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Co-integrated PIN-PMN-PT 2D Array and Transceiver Electronics by Direct-Assembly Using a 3D Printed Interposer Grid Frame

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Abstract

Tiled modular 2D ultrasound arrays have the potential for realizing large apertures for novel diagnostic applications. This work presents an architecture for fabrication of tileable 2D array modules implemented using 1-3 composites of high bandwidth PIN-PMN-PT single crystal piezoelectric material closely coupled with high voltage CMOS Application Specific Integrated Circuit (ASIC) electronics for buffering and multiplexing functions. The module, which is designed to be operated as a λ -pitch 1.75D array, benefits from an improved electromechanical coupling coefficient and increased Curie temperature and is assembled directly on top of the ASIC silicon substrate using an interposer backing. The interposer consists of a novel 3D printed acrylic frame that is filled with conducting and acoustically absorbing silver epoxy material. The ASIC comprises a high voltage switching matrix with locally integrated buffering and is interfaced to a Verasonics Vantage 128, using a local FPGA controller. Multiple prototype 5×6 element array modules have been fabricated by this process. The combined acoustic array and ASIC module was configured electronically by programming the switches to operate as a 1D array with elements grouped in elevation for imaging and pulse-echo testing. The resulting array configuration had an average center frequency of 4.55 MHz, azimuthal element pitch of 340 μm , and exhibited average -20dB pulse-width of 592 ns, and average -6dB fractional bandwidth of 77%.

Keywords

2D array transducer; ASIC; PIN-PMN-PT; Verasonics Vantage research ultrasound systems; tileable array module

I. INTRODUCTION

THE implementation of large 2D array apertures requires the close integration of a two-dimensional assembly of transducer elements with interface electronics located either immediately behind the elements or near the array (physically in the ultrasound probe handle). This close integration of hundreds or thousands of 2D array elements and processing electronics involves many of the same challenges that have been addressed in existing smaller 2D matrix arrays used in clinical practice; these include interconnect density, as well as beamforming and system channel count and the associated complexity of implementation. In addition, because of their size, large arrays must be made using high yielding processes if they are to be practical for production at reasonable cost.

Interconnection to a large number of 2D array elements has been addressed using sparse channel distribution [1]-[4]. Sparse element geometries reduce the number of processing channels needed; however, this is an imperfect solution because it leads to increased sidelobe energy and the signal to noise ratio (SNR) suffers due to lower echo energy [5]. Later work for implementation of 2D arrays improved the interconnect density to the elements using dense flex circuits [6]-[7] which allows more channels to be used. The use of a conductive backing fabricated by drilling holes in a matrix material [8] or building up a

grid of wire frames or graphite [9]-[10] has also been proposed. Recent implementations have integrated the 2D transducer arrays directly on interface electronics utilizing an interfacing surface layer such as epoxy and dense quarter wavelength matching materials [11]-[14] and by flip-chip bonding [15]-[16].

An important consideration for large aperture arrays being developed for novel imaging algorithm applications is overall yield. Poor yield of connections to the individual transducer elements can significantly degrade the performance of a beamforming array [17]-[19]. In addition, low yield on interface electronics has the potential to disable a large section of the array should a particular component of the interface and muxing electronics become inoperative. Lastly, a low yielding array process can result in a significant number of rejected parts, increasing the cost of the individual large area arrays, in effect limiting the availability and application of these devices. The proposed solution to improve yield during fabrication of large arrays is to take a modular approach [11] [20]-[22], where individual sub-modules are first fabricated, evaluated and sorted, such that only known good acoustic/electric modules may be integrated to form the much larger array.

To address the challenges for high density 2D transducer arrays, we have been developing modular integrated electronics and 2D array fabrication processes which implement closely integrated processing and sensing functions. In this paper, we provide a detailed description of the design, fabrication and testing of a prototype 2D array module based on this approach, including integrated electronics, and a novel acoustic stack module developed specifically for this prototype. The acoustic module consists of a 1-3 composite of PIN-PMN-PT (lead indium niobate-lead magnesium niobate-lead titanate) single crystal piezoelectric material; the design and process flow for fabrication of which will be described in detail. The acoustic stack is built on top of a novel 3D printed interposer backing which provides direct connection for the large number of 2D array elements to the surface of the interface ASICs as well as attenuating acoustic energy at the backside of the array. Backside attenuation is critical to suppress ringing and leads to improved bandwidth resolution [23] and excellent pulse width which results in high quality images with good axial resolution. The completed 2D module has been interfaced to a Verasonics Vantage 128 system for imaging, and wire-target images have been acquired, demonstrating performance of the array.

