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Interleaved Array Transducer with Polarization Inversion Technique to Implement Ultrasound Tissue Harmonic Imaging

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Abstract: In ultrasound tissue harmonic imaging (THI), it is preferred that the bandwidth of the array transducer covers at least the fundamental frequency $f_0$ for transmission and the second harmonic frequency $2f_0$ for reception. However, it is challenging to develop an array transducer with a broad bandwidth due to the single resonance characteristics of piezoelectric materials. In this study, we present an improved interleaved array transducer suitable for THI and a dedicated transducer fabrication scheme. The proposed array transducer has a novel structure in which conventional elements exhibiting $f_0$ resonant frequency and polarization-inverted elements exhibiting $2f_0$ resonant frequency are alternately located, and the thicknesses of all piezoelectric elements are identical. The performance of the proposed method was demonstrated by finite element analysis (FEA) simulations and experiments using a fabricated prototype array transducer. Using the proposed technique, $f_0$ and $2f_0$ frequency ultrasounds can be efficiently transmitted and received, respectively, resulting in a 90% broad bandwidth feature of the transducer. Thus, the proposed technique can be one of the potential ways to implement high resolution THI.

Keywords: finite element analysis (FEA) simulation; interdigital bonding process; interleaved array transducer; polarization inversion technique; tissue harmonic imaging

1. Introduction

Recently, tissue harmonic imaging (THI) based on nonlinear phenomenon has begun to be widely used in echocardiography because it can provide a high resolution, improved signal-to-noise ratio (SNR), and reduced near-field artifacts [1–9]. In general, axial resolution can be improved by using higher frequencies and broader bandwidth signals. With higher frequencies of harmonic signals compared to the fundamental frequency, THI can improve axial resolution. Otherwise, a conventional THI transducer uses a narrower bandwidth to filter out frequencies from the fundamental beam, so the axial resolution can be reduced. Therefore, to increase the resolution of THI, the bandwidths for $f_0$ transmission and $2f_0$ reception should be as broad as possible while minimizing overlap between the two components [10–12]. In order to increase the bandwidth of a transducer, a piezoelectric material with a high electromechanical coefficient can be used. A composite structure or optimized passive layers can contribute to broadening a bandwidth [13–16]. However, those methods have a limit to increase a bandwidth more than a certain level due to the single resonance feature of the piezoelectric material within the frequency range of interest, which is called an odd-order thickness-extensional vibration [17,18]. A capacitive micromachined ultrasound transducer (CMUT) and a piezoelectric micromachined ultrasound transducer (PMUT) can increase a bandwidth [19–22]. However, the inherent non-linear behavior of a CMUT is problematic for separating harmonic
components from a target, and the CMUT requires a high bias voltage that results in safety issue [19,20].

In order to overcome this limitation, some researchers have proposed a method of alternately arranging \( f_0 \) and \( 2f_0 \) elements in a single array transducer known as an interleaved array transducer for THI [23–25]. This method can achieve the maximal bandwidths of the \( f_0 \) and \( 2f_0 \) elements, respectively, and physically separate received \( f_0 \) and \( 2f_0 \) frequency components without using a band pass filter. However, the fabrication process of the conventional interleaved array transducer is complicated because the thicknesses of two types of piezoelectric elements are different. That is, the bonding process of a matching layer, a backing layer, and a flexible printed circuit board (FPCB) to the piezoelectric layer with a different thickness is quite challenging.

