PIN-PMN-PT Single Crystal 1-3 Composite based 20 MHz Ultrasound Phased Array

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Abstract: Based on a modified dice-and-fill technique, a PIN-PMN-PT single crystal 1-3 composite with the kerf of 12μm and pitch of 50μm was prepared. The as-made piezoelectric composite material behaved high piezoelectric constant (d_{33}=1500 pC/N), high electromechanical coefficient (k_t=0.81) and low acoustic impedance (16.2 Mrayls). Using lithography and flexible circuit method, a 48-element phased array was successfully fabricated from such piezoelectric composite. The array element was measured to have a central frequency of 20MHz and a fractional bandwidth of approximately 77% at -6dB. Of particular significance was that this PIN-PMN-PT single crystal 1-3 composite based phased array exhibits a superior insertion loss compared with PMN-PT single crystal and PZT-5H based 20 MHz phased arrays. The focusing and steering capabilities of such phased array were validated through Field II simulations. These promising results suggest that the PIN-PMN-PT single crystal 1-3 composite based high frequency phased array is a good candidate for ultrasound imaging applications.

Keywords: PIN-PMN-PT; 1-3 composite; high frequency; phased array

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# Tao Zhang and Dawei Wu are co-first authors of this paper.
1. Introduction

Over the past few decades, high frequency (≥20 MHz) ultrasonic imaging has attracted significant attention in biomedical research and clinical diagnosis [1–2]. Currently, single element transducers and linear arrays are in wide use [3–6]. There have been few studies on the high-frequency ultrasound phased array [7–10], despite being very useful in imaging practices by providing electronic-beam-focusing and steering capabilities. In addition, there are even fewer studies on composite-material-based high-frequency ultrasound phased arrays despite the numerous benefits of composite piezoelectric materials. The main difficulties lie in the fact that the pitch of a phased array is half that of a linear array at the same operating frequency, and the kerf of a composite material must be small to avoid spurious modes. The above facts give rise to a smaller kerf size and smaller element size, which pose even greater challenges for high frequency (≥20 MHz) phased array fabrication and piezoelectric material composite preparation.

In recent years, single-crystal piezoelectrics have been developing a revolutionary to substitute traditional PZT ceramics for ultrasonic transducer applications. Reportedly, PMN-PT single-crystals have been used to manufacture high frequency (≥20 MHz) phased arrays and some attractive results have been found [8–9]. However, the drawback of PMN-PT single-crystals is their relatively low-temperature usage range [11]. To make the devices maintain a better temperature stability, a high Curie temperature (T_c) ternary piezoelectric single crystal [Pb(In\_{1/2}Nb\_{1/2})O_3]-Pb(Mg\_{1/3}Nb\_{2/3})O_3-PbTiO_3, abbreviated as PIN-PMN-PT], which maintains a similar electromechanical and piezoelectric performance (d_{33} ~ 1500 pm V^{-1}, k_{33} > 90%) to a PMN-PT single crystal, has been developed [12–13]. In previous studies, the PIN-PMN-PT single crystal and its composite have been proved to be promising candidates for high frequency single element transducer fabrication [3,13,14]. Additionally, the single crystal 1-3 composite always exhibits a broader bandwidth than monolithic materials because of the much higher coupling coefficient and lower acoustic impedance of the composite. Therefore, there is a clear need to demonstrate the feasibility of the development of a PIN-PMN-PT single crystal 1-3 composite.
based high frequency (≥20 MHz) ultrasound phased array.

In this work, the design, fabrication, and characterization of a 1-3 composite piezoelectric material and a 20 MHz 48-element ultrasound phased array based on the prepared piezoelectric composite is presented.

2. Design and fabrication

In this design, the [001]-oriented single crystal with a composition of 0.27PIN-0.45PMN-0.28PT was selected. Figure 1 describes the 1-3 composite fabrication process, during which a modified dice-and-fill method was adopted to prevent the collapse and cracking of the elements. To obtain a high precision kerf width when dicing the PIN-PMN-PT single crystal, a 10-μm-thick nickel/diamond blade with a DAD323 dicing saw (DISCO, Japan) was chosen. First, the PIN-PMN-PT wafer was diced from two perpendicular directions with a 100 μm pitch and 80 μm depth to form periodic rods. Then, the kerfs with the width of around 12μm were filled by low viscosity epoxy (Epo-Tek-301, Epoxy Technology, USA) and the trapped bubbles were removed in vacuum. After epoxy solidification, the PIN-PMN-PT rods in the epoxy matrix were further diced in the two previous perpendicular directions with the same dicing pitch and depth to form equal areas. The newly formed kerfs were epoxy filled and cured again. Finally, to grind off the excess single-crystal and epoxy, a PIN-PMN-PT single crystal 1-3 composite with a 50 μm pitch and 80 μm depth was obtained. The main piezoelectric properties of the PIN-PMN-PT single-crystal 1-3 composite are listed in TABLE 1.

