Digital Object Identifier: 10.1109/ULTSYM.2008.0274

A PZT-P[VDF-TrFE] dual-layer transducer for 3-D rectilinear imaging

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Abstract— **The difficulties associated with fabricating and connecting 2-D arrays with large numbers of elements have limited the development of arrays with more than 5000 elements. However, 2-D arrays for rectilinear imaging of targets such as the breast, carotid artery, and musculoskeletal system require 128 x 128 = 16,384 to 256 x 256 = 65,536 elements. To simplify transducer design and system requirements, we propose a PZT-P[VDF-TrFE] dual-layer transducer array design which uses perpendicular 1-D arrays for 3-D imaging of targets near the transducer. This transducer design reduces the fabrication complexity and the channel count.**

Keywords-3-D, PZT, PVDF, P[VDF-TrFE],layer

I. INTRODUCTION

Previous attempts to develop arrays for 3-D rectilinear imaging mainly focused on suppressing clutter through unique sparse array designs. The designs included a Mills cross, vernier, and staggered patterns [1-3]. However, due to the extreme sparseness of these arrays where the number of elements greatly exceeds the number of system channels, some clutter is unavoidable. As another potential solution, Lockwood presented a crossed-electrode scheme using a hemispherically shaped array to scan a pyramidal volume [4]. Focusing would be done electronically, while steering would be accomplished mechanically due to the shape of the array. In similar work, we presented a row-column addressing technique to simplify interconnections of a 4 x 4 cm 2-D transducer array and verified its performance through simulations and experiments [5]. This transducer array is essentially a 1-3 composite with vertical and horizontal electrodes on the top and bottom respectively. Transmit and receive switching between the respective vertical and horizontal electrodes were accomplished with a simple diode circuit.

Dual-layer or multilayer transducers have been proposed for other diagnostic applications. Merks et al. investigated a multilayer approach to develop a piston-like transducer for acoustic bladder volume assessment using nonlinear wave propagation [6]. Operating in the 2 MHz range, this transducer uses a 29 mm diameter PZT piston for transmit and a PVDF film for receive. Saitoh developed a dual frequency probe multilayer ceramic for simultaneous B-mode and Doppler duplex imaging [7]. Using two wafers of PZT with polarities pointing in opposite directions, a dual frequency response probe was developed. The lower frequency range would be used for Doppler and the high frequency range would be used for B-mode imaging. Similar to Saitoh's work, Hossack proposed using a dual-layer design for harmonic imaging [8]. This design used two piezoceramic layers of equal thickness. Both layers of piezoceramic were used together as a single transducer to transmit a pulse at the fundamental frequency. Only the top layer was used for receiving the second harmonic giving increased sensitivity at the second harmonic.

As a new realization of the aforementioned row-column method, we propose a dual-layer design for 3-D imaging. This dual-layer design uses one piezoelectric layer for transmit and another separate piezoelectric layer for receive. The receive layer is closer to the target, and the transmit layer is underneath the receive layer. Each layer is an elongated 1-D array with the transmit and receive elements oriented perpendicular to each other. Ermert et al proposed a similar technique for ultrasound transmission imaging [9]. In this paper, we present a dual-layer PZT/P[VDF-TrFE], 5 MHz transducer array for 3-D rectilinear imaging. A 4 x 4 cm prototype dual-layer transducer composed of 256 PZT elements and 256 P[VDF-TrFE] elements was developed. We describe the fabrication, test, and initial imaging experiments with this transducer design.

II. METHODS

A. 3-D Rectilinear Scanning

For illustrative purposes, Figure 1 is a simplified schematic of the rectilinear 3-D scanning process using a dual-layer design with only 8 elements in each layer. The transmit layer contains a 1-D linear array along the azimuth direction and performs beamforming in the azimuth direction using the gray subaperture elements (Fig. 1A). In receive, a second layer contains a 1-D linear array with elements oriented perpendicular with respect to the transmit array and performs receive beamforming with the elements shaded in gray (Fig. 1B). By moving the locations of the transmit and receive subapertures in azimuth and elevation respectively, a 3-D rectilinear volume can be scanned.