In this study, we propose a novel interleaved array transducer for THI that is capable of overcoming the aforementioned issue. The proposed transducer also consists of \( f_0 \) and \( 2f_0 \) elements, which are placed alternately, but the thickness of the \( 2f_0 \) piezoelectric element is the same as that of the \( f_0 \) piezoelectric element. To achieve this effect, the polarization inversion technique (PIT), which is capable of generating an even-order thickness-extensional vibration, was employed for the \( 2f_0 \) element [26–29]. The PIT can increase the center frequency of the transducer by combining multiple piezoelectric layers with opposite poling directions. In this structure, the center frequency can be increased even though the total thickness of the piezoelectric layer is not thinner [28,29]. Since the thicknesses of all elements are identical, the fabrication process for interleaving elements is more convenient compared to the conventional fabrication method. Unlike the conventional PIT, which mainly uses LiNbO\(_3\) material and a co-firing fabrication technique, in the proposed technique, a common PZT-5H was selected as the piezoelectric material, and a mechanical bonding technique using an unloaded epoxy was used for PIT implementation. The performance of the proposed array transducer was evaluated by finite element analysis (FEA) simulation, and a prototype array transducer was subsequently fabricated for experimental demonstration.

The fundamental operational principle, design specifications, and FEA simulation results of the proposed array transducer are described in the Section 2. Experimental validation using the prototype array transducer and method of transducer fabrication are described in the Section 3. The discussion and conclusion are drawn in Section 4.

2. Materials and Methods

2.1. Polarization Inversion Technique

In the PIT, two sub-piezoelectric layers are bonded with opposite poling directions, and they operate as a single-piezoelectric layer. The PIT can simultaneously generate \( f_0 \) and \( 2f_0 \) based on odd-order and even-order thickness-extensional vibrations [26,29]. Only two electrodes are formed at the top and bottom sides of the combined piezoelectric layer. The position of the resonance frequencies and electrical impedances can be controlled depending on the thickness ratio of the two bonded layers [26,28,29]. The operational principle can be explained by elastic wave propagation, as shown in Figure 1. Figure 1a shows a single piezoelectric layer with one poling direction. When a voltage is applied to the piezoelectric layer in the same direction as the poling direction, the elastic waves with positive-polarity are propagated outward from interface A and B. The phases of the reflected signals at interface A and C are inverted due to the difference of the acoustic impedance between the active layer and medium. Thus, the elastic waves with negative-polarity are generated and propagated in the opposite direction based on principles of action and reaction. When observing the wave arrival time at interface A, the positive- and negative-polarity waves reach a \( 2d_1/v \) interval, and, thus, an ultrasound wave with the fundamental resonant frequency can be generated. In the case of Figure 1b with the PIT, two piezoelectric layers were combined together with opposite poling directions. In this scheme, the inversion ratio defined by the thickness of the inverted piezoelectric layer to the thickness
of the entire piezoelectric layer was 0.25. In the PIT, the thinner layer is called the inverted layer, and when the inverted layer is located at the front side of the transducer, we call it a front-side inversion model. When the voltage is applied, the positive-polarity waves reach interface A with the $d_1/v$ interval. The negative-polarity waves reach interface A with $2d_2/v$ and $2(d_1-d_2)/v$ intervals alternatively. When the position of the inverted layer is changed to back side of the transducer, as shown in Figure 2c (which is called a back-side inversion model), the operational principle is the same as in Figure 2b except for the starting time interval. In the case of Figure 1d with the PIT, two piezoelectric layers with a 0.5 inversion ratio were combined together for what is called a half-inversion model. When the voltage is applied, the positive- and negative-polarity waves reach interface A with a $d_1/v$ interval, which is half the time interval of Figure 1a. Thus, when the inversion ratio became 0.5, the resonance frequency could be increased to $2f_0$. Note that the total thickness of the piezoelectric layer with a 0.5 inversion ratio could be identical to that of a conventional piezoelectric layer with a fundamental resonance frequency.

