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Fabrication and Evaluation of Fully-Sampled, Two-Dimensional Transducer Array for “Sonic Window” Imaging System

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Abstract

A low-cost, fully-sampled, 3600 element 2D transducer array operating at 5 MHz and designed for use in a hand-held ultrasound system is described here. Four array configurations are presented – 1. array with both matching and pedestal backing layers, 2. array with a matching layer but no backing pedestal, 3. array with a backing pedestal but no matching layer, and 4. array with neither matching layer nor backing pedestal. Each array was characterized in terms of impedance measurements, pulse-echo response, and experimental beamprofile. Comparative finite element analysis simulations are also presented. Average estimated active element yield for the four arrays was 94%. The array with pedestal layer proved the most promising, providing a 26 % bandwidth and a 1.7 dB improvement in sensitivity with respect to the array with neither pedestal nor matching layer. Although this bandwidth is acceptable for our specific application (C-scan imaging), reverberations within the substrate material remain a potential challenge. We are currently working to fabricate a custom PCB material to address this concern, and may also consider using a pre-compensated transmit waveform or matched digital filter approach to further reduce the effects of such reverberations.

Introduction

Two-dimensional (2D) array transducers have been extensively researched by the ultrasound community for several years. The primary reason for their development is that they enable the design of systems that are capable of real-time formation of volumetric datasets because of their ability to perform beam steering in both elevation and azimuth. The increased number of elements that typically comprise a 2D array as compared to a standard 1D array, and the small element pitch in both azimuth and elevation – in the range of 200–400 μ m – result in high channel count (several thousand elements) and associated interconnect circuitry challenges. For these reasons, many early examples of these arrays were built with a sparse sampling of the available elements [1–6]. This was primarily necessitated by system hardware/interconnect limitations at the time of development. More recently, commercial diagnostic systems have been produced that use fully-sampled 2D arrays, including the 2D transthoracic cardiac transducer array [7] and a 2D catheter array [8–10]. These fully-sampled systems are designed for interrogating 3D volumetric datasets in real-time, requiring extensive beamforming hardware including, in the former example, partial array summing in the transducer handle.

The 2D array system being assembled in our laboratory (the “Sonic Window” [11]) is designed to be a low-cost, portable, pocket-sized scanner capable of generating real-time C-scan images

using a fully-sampled, 60×60 (3600) element PZT transducer array. The primary intended applications for this device include needle guidance for vascular access and guided biopsy. While this device is expected to be initially used mostly by nurses for guiding vascular access, we anticipate its eventual users will encompass ambulance- and battlefield-based paramedics.

Custom integrated circuitry that implements Direct-Sampled In-phase/Quadrature (DSIQ) beamforming [12], intended for use in the system, has been described previously [13,14]. DSIQ was specially developed for low-cost beamforming and involves acquiring a small number of complex samples and using phase-based sample correction – as opposed to time-based sample correction – prior to beamforming summation. In transmit mode, all elements are excited simultaneously (i.e. in parallel) to produce a plane wave. In the current implementation, two I/Q sample pairs are digitized from the received signal arriving at each individual element within the array. This approach performs adequately in comparison to traditional full-record, time-based compensation approaches when the bandwidth of the received signal is relatively narrow. Acquiring a C-scan image plane in the nearfield implies that the array be fully-sampled to provide uniform brightness and consistent, fine, spatial resolution. Additionally, the overall low-cost objective of combined transducer/beamformer (~US\$2000 sale cost) combined with a relatively high element ‘count’ necessitates an extremely low-cost approach to transducer array realization with a cost objective being that the manufacturing cost of the array be <US \$200. We believe that we have met this goal with our design. Although the manufacturing costs of commercial 1D and 2D arrays are not widely known, the list price of current commercial arrays is approximately two orders of magnitude greater than our estimated manufacturing cost.

In this paper we describe the design, simulation, fabrication, and validation of the 2D array used in the current “Sonic Window” system. Four versions of the array – one without a matching or pedestal layer (henceforth referred to as the “plain array”), one with matching layer (“matching array”), one with a soft pedestal mismatching/backing layer (“pedestal array”), and one with both layers (“combined array”) – were fabricated and compared in terms of element impedance, angular beamprofile, peak sensitivity, pulse-echo response, and bandwidth. We conclude with a discussion of the experimental results and the future direction of this research.

