitation. This resulted in synchronization of the output ultrasound frequency and driving signal (5MHz). Moreover, at 10 MHz, a second harmonic ultrasound of the input frequency was produced by a large AC swing (> 6 V<sub>pp</sub>) at coercive voltage biases of −2.3 V (negative polarity) or +2.5 V (positive polarity), which induced a periodical domain wall moving in the ferroelectrics. Accordingly, driving mode switching by tuning the DC bias provided the option to select the frequency for better imaging resolution and depth, resulting in a more comprehensive understanding of the anatomic structure of targets. For future biomedical imaging applications, driving conditions that can avoid predictable thermal injuries to the subject will be investigated. Below 10% duty cycles, sufficient cooling time would warrant safe usage without any self-heating problems of the transducer. Moreover, this value could be extended by packaging the PMUT with higher thermally conductive media such as silicon rubber compounds (RTV 615 and 655), which are well-established materials for producing the acoustic lenses of diagnostic transducers. This would mitigate any increasing heat on the transducer, since their thermal conductivity of 0.2 W/mK is slightly higher than that of the soybean oil (0.153 W/mK) used in this study.

**Declarations**

**Acknowledgments**

This work was supported by the Samsung Research Funding & Incubation Center for Future Technology (Grant No. SRFC-MAI702-03). Fabrication of the ferroelectric PMUT array, with the exception of the PMN-PZT growth procedure, was performed at the Korea Institute of Science and Technology (KIST) Micro-Nano Fabrication Center (Seoul, Korea). The PMN-PZT growth was performed at the Center for Electronic Materials in KIST.

**Competing interests:** The authors declare that they have no conflicts of interest.

**Author Contributions**

Seung-Hyub Baek and Byung Chul Lee conceived and initiated the project; Jin Soo Park designed the device; Jin Soo Park and Soo Young Jung fabricated the device and conducted the measurements; Jin Soo Park, Soo Young Jung, Dong Hun Kim, Seung-Hyub Baek and Byung Chul Lee analyzed the data;
Jung Ho Park, Tae Geun Kim, and Ho Won Jang contributed to the discussion. All the authors were involved in writing and reviewing the manuscript.

References


Figures

Figure 1

- Illustration of general strain-voltage curve for ferroelectric film. 
- Illustration of general polarization-voltage curve for ferroelectric film. 
- High frequency operation of ferroelectric PMUT. 
- Low frequency operation of the PMUT

Figure 2

- Fabrication process of 1-dimensional array of PMN-PZT PMUT. 
- Optical image of PMN-PZT PMUT. 
- Cross-sectional SEM image of PMN-PZT film on silicon. 
- Illustration of acoustic experimental set-up
Figure 3

a Polarization–voltage curve of grown PMN-PZT film. b Output pressures of 5 and 10 MHz frequencies under varying DC biases from −20 to +20 V. c Output pressure when driving with 20 Vdc. d Output pressure when driving with 10 Vdc. e Output pressure when driving with −2.3 Vdc

Figure 4

Conditions of AC swing voltage for high frequency ultrasound: a Output pressures generated from PMUT in high frequency operation. b Ferroelectric polarization hysteresis for a PMN-PZT thin film with applied voltage levels of 2, 4, 6, 10, 20, 40, 60, and 80 V_{pp}
Figure 5

Thermal infrared images of oil-immersed PMUT when it was driven by an over-coercive voltage swing. Each image was captured at 120 s after driving with various duty cycles and oil heights. The driving voltage was identical: 5 MHz, 10 cycles, and 80V_{pp} with −2.3 V_{dc} coercive voltage. The oil height was 1 mm for the following duty cycles: a 1%, b 5%, c 10%, and d 20%. The oil height was 7 mm in the following duty cycle cases: e 1%, f 5%, g 10%, and h 20%. Temperature-time profiles at center point of oil-immersed PMUT in the case of oil heights i 1 mm and j 7 mm
Figure 6

Ultrasound B-mode images of wire phantoms (0.1 mm diameter) acquired with Vantage 64 system. The six wire phantoms were located at depths of 4, 6, 8, 10, 12, and 14 cm in the oil: a 30 dB compressed image obtained from 5 MHz ultrasound sonication when 20 Vdc was applied to the PMUT. b 30 dB compressed image obtained from 10 MHz ultrasound sonication when −2.3 Vdc (Coercive voltage) was applied to the PMUT. c Axial beam profiles obtained from wire targets. d Lateral beam profiles obtained from a wire located at 4 mm depth

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- GraphicalAbstract.jpg