![Figure 1. Operational principle of the conventional and polarization inversion technique (PIT) models: (a) Conventional structure with a single piezoelectric layer, (b) polarization-inverted layer structure with a 0.25 inversion ratio (front-side inversion model), (c) polarization-inverted layer structure with a 0.25 inversion ratio (back-side inversion model), and (d) the PIT with a 0.5 inversion ratio (half-inversion model). Note that the time and frequency responses of the radiated ultrasound waves at interface A for each case were also demonstrated by computational simulation, as shown in Figure 2.](image-url)
Figure 2. Time and frequency responses of the radiated ultrasound waves at interface A for each case in Figure 1 based on MATLAB simulations: (a) Time and (b) frequency domain responses of the conventional model, (c) time and (d) frequency domain responses of the PIT with a 0.25 inversion ratio (front-side inversion model), (e) time and (f) frequency domain responses of the PIT with a 0.25 inversion ratio (back-side inversion model), and (g) time domain and (h) frequency domain responses of the PIT with a 0.5 inversion ratio (half inversion model).

In order to more clearly verify the time and frequency responses of the radiated ultrasound waves at interface A for each case in Figure 1, computational simulation was conducted by using MATLAB (The MathWorks, Inc., Natick, MA, USA). In this simulation, the center frequency was assumed to be 5 MHz, which was normalized in the final step. The propagation velocity was assumed to be 4192 m/s considering the PZT-5H material. In addition, for front-side inversion, back-side inversion, and half-inversion models, $d_1 = 1$, $d_2 = 0.25, 0.75$, and 0.5, respectively. The fundamental frequency $f_0$ of Figure 1a was generated as shown in Figure 2a,b. In the case of the PIT with a 0.25 inversion ratio in Figure 1b,c, the $f_0$ and $2f_0$ peak frequencies were generated (Figure 2c–f). The performance difference between the two models were the level of the center valley. The front-side inversion model provided a relatively shallow depth of the valley compared to that of the back-side inversion model. Thus, the front-side inversion model can be used for a broad bandwidth transducer, while the back-side inversion model can be used for a dual-peak transducer [29,30].
When the inversion ratio was 0.5, like in Figure 1d, the center frequency of the PIT was 2$f_0$, even though the thickness of the PIT model was the same as that of the conventional model described in Figure 2g,h. Unlike the previous interleaved array transducer, which used piezoelectric elements of different thicknesses to generate $f_0$ and 2$f_0$ ultrasounds, respectively, all piezoelectric elements of the proposed transducer have the same thickness. Therefore, the array transducer for THI can be efficiently fabricated including the bonding process for a matching layer, a backing layer, and an FPCB. In addition, the proposed transducer used a conventional mechanical bonding process and common piezoelectric material (PZT-5H), which are widely used in array transducers. Note that most previous studies about the PIT were conducted for a single element transducer using LiNbO$_3$ and complicated co-firing methods [17,18].

2.2. Design of Interleaved Array Transducer Based on FEA Simulation

For the performance evaluation of the proposed array transducer, an FEA simulation using the PZFlex software (OnScale, Cupertino, CA, USA) was conducted. The center frequencies for transmission and reception were chosen as 5 and 10 MHz, respectively, based on a commercial linear array transducer for THI. A common PZT-5H (CTS3203HD, CTS Corporation, Lisle, IL, USA) was used as the piezoelectric material, and a 2-2 composite structure based on the sub-dicing process was employed for a more efficient aspect ratio (element width/element height) less than 0.5 [31–35]. The inversion ratio was chosen as 0.5 to generate only 2$f_0$ frequency components. The piezoelectric element width was 301 $\mu$m, and the kerf width was 38 $\mu$m. After sub-dicing, the piezoelectric element width was 75 $\mu$m. The total thickness of the piezoelectric layer was 280 $\mu$m, and the aspect ratio of the sub-elements was thus 0.27. Two matching layers, i.e., aluminum powder (Metalplayer, Incheon, Korea) filled epoxy for the 1st matching layer and EPO-TEK 301 (Epoxy Technology, Billerica, MA, USA) for the 2nd matching layer were added on the piezoelectric layer, and tungsten powder (TaeguTec, Deagu, Korea) filled epoxy was used for a backing layer. The reference frequency used to design two matching layers was 1.5$f_0$, which is middle value between $f_0$ and 2$f_0$. The FPCB and bonding layer were included in this simulation, and the medium was water. Since the goal of this study was the performance demonstration of the proposed method, only eight elements were fabricated, i.e., four $f_0$ and four 2$f_0$ elements. Table 1 describes the design specifications of the proposed transducer, and Table 2 shows the material properties of the PZT-5H used in FEA simulation.