II. Methods

A. Modular Direct Assembly Array Concept

The concept for the modular direct assembly array with interposer backing is illustrated in Fig. 1. A wide aperture is created by tiling multiple array modules in both azimuthal and elevational directions. Each module consists of an acoustic stack with multiple matching layers (shown in white), the interposer backing (providing both electrical 2D connectivity and backside acoustic attenuation and shown in blue), and the respective interface ASICs for each of the modular arrays (shown as tan).

The ASICs used here consist of an array of unit cells each of which has a buffer amplifier and associated high voltage multiplexing circuitry. The ASIC grid consists of 5 columns of 8 unit cells each at a pitch of 340 μm in azimuth and 275 μm in elevation. The ASICs are

designed to be tiled in the azimuthal dimension to yield very wide apertures and can also be tiled in two rows in the elevation dimension to increase the elevational aperture for finer focusing in elevation. Tiling is facilitated by a design in which only 1 of the 4 edges of the device has bond pads. This configuration is not typical for production ASICs however it has been used for tiled sensor arrays [24]-[25] with direct assembly. Removing the bond pads from the 3 tiling edges allows the individual ASICs to be placed very close to each other and thereby minimize gaps which lead to acoustic dead area.

The interposer is a 2D grid of conducting pillars with acoustically-absorbing properties that has been fabricated with the aid of a 3D printed acrylic grid mold. The pitch in azimuth and elevation of the interposer matches with the respective dimensions on the ASICs, thereby making it possible to assemble the interposer and acoustic stack directly on to the surface of the electronics substrate. The 2D transducer array, in turn, is built directly on top of the interposer and it also matches exactly the pitch of the ASIC 2D array in azimuth and elevation.

The combined modular assembly is designed to implement a 1.75D array [26]-[27] which is capable of dynamic receive focus in elevation for uniform and reduced elevational slice thickness. This is intended to improve contrast to noise ratio (CNR) by reducing the effects of out of plane artifacts on inplane anechoic regions (e.g. fluid filled cysts). Imaging in the azimuthal dimension is accomplished by connecting each ASIC column to a unique Verasonics system channel. Imaging in the elevation dimension can be accomplished by synthetic aperture imaging by rows which can be done either on transmit or receive, or in both cases [27].

Fig. 1 illustrates one possible array configuration for the proposed modular array, consisting of 13 tiled modules in azimuth and 2 tiled modules in elevation. In this case, the pitches in azimuth and elevation match those of the existing ASIC. The azimuthal pitch is one lambda at the center frequency of 4.5 MHz. With 13 of the modules tiled in azimuth and 5 columns for each module, there are a total of 65 channels in this example configuration. The overall azimuthal aperture given the ASIC dimensions in Table 1 is 22 mm, and the elevational aperture is 4.5 mm. These dimensions assume no gaps between the arrays. Ultimately, the array could be increased to a full 9×44 mm aperture for clinical imaging by increasing the size of the ASICs in elevation. A redesigned ASIC could also be optimized for larger elevational pitch taking advantage of the reduced need for steering in elevation for a 1.75D array.

Using 128 of the Verasonics Vantage system channels to allow simultaneous access to all of the individual elements in elevation creates a 1.75D array capable of limited steering and imaging in the elevational dimension. It is also possible to use only 64 system channels in the azimuthal dimension and tie the mirrored elements together along the midline, which creates instead a 1.5D array that cannot be steered in elevation but uses fewer system resources.

Table 1 provides a summary of the design goals for the proposed modular 2D/1.75D array.

