A 2.5 MHz 2D Array with Z-Axis Backing

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Abstract

The design, fabrication and initial testing of a prototype fully λ/2 sampled, 2500 element 2D phased array is presented. The array utilizes a unique Z-axis electrical conductivity backing layer, to provide both acoustic attenuation and electrical interconnect for the signal channels. The electrical interconnect is designed to be in the acoustic shadow of the transducer elements so as to minimize the foot print of the array. A modular, demountable Pad Grid Array interconnect is used to connect to the backing of the array. Results are presented for measurements of the single element properties of electrical impedance, pulse echo waveform and spectrum, directivity and cross talk.

I. INTRODUCTION

There has been much discussion in the recent literature about the need and desirability of 2D acoustic phased arrays for medical imaging. The theoretical aspects of 2D arrays have been discussed [1], and extensive experimental work has been done on coarsely sampled 2D arrays [2], [3].

There has not been extensive discussion on the fabrication of fully sampled, λ/2 pitch 2D phased arrays. Such arrays are difficult to build, the number of potential signal channels exceeds the capability of most present day commercial medical ultrasound machines, and the interconnection of such arrays is a formidible challenge.

This paper discusses the design, fabrication and initial single element characterization of a fully λ/2 sampled 2D phased array, and the interconnect system used with the array. A novel z-axis electrical backing layer was developed with the intent to optimize the acoustic properties of the backing layer, and the interconnect density. A high density Pad Grid Array was also developed in order to make this interconnect system demountable.

II. ARRAY DESIGN AND FABRICATION

The present 2D array was designed with a center frequency of 2.5 MHz, motivated by the penetration depth for cardiac applications, the obtainable spatial resolution, and relative ease of fabrication. An active aperture of 15 mm was chosen to match the typical acoustic window for transthoracic ultrasound measurements. The array was sampled at λ/2 in order to provide full capability for steering and focussing, resulting in a 50 x 50 array with 2500 active elements.

The array was designed with a PZT piezoelectric layer with inactive oversized guard elements surrounding the active elements. The transducer elements were diced to provide acoustic isolation and then back filled with an epoxy and glass microsphere mixture Without this back filling operation the individual elements are susceptible to damage during assembly, thus reducing the yield. In Fig. 1 a partial top view of the array is shown, drawn to scale. At the upper left corner is a large square inactive guard element, shown hatched. The top row and the left column are also peripheral inactive guard elements. The active elements are shown with a small black square in the middle of each element. This black square represents the cross sectional end of the Z-axis electrical conductor in the backing. The active elements are 250 x 250 μm in cross section. Note that the rear of the PZT resonator has a full 250 x 250 μm electrode that is in electrical contact with the end of the Z-axis electrical conductor in the backing.

For the piezoelectric layer, PZT-5H was chosen for its acoustic properties and for its machinability. The matching layer was fabricated from epoxy impregnated graphite. The backing layer was chosen for its acoustic properties and for its Z-axis electrical conductivity. The acoustic properties of the backing layer were determined by an electrically insulating epoxy matrix with Tungsten powder to increase the attenuation. The electrical conductivity properties were determined by imbedded BeCu wires, discussed below.

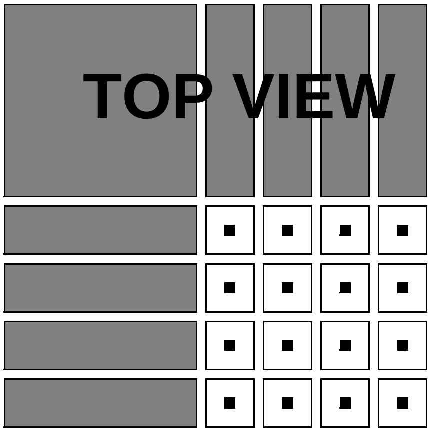

Figure 1: Top view of one corner of the array, drawn to scale. The active elements each have a BeCu wire in the center.