### Table 1. Design specifications of the proposed transducer used in the finite element analysis (FEA) simulation.

|                        | Conventional $f_0$ Element | PIT 2$f_0$ Element |
|------------------------|---------------------------|-------------------|
| Center frequency [MHz] | 5                         | 10                |
| Element number         | 4                         | 4                 |
| Element width [\(\mu m\)] | 301                       |                   |
| Sub-element width [\(\mu m\)] | 75                        |                   |
| Kerf size [\(\mu m\)]  | 38                        |                   |
| Total thickness of piezoelectric layer [\(\mu m\)] | 280                       |                   |
| Thickness of 1st matching layer [\(\mu m\)] | 80                        |                   |
| Thickness of 2nd matching layer [\(\mu m\)] | 100                       |                   |
| Piezoelectric material | PZT-5H                     |                   |
| 1st Matching layer material | Aluminum powder filled epoxy |                   |
| 2nd Matching layer material | Unloaded epoxy             |                   |
| Backing layer material  | Tungsten powder filled epoxy |                 |
On the other hand, the PIT element had a 11 MHz center frequency with a pulse–echo response of the conventional element. In the case of the conventional element, the electrical impedance was 173 $\Omega$ at a resonance frequency of 5 MHz (Figure 4a), and the PIT element was 26.2 $\Omega$ at a resonance frequency of 10.3 MHz (Figure 4b). In the case of the pulse–echo simulation, the conventional element had a 5.3 MHz center frequency with a $-6$ dB bandwidth of 71.1% (Figure 4c). On the other hand, the PIT element had a 11 MHz center frequency with a $-6$ dB bandwidth of 28.5% (Figure 4d). From those results, it was verified that the PIT elements only generated 2$f_0$ resonance frequency components successfully.

### Table 2. Material properties of the PZT-5H used in the FEA simulation.

| Property                              | Value         |
|---------------------------------------|---------------|
| Elastic stiffness $c_E$ $(10^{10}$ N/m$^2)$ | $c_{11} = 13.7$ |
|                                       | $c_{12} = 8.8$ |
|                                       | $c_{13} = 9.23$ |
|                                       | $c_{33} = 12.6$ |
|                                       | $c_{44} = 2.2$ |
|                                       | $c_{66} = 2.5$ |
| Mechanical Q                          | 90            |
| Dielectric permittivity $\varepsilon /\varepsilon_0$ | $\varepsilon_{11} = 1305.8$ |
|                                       | $\varepsilon_{33} = 1200.2$ |
| Piezoelectric stress $\varepsilon$ (C/m$^2$) | $\varepsilon_{13} = -9.4$ |
|                                       | $\varepsilon_{33} = 22.5$ |
|                                       | $\varepsilon_{15} = 16.1$ |
| Density $(\text{kg/m}^3)$             | $\rho = 7820$ |