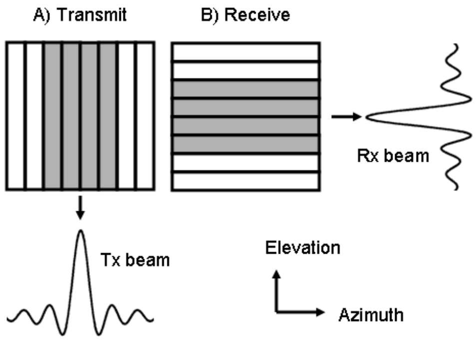

Fig. 1. 3-D scanning process of the dual-layer transducer

B. Dual-layer transducer design and fabrication

Figure 2A shows the acoustic stack of the dual-layer transducer suing PZT and P[VDF-TrFe]. This acoustic stack consists of a 9.3 MRayl acoustic impedance backing, a 300 µm thick PZT-5H layer for transmit, a 25 µm thick prototype flexible circuit (Flex1), a 25 µm thick P[VDF-TrFE] copolymer, and another 25 µm thick flexible circuit. A Samtec connector (Samtec USA, New Albany, IN), soldered to the flex circuit, serves as the interface to a printed circuit board with a mating connector.

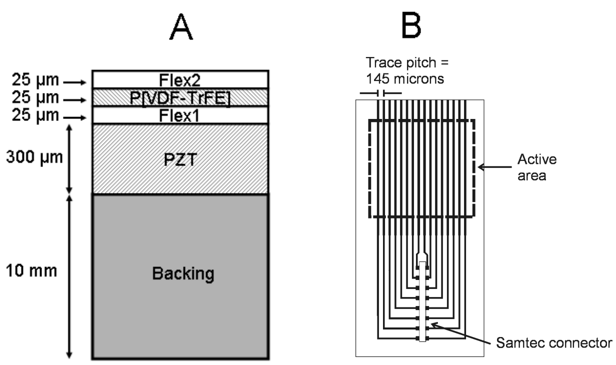

Fig. 2 Acoustic stack of the dual-layer transducer and schematic of the flexible circuits.

The copolymer chosen was 25 µm thick, which translates to a half wavelength resonance frequency of 48 MHz. This thickness was chosen to yield an electrical impedance magnitude comparable to a PZT 2-D array element for reasonable SNR performance. The copolymer elements are defined by the copper traces on the flexible circuit. Overly high crosstalk is not expected since this copolymer has low lateral coupling. Furthermore, the two flex circuits combined with the copolymer layer serve as a simple matching layer, although not optimal, for the PZT transmit layer. A photo of the finished prototype is shown in Figure 3.

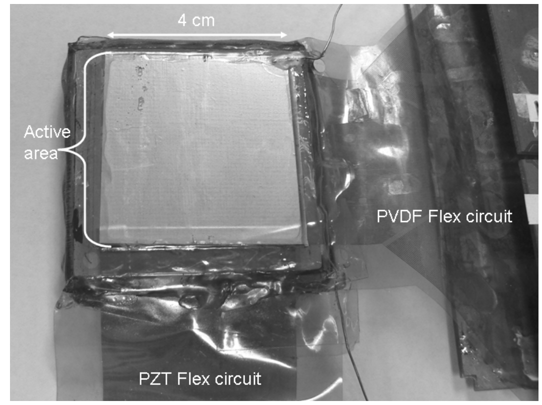

Figure 3. Photo of the prototype dual-layer transducer

After transducer fabrication, electrical impedance measurements were made using an Agilent 4294A (Santa Clara, CA) impedance analyzer. Pulse-echo measurements were made in a water tank using a Panametric 5072PR pulse/receiver (Waltham, MA) with an aluminum plate reflector. Crosstalk measurements of the copolymer and PZT layers were also made using an Agilent 33250A function generator. A 200 $mV_{p\text{-}p}$, 5 MHz, 20-cycle burst was applied on one element while measuring the voltage on the neighboring element with 1 MΩ coupling on the oscilloscope.

C. Data acquisition

Next, the dual-layer transducer was interfaced with a Sonix RP ultrasound system (Ultrasonix, Vancouver, Canada) using a custom printed circuit board. In these experiments, one PZT element was connected to one channel of the Sonix system configured to operate in transmit mode only. 64 copolymer elements were each connected to individual system channels configured to operate in receive mode only. Data was collected 100 times and averaged. A different set of 64 receive elements was used until data from all 256 receive elements were collected. This process was repeated until all transmit and receive element combinations were acquired.

D. Beamforming, Signal Processing, and Display

The acquired data was then imported into Matlab (Mathworks, Natick, MA) for offline 3-D delay-and-sum beamforming, signal processing, and display. After averaging, dynamic transmit (azimuth) and receive (elevation) focusing was done with 0.5 mm increments with a constant subaperture size of 128 elements, or 18.56 mm. A 3-D volume was acquired by selecting the appropriate transmit and receive subapertures. The rectilinear volume contained 255 x 255 = 65,025 image lines and a size of 37 (azimuth) x 37 (elevation) x 45 (axial) mm. After 3-D beamforming, envelope detection was done using the Hilbert transform. Images were then log-compressed and displayed with a dynamic range of 20 to 30 dB. Azimuth and elevation B-scans are displayed along with C-scans which are parallel to the transducer face. The generalized coherence factor developed by Li and Li [10] was used to suppress sidelobes and clutter.