B. Acoustic Stack-Up

Fig. 2 illustrates the cross-section of the stack-up for the unit array modules. The module includes the ASIC substrate with gold bumped pads that are bonded to the interposer bottom terminals with conductive adhesive. The interposer itself is a 2D array of cured conductive epoxy pillars, which are each topped by a 1-3 composite pillar array of PIN-PMN-PT piezo material. The composite pillars are then covered by two distinct matching layers and an intervening gold sputtered electrode linking them all together to create the common ground connection. This transducer ground is further connected to interposer pillars which bring it down to be made available to the ASIC for connection to the system ground.

C. Process Flow

The complete process flow for fabrication of the direct assembly transducer/ASIC module using the 3D printed interposer grid is summarized in Fig. 3. The process begins with fabrication of the interposer which serves both as an acoustic backing absorber and also as a 2D interconnect that links the transducer elements to the ASIC. The next step in the process is fabrication of the composite which is done in the lab using standard dice and fill methods. This is followed by casting and lapping of the first matching layer which is a silver loaded epoxy. The composite and first matching layer are then assembled to the interposer to form the acoustic stack. The stack is diced in the X and Y dimensions to singulate the 2D array elements. The kerfs are filled, the top electrode is sputtered, and then the second matching layer is laminated on top of the array. The completed acoustic stack is then assembled to the ASIC modules using conductive adhesive. The ASICs are fabricated by an external vendor and come singulated for assembly; they are mounted to a PCB and wire-bonded for connection of the I/O pads to the system. Each of these steps are described in further detail below.

III. Acoustic Stack Design

A. Composite

Composite piezo material is used extensively for single element transducers as well as for linear arrays [28]; however, it is not commonly used for 2D arrays. Here we construct a 1.75D array which is in effect a hybrid between a linear and a 2D array. In this case, using 1-3 composite is beneficial to obtain high fractional bandwidth (FBW). The composite is composed of piezo pillars of single crystal material (e.g. PIN-PMN-PT) with the kerf being filled with non-conducting epoxy (e.g. EPO-TEK 301). The main advantage of a piezo composite, be it 1-3 composite or 2-2 composite, is in reducing coupling of acoustic energy into lateral modes, which would normally decrease the electromechanical coupling coefficient of the piezo material [29].

The goal for composite fabrication is to approximate k_{33} for the material which corresponds to exclusive resonance in the longitudinal mode. This can be accomplished as long as the element heights are greater than twice their width. As an example, the bulk k_T for the PIN-PMN-PT material used (PIN24, CTS Corp., Bolingbrook, IL, USA) is 0.5, [30] (slightly lower than that for PMN-PT material which is typically 0.6), whereas k_{33} is 0.89. The use of

composites results in improvement in FBW [31] that is associated with this increase in electromechanical coupling.

In general, 2D arrays are not made using composite material since they are pitched at $\lambda/2$ to reduce the effects of grating lobes when steering greater than 30° off axis which is necessary for volumetric imaging. This design choice ($\lambda/2$ pitch) results in pillars with a high aspect ratio and is therefore similar to a 1-3 composite. However, for the case of a linear array, the pitch is most often chosen to be λ because there is not a requirement for extensive steering, and also, due to the fact that a larger pitch array is easier to fabricate. The fabricated array presented here is a linear array which is intended to have wide bandwidth and is subdivided into multiple elements in elevation in order to create a finely focused elevational plane. The array is diced to create a composite in both the lateral and elevational dimensions in order to take full advantage of high FBW in both the azimuthal and elevational planes.

Design of the composite can be completed simply by assuming half width pillars; however, if we do so then we give up a significant amount of acoustic output, since only one quarter of the aperture is active with a 25% volume fraction (VF) 1-3 composite. We may increase the width of the composite pillars, thereby increasing the VF to increase the acoustic output of the array; however, at some point the electromechanical coupling coefficient for the material will drop significantly as the material begins to look more like bulk material than a true composite. For our application, where penetration is important, we wish to maximize both the acoustic output as well as the FBW by judicious choice of the VF for the specific piezo and matrix materials that we will use for the composite. In addition, we would like to obtain a model of the composite material for simulation purposes to aid in optimizing properties for the acoustic matching layers.