### 2.3. FEA Simulation Results

Figure 3 shows a cross-sectional image of the proposed array transducer obtained from FEA-based software (OnScale, Cupertino, CA, USA). Only six elements are shown from the simulated eight elements. The conventional elements and PIT elements with a 0.5 inversion ratio were alternatively arranged, and identical matching layers were applied to all elements. The thicknesses of the piezoelectric layers for $f_0$ ultrasound transmission and reflected 2$f_0$ ultrasound reception were identical to each other even though the resonance frequencies were different. Figure 4 shows the electrical impedance and pulse–echo response of the conventional element and the PIT element. In the case of the conventional element, the electrical impedance was 173 $\Omega$ at a resonance frequency of 5 MHz (Figure 4a), and the PIT element was 26.2 $\Omega$ at a resonance frequency of 10.3 MHz (Figure 4b). In the case of the pulse–echo simulation, the conventional element had a 5.3 MHz center frequency with a $-6$ dB bandwidth of 71.1% (Figure 4c). On the other hand, the PIT element had a 11 MHz center frequency with a $-6$ dB bandwidth of 28.5% (Figure 4d). From those results, it was verified that the PIT elements only generated 2$f_0$ resonance frequency components successfully.

![Figure 3](image-url) **Figure 3.** FEA-based schematic diagram of the proposed array transducer using the PIT for tissue harmonic imaging (THI). The array transducer was composed of the conventional elements for transmitting $f_0$ ultrasounds and the PIT elements for receiving reflected 2$f_0$ ultrasounds. The conventional elements exhibited the same poling direction, but the PIT elements exhibited the opposite poling direction. The identical matching layers were applied to the proposed model.
3. Experimental Validation

3.1. Fabrication of Prototype Array Transducer with PIT and Novel Interleaved Technique

In order to experimentally demonstrate the performance the proposed transducer, a prototype array transducer with the PIT was built based on the FEA-simulated design specifications. First, three bulk-type PZT-5H plates with dimensions of $4 \times 15 \times 0.5$ mm were prepared, as described in Figure 5. One of them was used for the conventional elements, and two of them were used for the PIT elements. One part was lapped to 280 µm for the 5 MHz resonance. For the PIT elements, two parts with negative polarity were lapped as 140 µm. Chrome/Gold (500 Å/2000 Å) was sputtered on the lapped surface of each part to form the electrodes. After bonding two parts with opposite poling directions by using epoxy (EPO-TEK 353ND, Epoxy Technology, Billerica, MA, USA), they were diced to form a 2-2 composite using a dicing saw (DAD322, DISCO Corp., Tokyo, Japan). After dicing the conventional elements with the same process, two types of piezoelectric components were alternatively assembled and bonded to the FPCB. After sub-dicing, unloaded epoxy was used to fill the kerfs. Subsequently, they were bonded to the backing layer, which was made using the mixture of tungsten powder and EPO-TEK 301. The first matching layer with a thickness of 80 µm and the second matching layer with a thickness of 100 µm were bonded on the surface of piezoelectric material in sequence. In the case of the first matching layer, aluminum powder with a 1–3 µm particle size and EPO-TEK 301 epoxy were mixed, resulting in a 70% volume fraction ratio. The reference frequency used to make two matching layers was $1.5f_0$, which was a middle value between $f_0$ and $2f_0$.

Figure 6 shows the manufacturing process of the prototype array transducer, focusing on the process of alternately assembling arrays, i.e., the interleaving process. In the case of the conventional interleaving process, the interdigital bonding process, two types of elements are combined up and down [36–40]. Therefore, the interleaving process should be performed while looking at the side,
which makes the work very inconvenient and parts easily damageable. However, the proposed interleaving method is more efficient than conventional techniques because it can monitor and assemble the two types of elements while looking down. Therefore, it is possible to more safely and accurately adjust the kerf between elements. Figure 7a shows the fabricated prototype array transducer after bonding matching and backing layers. A red-dotted circle indicates the position of the eight elements. Figure 7b shows a magnified photograph of the red-dotted circle in Figure 7a, which was composed of the conventional element and the PIT element. The alternately arranged \( f_0 \) and \( 2f_0 \) elements are clearly shown in Figure 7b. The bonding layer of the PIT can be seen in Figure 7c, and the same thickness of the two types of elements can be confirmed.

**Figure 5.** Fabrication process of the proposed prototype array transducer. The improved interleaved technique was employed for this fabrication.