We acquired 3-D volumes of home-made gelatin phantoms containing 5 pairs of nylon wire targets with axial separation of 0.5, 1, 2, 3, and 4 mm. A second phantom containing an 8 mm diameter cylindrical anechoic cyst phantom was also used. Graphite powder was added to provide scattering.

III. EXPERIMENTAL RESULTS

Figure 4 shows the electrical impedance in air of the dual-layer transducer experimentally using an impedance analyzer and by simulation using the 1-D KLM model. For the PZT, the simulated impedance magnitude was 70 Ohms at a series resonance frequency of 4.4 MHz while the experimental impedance curve showed a series resonance of 78 Ohms at 5 MHz. The phase plots peak at 5.5 MHz for the KLM simulation and at 6.04 MHz in the experimental case. The additional resonance in the 8-9 MHz range is most likely due to the flex and copolymer layers. In the simulation, the impedance magnitude of the copolymer was 1.6 kΩ at 5 MHz while the measured impedance magnitude was 1.3 kΩ. No resonance peaks are seen in the impedance magnitudes, and the phase remains near 80° to 85°.

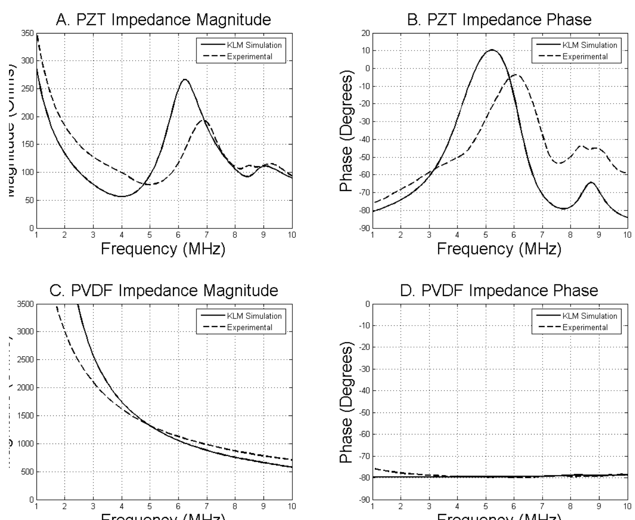

Figure 4. Simulated (solid lines) and experimental (dashed lines) impedance measurements of PZT and PVDF layers.

Figure 5 shows the simulated and experimental time and frequency responses of the pulse-echo signals. In simulation, the center frequency was 5.7 MHz with a -6 dB fractional bandwidth of 90%. Experimentally, the center frequency was 4.8 MHz with a -6 dB fractional bandwidth of 80%. Low amplitude reverberations after the pulse peak are seen in both the simulation and experimental pulses in the time domain. A notch in the 7-8 MHz range is seen in both simulation and experimental spectra. For the PZT layer, the average nearest-neighbor crosstalk at 5 MHz was -30.4 ± 3.1 dB, and the average crosstalk for the copolymer layer was -28.8 ± 3.7 dB. The copolymer layer showed only slightly higher crosstalk than the PZT layer even though no dicing of the copolymer layer was done.

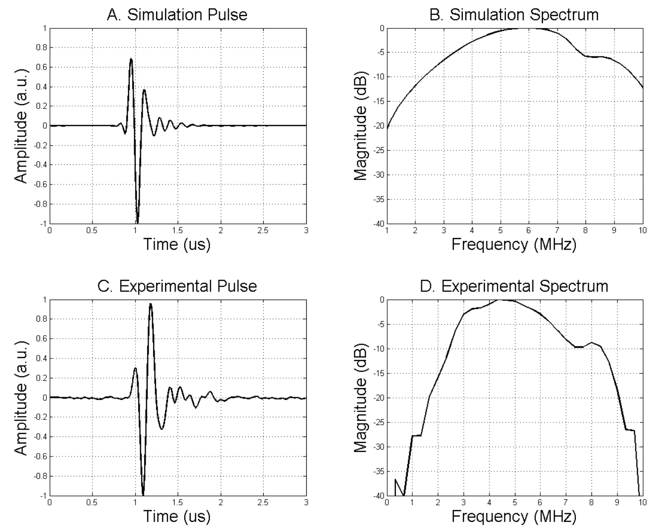

Figure 5. Simulated and experimental pulse and spectra of the dual-layer transducer.