Methods

Design and Simulation

The array design described here significantly improves upon the project’s previous array specification, which consisted of a 32×32 (1024) element, fully-sampled array operating with a center frequency of 3.3 MHz [11]. The center frequency for this revision of the array was increased to 5 MHz with a corresponding decrease in PZT thickness from 530μm to 322μm. Element pitch was reduced from 635μm to 300μm and the elements are sub-diced to reduce lateral modes in the 250μm × 322μm elements. Subdicing ensures that the element Width to Height (W/H) ratio is 0.34, which provides adequate decoupling (i.e. frequency separation) of element width resonant modes from element thickness resonant modes [15]. In order to maintain an inexpensive fabrication process, we have chosen to use a two-layer printed circuit board (PCB) substrate, as in the previous design, in place of a more-costly approaches such as epoxy-loaded wireguide-based absorptive backing [16].

Finite element analysis (FEA) simulations (PZFlex, Weidlinger Associates, Los Altos, CA, USA) of the proposed geometry were performed to predict the performance of this new design. PZFlex uses a time domain solver, and is thus well-suited to calculating transient response in an efficient manner [17]. Three-dimensional simulations were employed to verify impedance response, pulse-echo response, and angular beamprofile of all four array configurations.

Figure 1 illustrates the FEA model of a three-by-three array of subdiced elements. Quarter-symmetry was used in order to reduce computation time. The bottom of the PCB was assigned a free boundary condition in all FEA simulations. Free boundary conditions were used on the top of the model during simulations in air, while this was replaced with a water-column and an absorbing boundary condition for simulations of the array in water. These boundary conditions were used because of the pulse-echo configuration of the simulations. External (non-mirrored) sides of the model were assigned an absorbing boundary condition for single-element simulations, while symmetry conditions were applied for pulse-echo simulations where the intent is to simulate a plane-wave transmit pulse and the single-element response to the resulting echo generated from an infinitely long reflector.

Fabrication

Illustrated schematically in Fig. 2 is a cross-section of the assembled array. A patterned fill indicates layers whose thicknesses are altered to produce backing and matching layers.

The transducer arrays were constructed on custom printed circuit board (PCB) substrates. The material properties of the PCB are described in Table 1. Each board (fabricated by Coastal Circuits, Redwood City, CA, USA) possesses 60×60 (3600) straight “through holes” (silver-filled holes, 150μm in diameter, with gold-plated copper pads) enabling electrical connection to each individual element. The pads have a 300μm center-to-center spacing to match the array geometry, thus circumventing the need for “fan-out” traces in the PCB. The black columns in Fig 2 are silver-filled through-holes, while the PZT elements, shown in gray, are sub-diced to half-depth and electrically isolated from neighboring elements by dicing cuts that extend 100μm into the glass reinforced plastic (GRP, “FR-4”) PCB material. Ideally, the sub-dicing kerfs would be full depth, but this was not achieved because a full depth cut significantly weakens the conductive bond between the PCB and array elements, causing increased element loss during fabrication. Electrically conductive silver epoxy (Cho-Bond 584, Chomerics, Woburn, MA, USA) forms a meniscus at the edge of the array that may electrically short edge elements. Therefore, a perimeter of inactive elements surrounds the 60×60 array of active elements. This perimeter of inactive elements has the added benefit of serving to protect the “live” edge elements from damage during the remaining fabrication processes and aiding array element homogeneity by providing a boundary condition for these “live” edge elements that is more similar to that experienced by the interior elements.

Fabrication of the 2-D array involved attaching the transducer ceramic (PZT-5H – 3203HD, CTS-Ceramics, Albuquerque, NM, USA) to our custom PCB using Cho-Bond. The Cho-Bond epoxy was spread in a thin, uniform layer on the PCB bonding surface using a straight razor blade. The primed ceramic surface was brought into contact with the layer of epoxy and was aligned with the PCB and pressed into the epoxy. This assembly was then clamped together (approximately 210 kPa) and cured for three hours at 50°C. For the case in which a backing epoxy pedestal is used, this pedestal is cast in-place on the PCB prior to PZT bonding. Plastic shim stock was used to set the height of the pedestal to 200μm, which is the greatest allowable thickness imposed by the limited exposure of the dicing blade used during fabrication.