**Figure 6.** Fabrication process of the proposed prototype array transducer focusing on the novel interleaved technique.
3.2. Experimental Results

The electrical impedance and pulse echo response were measured by using an impedance analyzer (4294 A, Keysight, San Jose, CA, USA) and a pulser/receiver (5073PR, Olympus, WA, USA), respectively. Figure 8 shows the experimental setup to measure the pulse echo response. Figure 9 shows the measured electrical impedance and pulse–echo response using the fabricated prototype array transducer. The electrical impedance was measured in the air medium. The electrical impedance of the conventional $f_0$ element and $2f_0$ element with the PIT were 234.8 Ω at a resonance frequency of 5.2 MHz and 183 Ω at a resonance frequency of 10.5 MHz, respectively. The measured center frequency of the $f_0$ element was 5.8 MHz with a $-6$ dB bandwidth of 55%. The $2f_0$ element had a 10.2 MHz center frequency with a $-6$ dB bandwidth of 31.2%. Thus, it was verified that the conventional elements can transmit $f_0$ ultrasounds and the PIT elements can receive reflected $2f_0$ ultrasounds even though the total thicknesses of the two types of elements were identical. Thus, THI can be implemented by using the proposed transducer. Figure 10 shows the pulse–echo response when the $f_0$ element transmitted the impulse signal, and the $2f_0$ element received the reflected ultrasounds. From this experiment, it can be considered that the total $-6$ dB bandwidth of the proposed transducer was 90%, including a shallow valley point. Considering that the typical $-6$ dB bandwidth of the PZT-5H was about 70%, the performance of the proposed method was about 20% higher than the conventional model.
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Figure 8. Experimental setup for pulse–echo measurement. Two pulsers/receivers were used for independent pulse–echo test of each element and the test for transmitting $f_0$ and receiving reflected $2f_0$ frequency components: (a) Schematic diagram and (b) photograph of (a).

Figure 9. Measured electrical impedance (solid line: magnitude; dashed line: phase) and pulse–echo responses (solid line: frequency-domain spectrum; dashed line: time-domain waveform) of the proposed linear array transducer with matching layers: (a) Electrical impedance of the conventional element, (b) electrical impedance of the PIT element, (c) pulse–echo response of the conventional element, and (d) pulse–echo response of the PIT element.
4. Discussion and Conclusions

In order to efficiently implement THI, the bandwidth of the ultrasound array transducer should be broad enough to cover from $f_0$ to $2f_0$. However, since most single-layer piezoelectric materials have an odd-order resonance and a single resonance is normally dominant within the region of interest frequency range, it is challenging to make a broad bandwidth array transducer. The interleaved array transducer does not require a broad bandwidth because it physically separates the transmitting and receiving elements without using the band pass filter, and each full frequency bandwidth for $f_0$ and $2f_0$ can be used for THI. One of the main limitations of this method is that the thicknesses of two types of elements are different and thus, the fabrication process is difficult. In this study, we proposed an improved interleaved array transducer exhibiting the uniform thickness of the piezoelectric layer even though two types of elements with different resonance frequencies are mixed alternatively. This can be achieved by employing the PIT, especially with an 0.5 inversion ratio capable of generating a $2f_0$ frequency component based on the conventional thickness for the $f_0$ resonance frequency.

In the FEA simulation and experiment using a prototype array transducer, $f_0$ and $2f_0$ frequency components were successfully generated. To assemble pre-diced two types of elements, two plates should be carefully interleaved. Different from the conventional interleaved technique, we proposed a modified fabrication process by combining two plates side by side. In the conventional method, it is difficult to align the piezoelectric rods because most of the process should be performed by looking at the side, but the proposed method is performed while looking at the top, so relatively convenient and accurate alignment can be achieved. That is, since the thicknesses of the two plates are the same, it is easy to align the elements and to combine the FPCB and the backing layer.