The concept of electrically conductive paths in an otherwise electrically insulating backing material has been discussed previously [4]. The use of etched BeCu leadframe material in an otherwise insulating matrix provides the desired electrical conductivity from the rear electrode of the piezoelectric resonator to the rear of the backing layer. Two leadframes are required for each column of the array. One is the trace leadframe for the desired electrical conductivity path, and the other is the spacer leadframe to ensure the correct spatial pitch of the traces. A typical pair of leadframes is shown schematically in Fig. 2.

The window frame area at the periphery is used for support and alignment, and is eventually discarded. The trace leadframe is 50 µm thick and 50 µm wide where it connects to the piezoelectric element. It flares to 100 µm wide at the rear of the backing layer to increase the contact area with the interconnect system. At the rear of the piezoelectric element a 50 x 50 µm stub of BeCu has no measurable effect on the impulse response of the 250 x 250 µm acoustic element.

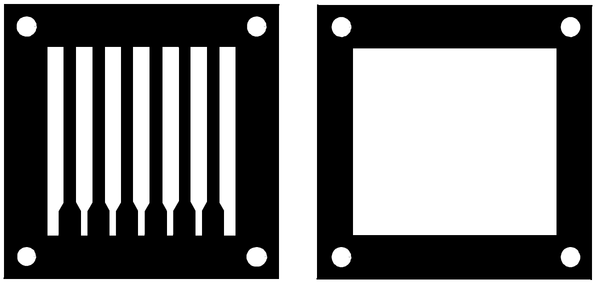

Figure 2: Leadframe patterns. a) the trace leadframe, b) the spacer leadframe.

The leadframes are stacked into a fixture where they are aligned, stretched and potted into the insulating backing material. The backing is cured for 24 hours at 70 C. After machining, a solid CrAu electrode is placed on the top and bottom of the backing in preparation for the eventual patterning of the top and bottom 250 x 250 mm electrode pattern. The electrical resistance from top to bottom along the trace is less than 1 Ω.

The final 2D array is fabricated by thin line bonding the matching layer and piezoelectric layer onto the machined backing layer, using a low viscosity epoxy. The backing layer is then diced 10 µm deep into a pattern of 250 x 250 µm electrode pads, for the PGA interconnect system, discussed below. The 50 x 100 µm ends of the leadframes are electrically connected to these electrode pads. The array is then diced through the matching layer, the piezoelectric layer and 50 µm into the backing layer.

Once diced, the 50 µm saw kerf in the array is back filled with a mixture of hollow glass microspheres in an epoxy matrix [5]. The microspheres have a median diameter of 12 µm. The kerf filling is used to protect and stabilize the fragile elements, but the kerf filling also reduces the directivity of the individual elements. To provide a moisture seal and an electrical ground plane, the array has a 0.00025 inch Au plated MYLAR film stretched and bonded across the front of the elements.

For a densely sampled 2D array, a demountable interconnect is desirable because it allows for the interchange of both the interconnect and the array with a minimal amount of rework. Such a demountable, high density interconnect technology, referred to as a Pad Grid Array (PGA) was discussed at the 1992 SPIE Conference [6]. The interconnect technology used here is a larger size and higher density version of that PGA. The basic concept is to terminate the coaxial signal cables onto flex circuits and to attach the flex circuits to a ceramic plate with a 50 x 50 grid of holes that matches the layout of the 2D array, hence a Pad Grid Array. Each flex circuit carries 50 signal lines. The PGA provides 250 x 250 µm pads on a 300 x 300 µm pitch in a 50 x 50 grid.

A schematic drawing of the array and the PGA is given in Fig. 3. The array is bonded, on the four sides of the arrary, to an adapter plate. This plate allows the array to be bolted to the PGA. A Z-axis electrically anisotropic elastomer, comprised of a silicone sheet 500 µm thick with 30 µm diameter Au plated wires on a 100 x 100 µm pitch spacing is used to connect the array and PGA together, and to provide adequate mechanical compliance [7]. Further details of the PGA fabrication and specifications will be published elsewhere [8].