<table>
<thead>
<tr>
<th>TABLE 1. Properties of piezoelectric single crystal 1-3 composite</th>
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<tbody>
<tr>
<td>Piezoelectric material</td>
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<tr>
<td>Polymer</td>
</tr>
<tr>
<td>Longitude velocity</td>
</tr>
<tr>
<td>Density</td>
</tr>
<tr>
<td>Acoustic impedance</td>
</tr>
<tr>
<td>Piezoelectric constant</td>
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<tr>
<td>Electronmechanical coupling coefficient</td>
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<tr>
<td>Loss tangent</td>
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</table>
Fig. 1. Schematic of the modified dice-and-fill method used for phased array fabrication.

After sputtering Au/Cr (150 nm/100 nm) layers on both sides of the 1-3 composite, E-solder 3022 was added as the backing layer, and lithography was used to pattern 48 elements with a 38 μm width, 3 mm length, and 12 μm kerf, as presented in Fig. 2(A). Then, a piece of 30 μm polyimide-based flexible circuit with gold patterns was attached to the front of the array using Epo-Tek 301 epoxy for electrical connections, as shown in Figs. 2(B)-(C). Because the flexible circuit has a specific acoustic impedance of 3.4 Mrayl, it can also act as a matching layer. Lastly, the 48-element side-looking phased array was encapsulated in a 3D-printed housing, as depicted in Fig. 2(D). The acoustic design parameters for piezoelectric single crystal 1-3 composite phased array transducer are listed in TABLE 2.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Acoustic Impedence/MRayl</th>
<th>Thickness/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matching layer</td>
<td>Polyimide-based flexible circuit</td>
<td>3.4</td>
<td>0.03</td>
</tr>
<tr>
<td>Piezoelectric layer</td>
<td>Single crystal 1-3 composite</td>
<td>16.2</td>
<td>0.08</td>
</tr>
<tr>
<td>Backing layer</td>
<td>E-solder 3022</td>
<td>5.92</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Using the Krimholz, Leedom, and Mattaei (KLM) equivalent circuit-based software package PiezoCAD (Sonic Concepts, Woodinville, WA), the simulated pulse-echo waveform and frequency spectrum of the Phased Array transducer are shown in Fig. 3. When the thickness of machining layer was set to be 0.03mm and the thickness of the backing material was set to be 3.5mm (which was thick enough to absorb backward transmitted signal), an optimized pulse-echo response of the bandwidth was 81.7% and the central frequency was 20.9MHz.
Fig. 3. The simulated pulse-echo waveform and frequency spectrum of the transducer using the PiezoCAD software

3. Characterization and discussions

Figure 4 shows the measurements of the electrical impedance and phase for the array elements using the impedance analyzer Agilent 4294A. It is clear that no critical differences can be found among the 48 elements, indicating that all the elements are uniform. The peaks in the phase curves are located at 20.4 MHz, suggesting that the operational frequency for the array is approximately 20 MHz. According to the IEEE standard \[15\], the thickness mode of the electromechanical coupling coefficient \( k_t \) for each array element can be determined from the following equation:

\[
k_t^2 = \frac{\pi f_r}{2 f_a} \tan \left( \frac{\pi}{2} \frac{f_a - f_r}{f_a} \right)
\]

where \( f_r \) and \( f_a \) are the resonant and antiresonant frequencies, respectively. Substituting the appropriate values into Eq. (1), \( k_t \) was calculated to be 0.81. This value is similar to those reported in the literature \[13,16\].
Fig. 4. (A) Electrical impedance magnitude and (B) phase as a function of frequency for 48 elements.