To increase the bandwidth of each element, a matching layer should be attached. Since the center frequency of this array transducer is different, the center frequency used for designing the matching layer should be optimized. Normally, the thickness of the matching layer is a quarter wavelength in the matching material. That can be controlled depending on the application. In our design, the reference frequency was 1.5 $f_0$ considering the $f_0$ and $2f_0$ center frequencies of two types of elements. Thus, there will be reduction of resolution for $f_0$ and $2f_0$ frequency components compared to the conventional interleaved array transducer. In the case of the experiment of transmitting $f_0$ ultrasounds and receiving reflected ultrasounds with the $2f_0$ element, the total $-6$ dB bandwidth was 90%, which is a broad bandwidth compared to the conventional PZT-5H with a bandwidth of about
70%. That is the proposed method that can implement a broad bandwidth by using two types of independent elements rather than a single element transducer.

In the proposed technique, a 1.5 \( f_0 \) frequency was used for designing two matching layers, and thus, the \(-6\) dB bandwidths of the conventional elements and the PIT elements may be reduced compared to the best condition of two types of elements. Therefore, the imaging performance of the proposed technique may be slightly reduced compared to the conventional interleaved array transducer. However, if more optimized reference frequency and thicknesses of matching layers are chosen, the \(-6\) dB bandwidths of the conventional elements and the PIT elements can be increased more. Like the conventional interleaved array transducer, the proposed method also has a grating lobe issue due to its large pitch. In order to minimize grating lobe generation, controlling the amplitude of the input signal or using a variable pitch will help to solve this problem. The proposed technique has advantages about several manufacturing processes compared to other interleaved transducers for THI, but it requires manufacturing challenges and high costs compared to conventional non-interleaved THI transducers. The interleaved array transducer is not a replacement for conventional THI transducers, but it is one of the useful transducers to implement THI. Each of them has advantages and disadvantages. This manuscript provides information on an improved interleaved array transducer that can also be a useful THI transducer. Additionally, since the imaging system has not yet been prepared, pulse–echo measurements were mainly performed. In the future, we plan to conduct tissue harmonic B-mode (brightness mode) imaging tests using the imaging system.

In this study, we demonstrated that the PIT can be applied to an ultrasound linear array transducer for THI. The proposed transducer is composed of single layer piezoelectric elements for transmitting \( f_0 \) ultrasounds and PIT elements for receiving \( 2f_0 \) ultrasounds, and these are alternately arranged. In the proposed transducer, each element has a unique resonant frequency, so not all elements need to have a broad bandwidth for THI. If the design specifications of the proposed transducer are more optimized, the frequency bandwidth of \( f_0 \) and \( 2f_0 \) can be further increased. Unlike previous studies that used piezoelectric elements of different thicknesses for \( f_0 \) and \( 2f_0 \) ultrasounds, all piezoelectric elements of the proposed transducer have the same thickness, which makes it possible to efficiently manufacture array transducers for THI. To make an interleaved type transducer, a novel interleaved method was introduced, and its performance was also successfully demonstrated. Unlike the conventional method, it is possible to arrange elements while looking down from the top, so more convenient operation is possible. Additionally, the proposed transducer used a conventional physical bonding process to form the polarization-inverted piezoelectric layer, and a popular piezoelectric material, i.e., PZT-5H, was employed. Our simulation and experimental results also showed that multiple piezoelectric layers with a 0.5 inversion ratio can generate higher frequency ultrasounds. Therefore, an interleaved array transducer based on the PIT could be a promising way to conduct high resolution THI.

**Author Contributions:** C.Y.P. conducted the FEA simulations, fabricated a prototype array transducer, and measured data; J.H.S., E.Y.J., and H.S.L. participated in writing and editing the Materials and Methods section and demonstrated the principle of the PIT using software; J.S.J. conceived a novel structure of the array transducer, wrote a manuscript, and supervised all the works. All authors have read and agreed to the published version of the manuscript.

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