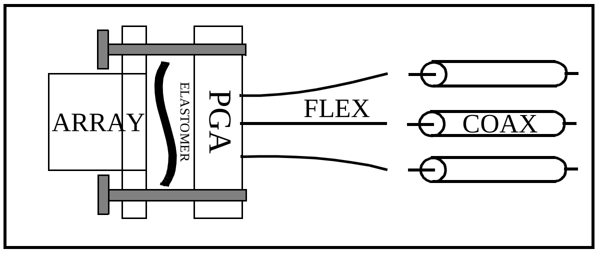

Figure 3: Schematic of the array, elastomer and PGA.

This elastomer requires 300 psi to provide reliable electrical contact resistance of a few hundred mΩ. In the typical case, between 4 and 9 wires in the elastomer contact each 250 x 250 µm thin film electrode pad.The 100 µm pitch of the elastomer reduces the requirements for registration between the elastomer and both the array and the PGA.

Two partially terminated PGAs were fabricated in order to evaluate the interconnect technology. In each case, the PGA was fully assembled with a full set of 50 flex circuits, but only a subset of the flex circuits were connected to the coaxial cables. A set of subarrays were terminated to evaluate regional uniformity, consisting of a central 8 x 8 subarray and 4 subarrays of 4 x 4 elements at the periphery. In the second partially terminated PGA, a "+" and an "x" pattern were chosen to evaluate linear uniformity across the whole array.

III. MEASUREMENT RESULTS

To initially characterize the array, the air loaded electrical impedance was measured, using a 50 Ω coaxial Tungsten tipped probe. At the design center frequency of 2.5 MHz, the impedance is Z = 4 - j10 kΩ. Clearly the impedance is dominated by the reactive component.

To characterize the thermal stability of the array, and the Z-axis backing with embedded BeCu wires, the array was thermally cycled for 24 hours at 50 C, 60 C, and 70 C in normal room air, with ~50% relative humidity. No loss of contact to any array element was detected.

A comparison of the single element normalized directivity data, $A(\theta)/A(0)$, from an array with epoxy/microsphere filled kerfs and the CW theory [9],[3] (with a 250 µm size element, and λ=600 µm), is shown in Fig. 4. The data is from the pulse echo signal reflected off of a steel plate at a range of 1.5 cm. The FWHM value for the array is 36 degrees, while the CW theory predicts a FWHM of 76 degrees. The measured values are substantially smaller than the theoretical prediction which does not include cross talk through the backing or the kerf filling. In these arrays, acoustic cross talk is dominated by acoustic propagation through the undiced portion of the backing.

For a 2D array, relevant cross talk comes from both acoustic and electrical sources. For a characterization of the electrical cross talk, a 200 V excitation pulse, from a 5052UA Panametrics pulser/receiver, with a 50 Ω output impedance, was applied through a 50 Ω tungsten tipped coaxial probe to the rear surface of the backing of an air loaded array. The nearest neighbor cross talk is -42 dB, down from a 0 dB reference at the excited element. The voltage developed on the adjacent elements drops until the 6th element where it levels off to about -70 dB. Most of the electrical cross talk is from the backing where there are 50 x 50 µm BeCu wires, 250 µm apart for a 15 mm length, embedded in an epoxy matrix.

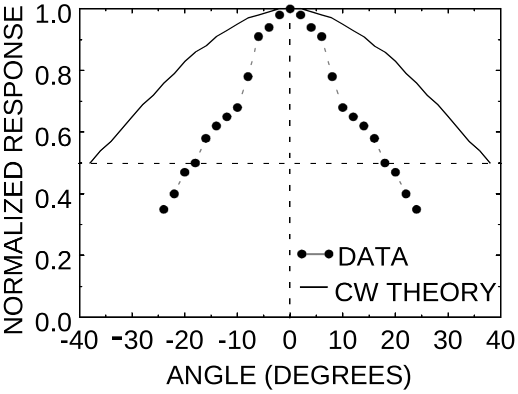

Figure 4: Comparison of CW theory and directivity data.