Figure 6A-C show the azimuth B-scan, elevation B-scan, and C-scan respectively when the short axis of the wires is in the azimuth direction. All images are log-compressed and shown on a 20 dB dynamic range. The elevation B-scan (Fig. 6B) shows the pair of wires with 0.5 mm axial separation. The two wires are discernible. The C-scan, taken at a depth of 35 mm, is parallel to the transducer face. Here, one can also see the presence of sidelobes along side the wires. Figures 6D-F show the axial wire target phantom with the short axis of the wires in the elevation direction. The pair of wires with 0.5 mm axial separation is discernible in the azimuth B-scan while the short-axis view is shown in Figure 6E. Figure 6F shows the C-scan where sidelobes are again present.

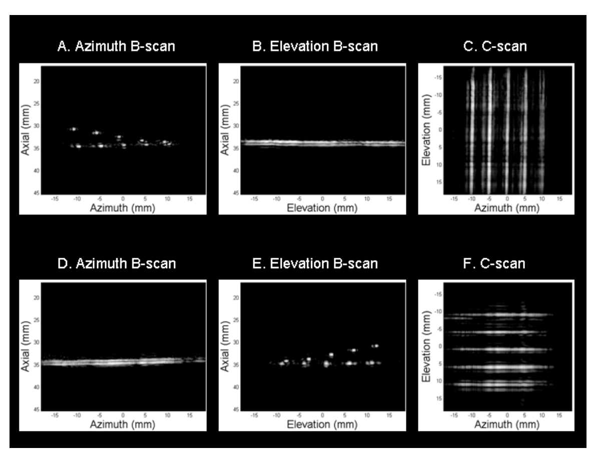

Figure 6. Experimental axial wire target images with short axis in azimuth (A-C) and short axis in elevation (D-F). All

images are log compressed and shown with 20 dB dynamic range.

Figure7 contains images of the 8 mm diameter cyst phantom. Figures 7A-C show two perpendicular B-scans and a C-scan with the short axis of the cyst in azimuth, and Figures 7D-F show the cyst with the short axis in elevation.

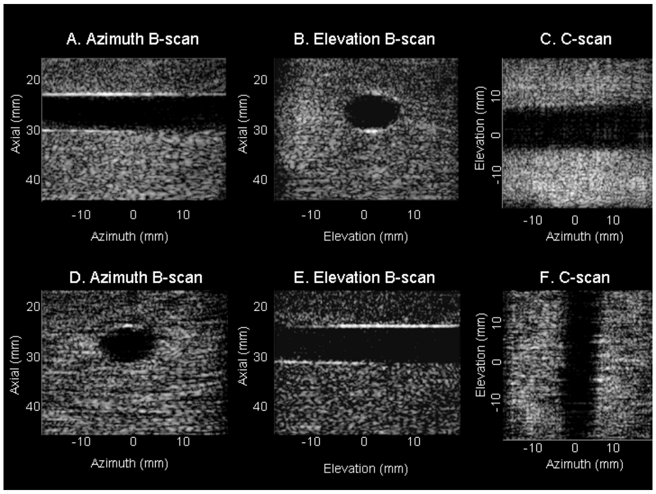

Figure 7. Experimental cyst images wit the cyst short axis in azimtuh (A-C) and the cyst short axis in elevation (D-F). All images are log-compressed and shown with 30 dB dynamic range.

IV. Discussion and Conclusions

In this paper, we described the design, test, and fabrication of a prototype dual-layer transducer using PZT/P[VDF-TrFE] for transmit and receive respectively. Our experimental results indicate the feasibility of 3-D imaging using a dual-layer transducer array with reduced fabrication complexity and a decreased number of channels compared to a fully sampled 2-D array of comparable size. Experimental metrics of transducer performance we compared to 1-D simulation results. Preliminary 3-D images of axial wire targets and anechoic cyst phantoms were acquired. Sidelobes from the wire targets were present most likely because of variability of element-to-element sensitivity. Future work will focus on developing high frequency (8-14 MHz) dual-layer transducers. This will involve using thinner PZT material, but the same copolymer thickness could be used. We will also investigate modifying this design for 3-D transrectal imaging of the prostate where the dicing direction of the PZT will be parallel to the long axis of the probe. The flexibility of the copolymer material also makes it easy to mold around a cylindrical form.

V. Acknowledgment

The authors would like to thank Jon Cannata and Jay Williams for help with transducer fabrication. Funding is provided by NIH grant 5R21CA112174-02 and the Wallace H. Coulter Foundation.

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