Subdicing was performed using an automated dicing saw (DAD-2H/6T, Disco, Tokyo, Japan) and a dicing blade with a 24μm width and 698μm exposure (H155RM2570, Asahi Diamond, Tokyo, Japan). After subdicing, the ceramic was diced with a 40μm width and 1.2mm exposure (NBC-ZH2040-27HDGH, Disco, Tokyo, Japan) blade to a full-depth of 100–150μm into the PCB surface. The greater exposure of this blade permitted the use of a thicker epoxy layer when fabricating the pedestal and combination arrays, while the greater kerf-width afforded by the wider blade ensured neighboring elements were electrically isolated. The wider blade used for dicing was necessary because the ChoBond epoxy can be dragged across narrower kerfs during dicing. A narrower dicing blade was used for the subdicing cuts in order to preserve

element electrode surface area. While the use of a narrow blade limits the maximum allowable exposure, this did not present a problem because the shallower subdicing cuts do not require a large exposure. Figure 3 is a microscope image of the top surface of four elements after dicing and subdicing.

The array kerfs were backfilled using a low viscosity, non-conductive, potting epoxy (Hysol RE2039/HD3561, Dexter Corp., Industry, CA, USA) that wicked into the interior kerfs via capillary action. The potting epoxy was cured for 3 hours at 60°C.

A gold-plated polyester electrode (16µm thick) was subsequently bonded to the top surface of the array using Cho-Bond epoxy. For the case in which a matching layer is used, it was cast in-place on top of the gold foil using the same method described for forming the pedestal. The PCB was then encapsulated with a 0.5mm thick layer of room-temperature-vulcanizing (RTV) silicone rubber (polydimethylsiloxane (PDMS) – Sylgard 184 RTV, Dow Corning, Midland, MI, USA) that provides protection and isolation during water-tank testing.

Ideally, the array would be tested *in situ* – attached to the working integrated transmitter/receiver hardware. However, due to the unavailability of working hardware, it was necessary to approximate the operating conditions using a laboratory prototype approach. After all necessary single-element measurements had been taken (described below), 3575 of the 3600 single-element connection terminals on the back of the circuit board were shorted together using silver epoxy and a piece of gold-plated polyester electrode with a small square opening scribed in the center, where fewer than 1% of the individual connections remained open. This modification to the driving electrodes allowed us to simulate a plane-wave transmit, single-element receive pulse-echo experiment in the absence of the final driving circuitry. Electrical signal interconnect between the array PCB and driver/receiver IC electronics will be achieved through direct, gold-bump attachment and epoxy potting.

Measurements

Individual element impedance measurements were made using an impedance analyzer (HP 4192A, Hewlett-Packard, Palo Alto, CA, USA) prior to silicone RTV encapsulation. Element yield was then calculated by dividing the number of “good” elements by the total number of tested elements. An element was classified as “good” if it was neither shorted to ground nor a pure capacitive connection (i.e. no piezoelectric activity) and if its impedance magnitude did not indicate that it was shorted to a neighbor element (i.e. half the expected amplitude). Sparse sampling of elements using a manual approach was necessary because the intended interconnect circuitry was not available at the time of testing. A 13-by-13 grid of elements – regularly spaced across the array and encompassing the entire perimeter – was sampled. The element sampling pattern is illustrated in Fig. 4.

After RTV encapsulation, a pulse-echo experiment was performed using an approximated plane-wave transmit and single-element receive. The experimental apparatus is illustrated in Fig. 5. This mode was chosen as it more closely approximates the operation of the array in its final application of low-cost C-scan imaging with receive-mode beamforming. The transducer array was positioned parallel to the water surface so as to propagate a transmit waveform downwards into the water bath, while a polished aluminum reflector was placed 30mm below the face of the transducer. A gold-plated polyester film was used to short 3575 of the 3600 driving electrodes, and was excited by a 5-level ($\pm 100V$, $\pm 50V$, $0V$) pulse centered at 5 MHz with a PRF of 200 Hz. This driving waveform is illustrated in Fig. 6, and was chosen to reduce the energy of the 3rd harmonic compared to both unipolar and bipolar driving functions. The 5-level driving function is simple to implement in the context of this device, which uses a plane-wave transmit (i.e. effectively a single transmit channel). This input function was programmed on an arbitrary waveform generator (AWG310, Sony/Tektronix, Beaverton, OR) and amplified

(325LA RF power amplifier, ENI, Rochester, NY) to approximate the designed 5-level pulse. The single-element output was amplified (5676 Pulser/Receive, Panametrics, Waltham, MA, USA) and recorded from one of the single driving electrodes left open on the back of the transducer board and averaged 1,000 times on the digital sampling oscilloscope (DSO-LC334A, LeCroy, Chestnut Ridge, NY, USA) to increase SNR.