The PGA interconnect system has an electrical cross talk level of -60 dB in the frequency range of interest, mostly determined by the flex circuit geometry. The 500 µm thick elastomer, with 100 x 100 µm pitch wires, also has a measured electrical cross talk level of below -60 dB in the frequency range of interest.

The 2D array and the PGA interconnect were evaluated as a system in a pulse echo mode. A typical pulse echo waveform reflected off of a flat stainless steel target, 1.5 cm away, is shown in Fig. 5. The total receiver gain for this data is +20 dB, with an excitation voltage of 150 V from the pulser/receiver. The spectrum of this signal is shown in Fig. 6, where the -6 dB center frequency of the spectrum is at 2.3 MHz, and the -6 dB fractional bandwidth is 50%. For this measurement, no additional series or shunt tuning elements were used in addition to the tuning provided by the approximately 3 meters of 50 Ω coaxial cable.

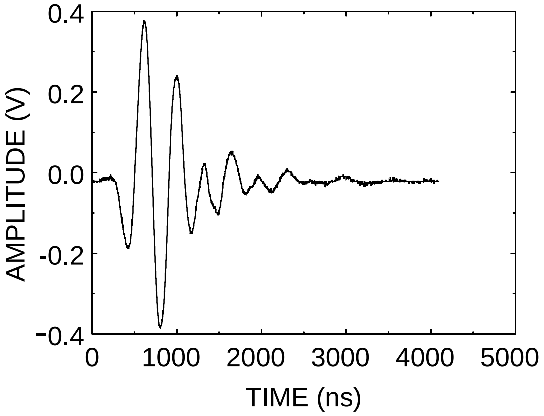

Figure 5: Waveform from the 2D array through the PGA and cable

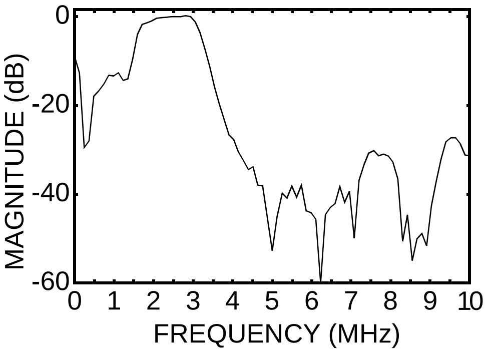

Figure 6: Frequency spectrum from the 2D array through the PGA and cable.

The effect of the elastomer was studied by examining the dependence of the pulse height variation on elastomer thickness, compression and wire pitch. Three types of elastomers were investigated, 100 x 100 µm pitch of 300 µm thickness, 50 x 200 µm pitch of 300 µm thickness, and 100 x 100 µm pitch of 500 µm thickness. For these geometries, the 500 µm sample, with 35% compression, gave the best performance. With this elastomer, the array elements, through the PGA interconnect, had pulse echo waveforms that were characteristic of the 2D array transducer elements themselves. A random pattern of 3% of the total elements was not successfully connected by the elastomer, and varied with each reassembly of the array and PGA. The variations in pulse height, due to the elastomer, were also random with regard to position in the array or assembly history. The elastomers used here are capable of at least 5 mate/demate cycles.

IV. DISCUSSION

In conclusion, a fully λ/2 sampled, 2.5 MHz, 2500 element 2D phased array was built and the initial single element performance was characterized both as an independent module, and through a demountable high density interconnect. The array utilizes a unique Z-axis backing layer, to provide both acoustic attenuation and electrical interconnect for the signal channels. This work demonstrates the feasibility of such densely sampled 2D arrays. Further work, such as synthetic aperture reconstruction, is required to fully characterize the full 2D array performance.

V. ACKNOWLEDGMENTS

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