The pulse-echo response of the representative element of the phased array transducer was acquired in a deionized water tank at room-temperature using a pulser receiver (5900PR, Panametrics, Inc., Waltham, MA). The echo was reflected by an X-cut quartz plate target, the waveform of which was recorded using a 1-GHz oscilloscope (LC534, LeCroy Corp., Chestnut Ridge, NY). As shown in Fig. 5(A), the random array element exhibits a central frequency of 20 MHz, bandwidth at -6 dB of approximately 77%, and peak-to-peak echo amplitude of 0.26 V, which is closed to the simulated central frequency of 20.9 MHz with a -6 dB bandwidth of 81.7%. It should be noted that, as described in Fig. 5(B), the array exhibits a good uniformity in acoustic performance.

Fig. 5. (A) Measured pulse-echo response performance of random element; (B) Sensitivity and bandwidth of the pulse-echo signal for each element.
The insertion loss (IL) and crosstalk were measured using several cycles of a sinusoid pulse produced by a Sony/Tektronix AFG2020 arbitrary function generator. In consideration of the compensation for the attenuation in water ($2.2 \times 10^{-4}$ dB mm$^{-1}$ $\times$ MHz$^2$) and the loss caused by the imperfect reflection from the quartz target (1.9 dB)$^1$, the IL was calculated using

$$IL = 20\log \frac{V_R}{V_T} + 1.9 + 2.2 \times 10^{-4} \times 2d \times f_c^2$$  \hspace{1cm} (2)$$

where $f_c$ is the center frequency, $V_T$ and $V_R$ are the transmitting and receiving amplitudes, and $d$ is the distance between the target and transducer. The IL value of the phased array elements was measured to be -19.7 dB, which is superior to those of PMN-PT single crystal and PZT-5H based high frequency (≥20 MHz) phased arrays$^{[7-9]}$. This phenomenon is probably related to the high Curie Temperature of PIN-PMN-PT single crystal. The heat induced by lapping and dicing in fabrication process produces nearly no effluence to its electrical properties. Therefore, PIN-PMN-PT single crystal 1-3 composite array element can sustain a high piezoelectric performance. At the center frequency, the measured crosstalk between the nearest neighbor array elements was -38 dB.

To predict the imaging performance of the obtained phased array, the Field II Ultrasound Simulation Program was employed. In the simulation, an aperture consisting of 48 active elements of the array was assumed to test the focusing capability of the phased array. Multiple point targets located evenly between 0–10 mm along the aperture central axis were first created. The simulated result is presented in Fig. 6A in a 60 dB dynamic range and the focal distance is about 3.2 mm. The imaging performance can be improved by applying apodization, as shown in Fig. 6B. The steering capability of the 48-element phased array was further explored by simulating its B-mode images. In the simulation, nine points were assumed at (3 mm, 45°), (3 mm, 0°), (3 mm, -45°), (6 mm, 45°), (6 mm, 0°), (6 mm, -45°), (9 mm, 45°), (9 mm, 0°), and (9 mm, -45°) in the polar plane. In Fig. 6C, side-lobes only appear at the 45° off-axis points, because the pitch of the fabricated array is 50 µm and the half-wavelength of the 20-MHz sound wave in water is 37.5 µm, thus, the side-lobes
appear at arcsin(37.5/50), which is 44°. The image results also indicate that the ultrasound energy is concentrated at about 3 mm along the axis. The image resolutions of the points deteriorate when they are off-axis or move away from the 3-mm distance.

Fig. 6. Point spread function phantom-imaged (A) without and (B) with apodization. (C) Simulated phased array image of nine-point targets.

4. CONCLUSIONS

A PIN-PMN-PT single crystal 1-3 composite was prepared using a modified dice-and-fill technique. High piezoelectric constant ($d_{33}=1500$ pC/N), high electromechanical coefficient ($k_e=0.81$) and low acoustic impedance (16.2 Mrayls), were observed for the as-made piezoelectric composite material. A 20 MHz 48-element phased array was fabricated successfully from such piezoelectric composite. The electric impedance resonance curve, pulse-echo response and bandwidth of array element were experimentally confirmed. The focusing and steering capabilities of the array were validated through simulations. The results suggest that the PIN-PMN-PT single crystal 1-3 composite based high frequency phased array is promising for ultrasound imaging applications. The next step of this work is to build an electronic system to experimentally study the focusing, steering, and imaging performances of this phased array.
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