Beam profile data were recorded for a single element in the array. The array was placed in the water-tank oriented face-down at the surface of the water. A hydrophone (GL-0085, Onda Corp., Sunnyvale, CA) was positioned 15mm (in the far field) beneath the array. A single element in the array was excited with a 5-level ($\pm 100\text{V}$, $\pm 50\text{V}$, 0V) pulse as described above. Electrical termination to the $225\mu\text{m}$ -square element was achieved using a non-attenuating, spring-loaded oscilloscope probe to ensure reliable electrical connectivity throughout the two-hour measurement. The hydrophone output was amplified (5676, Panametrics, Waltham, MA, USA) and displayed on a DSO. The hydrophone was aligned using a two-axis of rotation positioning stage in which the hydrophone was mounted, and a two-axis motion controller (MM3000, Newport, Irvine, CA) operating $0.1\mu\text{m}$ -resolution Newport linear stages (UTM100CC,1) until a minimum propagation delay and maximum signal amplitude were observed. The motion controller was used to step the hydrophone through a 98 mm path centered across the active element and parallel to the face of the transducer in $245\mu\text{m}$ increments, totaling 401 measurements per beamprofile experiment. The amplified hydrophone output was recorded for each step of the Newport stages. The waveforms were filtered using a 32-tap bandpass FIR filter with cutoff frequencies of 700 kHz and 10 MHz, and a Hilbert transform was used to determine the envelope of the acquired data. The maximum value of the envelope was then used to compute the element's angular intensity. During the course of this experiment, on-axis one-way pitch-catch acoustic waveforms were recorded for further analysis.

Results and Discussion

Impedance

Figure 7 illustrates average element impedance magnitude for all fabricated arrays. Among the 169 regularly spaced elements that were sampled to generate the data presented in Fig. 7a, 164 were viable (97%). Although five elements in the array were non-functional, three of these five elements were located on the edge of the array. If perimeter-elements are omitted from the calculation of element yield, we obtain an estimated 98% viable element count. We have achieved similarly high percentages of viable elements in each of three plain arrays fabricated to-date. The estimated viable element yield of the pedestal, matching, and combined arrays were 90.1%, 88.4%, and 99.2%, respectively.

Pitch-Catch

The PCB backing material to which the ceramic is bonded contains a fiberglass weave designed to improve rigidity. This weave pattern dictates that the thickness of the backing is spatially variant (to a small degree) and that the elastic modulus is also spatially variant. Figure 8 illustrates the pitch-catch acoustic output of two random elements in the plain array to demonstrate that the pulse tails become out-of-phase with one another. Therefore, when averaged, the amplitude of the pulse tails would be reduced as a result of the spatially varying thickness/properties of the PCB backing material. This suggests that an absorptive backing material would help reduce ringdown, and therefore broaden the frequency response, which is exactly what is observed both experimentally and in simulations.

Figure 9 illustrates the experimental and FEA-derived pitch-catch acoustic output of each of the four fabricated arrays. The experimental data shown is the result of averaging the output

of ten randomly selected elements within each array. The combined matching/pedestal array is observed to have the greatest sensitivity of those geometries simulated. The envelope amplitude of the combined array main pulse is 3.6 MPa, while that of the pedestal array is 3.4 MPa and that of the matching array is 2.5 MPa. The overall gain in element sensitivity observed in the combined array is 2.2 dB over the plain array, which is a product of the improved acoustic match to water afforded by the matching layer and the reduction in backing-block reverberation achieved by using a pedestal layer.

The experimental pitch-catch data are in good agreement with simulation results. There is a small pulse in the experimental traces between 2.5 μ s and 3.5 μ s. This is also observed in the FEA data, and is the result of a multi-path echo originating from the inside surface of the 0.5mm-thick PDMS encapsulation layer. While this pulse is well aligned at 3 μ s in the FEA traces, the variation in delay for this pulse in the experimental data is due to small differences in the RTV layer thickness from one array to the next.

Pulse-Echo

Table 2 summarizes the center frequency and bandwidth data for these results. Although it is observed (in Fig. 8) that incoherent signal averaging can reduce the ringdown signal, which has the potential to increase apparent signal bandwidth, this is not observed in this experiment because the receive signal path does not benefit from any averaging effect. In the final application, a 10 $\times$ 10-element (or larger) receive aperture will be used when the driving circuitry is finalized, which should improve signal bandwidth.

As anticipated, the recorded signal from the array with pedestal layer possesses greater bandwidth than that of the simple PZT-on-PCB plain array. The soft backing layer does appear to slightly reduce the center frequency. The matching layer does not improve the signal bandwidth to the extent that it is improved by the inclusion of a pedestal layer, but it does not suffer a large reduction in center frequency. The combined pedestal/matching layer array possesses a reduced center frequency and narrower bandwidth than observed in the plain array.

Beamprofile

Figure 10 illustrates the experimentally measured transmit angular beam pattern curves for all four fabricated arrays, and the FEA result for the “plain” transducer array. Experimental data differ significantly from the theoretical beam plot, calculated using the single element directivity equation derived by Selfridge for the soft baffle case [18]. The FEA has provided a better matching beam pattern to the theoretical curve. The reduced experimental single element angular response is almost certainly due to acoustic crosstalk through the PCB, and is possibly related to the source of the narrow bandwidth and excessive ringing observed in the pulse-echo data [19].

Conclusions

Four 2D array configurations were fabricated and characterized. Among these, the plain array and the array with pedestal layer have the greatest potential for use in the “Sonic Window” array. The array with matching layer did not provide the desired improvement with respect to the plain array in terms of element sensitivity, which was reduced by 0.5dB. It suffered from a narrower bandwidth of 21.7% with respect to the pedestal array (26.0%), and also had the most directional beamprofile in experimental conditions. The “combined” array’s performance was compromised by reduced center frequency and bandwidth, and also required the most complex fabrication process amongst the arrays. The pedestal array possesses greater sensitivity (1.7 dB improvement) and bandwidth (11.9% improvement) with respect to the

plain array, and is only marginally more complicated to fabricate. It also lacks sidelobes in the experimentally observed beamprofile measurement.

Ringling and reflections in the backing material continue to be a challenge in this design. Currently, we are developing an in-house PCB material with more desirable acoustic properties than the current FR-4 material (i.e. greater attenuation) [20]. Additionally, a pre-compensated transmit waveform could be considered to help reduce the extended ringdown caused by crosstalk [21]. Although our driving circuitry is limited to five voltage levels, extension to a more sophisticated waveform is more feasible that would normally be the case since we effectively require only a single transmit channel. It is also possible to use a matched digital filter approach to compensate in part for imperfections in the pulse-echo spectral response.

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Figure 1. PZFlex model of 2D array without matching or pedestal layers. A 3×3 section of the array is modeled.

Figure 2.

Cross-section of transducer array and PCB substrate. Patterned areas indicate conductive silver-epoxy layers whose thickness is altered when incorporating matching and/or pedestal layers. Note: Schematic not to scale.

Figure 3.
Microscope image of four diced and sub-diced elements. 300 μm scale bar shown bottom left.

Figure 4. Sampling pattern used for impedance measurements. White indicates a functional element and black indicates a non-functioning element. Grey elements were not tested.

Figure 5.
Plane-wave transmit, single-element receive pulse-echo experimental approach.

Figure 6.
The time- and frequency-domain representations of the 5-level driving function, plotted alongside commonly used unipolar and bipolar driving functions.

Figure 7. Impedance magnitude for a) plain, b) pedestal, c) matching, and d) combined arrays. One-standard-deviation error bars superimposed.

Figure 8. Ringing in the transmit pulse from different array elements are relatively incoherent due to inhomogeneities in the PCB substrate.

Figure 9.

Experimental pitch-catch acoustic output of each of the four arrays is illustrated here in black, while the FEA results are in gray. A) Plain array, b) Pedestal array, c) Matching array, and d) Combined array.

Figure 10.

Experimental beamprofiles are illustrated in the left-hand plot, while the FEA beamprofile prediction is illustrated in the right-hand plot. Each axis contains the soft-baffle theoretical curve.

Table 1

Material properties of PCB substrate

Property (units)	Value
Density (kg/m ³)	1960 [*]
Longitudinal wave propagation (m/s)	3230 [*]
Shear wave propagation (m/s)	1610 [†]

^{*} Measured experimentally,[†] Estimated

Table 2

Pulse-echo frequency response characteristics

Plain	Pedestal
$f_c = 5.32 \text{ MHz}$ -6dB Fractional Bandwidth = 14.1%	$f_c = 4.48 \text{ MHz}$ -6dB Fractional Bandwidth = 26.0%
Matching	Combined
$f_c = 4.97 \text{ MHz}$ -6dB Fractional Bandwidth = 21.7%	$f_c = 2.95 \text{ MHz}$ -6dB Fractional Bandwidth = 12.8%