An analytical model for composites which has been described previously in the literature [32]-[33] was used for optimization and comparison with fabricated results. Using the model, the density of the composite material is defined by

$$\bar{\rho} = \nu \rho^C + \tilde{\nu} \rho^P \quad (1)$$

where, ν is the VF of the piezo material in the composite, $\tilde{\nu} = 1 - \nu$, is the VF for the matrix material, ρ^C is the density of the piezo material and ρ^P is the density of the matrix material. The composite values for the longitudinal mode for the elastic stiffness, piezoelectric, and dielectric constants are given by

$$\bar{c}_{33}^E = \nu \left[c_{33}^E - \frac{2\tilde{\nu}e_{31}(c_{13}^E - c_{12})^2}{\gamma} \right] + \tilde{\nu}c_{11} \quad (2)$$

$$\bar{e}_{33} = \nu \left[e_{33} - \frac{2\tilde{\nu}e_{31}(c_{13}^E - c_{12})}{\gamma} \right] + \tilde{\nu}c_{11} \quad (3)$$

$$\bar{\epsilon}_{33}^S = v \left[\epsilon_{33}^S - \frac{2\tilde{v}e_{31}^2}{\gamma} \right] + \tilde{v}\epsilon_{11}^P \quad (4)$$

$$\bar{c}_{33}^D = \bar{c}_{33}^E + \bar{\epsilon}_{33}^2 / \bar{\epsilon}_{33}^S \quad (5)$$

where $\gamma = v(c_{11} + c) + \tilde{v}(c_{11}^E + c_{12}^E)$ is used to simplify the notation.

The electromechanical coupling coefficient $\bar{k}_t$, the acoustic impedance, $\bar{Z}$, and the longitudinal velocity, $\bar{v}_l$, for the composite are then determined as follows,

$$\bar{k}_t = \bar{\epsilon}_{33} / (\bar{c}_{33}^D \bar{\epsilon}_{33}^S)^{1/2} \quad (6)$$

$$\bar{Z} = (\bar{c}_{33}^D \bar{\rho})^{1/2} \quad (7)$$

$$\bar{v}_l = (\bar{c}_{33}^D / \bar{\rho})^{1/2} \quad (8)$$

Table 2 summarizes the material parameters used for the bulk piezo material, PIN24%-PIN-PT, (CTS Corp., Bolingbrook, IL, USA), as well as the matrix material EPO-TEK 301 (Epoxy Technology, Billerica, MA, USA). Analytical results were computed for $\bar{Z}$, $\bar{k}_t$, $\bar{\rho}$, and $\bar{v}_l$, with respect to VF given the material parameters in Table 2, using Matlab (MathWorks, Natick, MA, USA). A VF of 65% was selected as a reasonable tradeoff between sensitivity, bandwidth and ease of fabrication. The values of the acoustic parameters predicted by the analytical model for this VF are summarized in Table 3.

The acoustic/electric module (described in Section IV below) utilized an ASIC that incorporates a buffer amplifier at each element to help match the impedance of the transducers to the system cable and input impedance. This ASIC buffer has a bandpass response that peaks at low frequency. To counteract this effect and obtain wider bandwidth, we designed the composite to be centered at a frequency of 6.25 MHz which is higher than our final array design frequency of 4.5 MHz.

The λ pitch at $f_c = 4.5$ MHz can be calculated given the speed of sound, c , in tissue as follows:

$$\lambda = \frac{c}{f_c} \quad (9)$$

which results in a pitch of $1540 \frac{m}{s} / 4.5 MHz = 342 \mu m$. This element pitch matches the azimuthal pitch of the ASIC electronics. For the elevational pitch, we use the designed pitch of the ASIC in elevation, 275 μm , which provides a slight advantage for steering in elevation

if needed. The 1-3 composite pillar pitch for these array pitch values was 170 μm , and 138 μm in azimuth and elevation, respectively. For the 65% VF, corresponding composite pillar widths were 137 and 111 μm in azimuth and elevation respectively. For simplicity of fabrication, a dicing kerf of 30 μm was used in both dimensions.

B. Composite Thickness and Matching Layer Design

The thickness for the composite at the 6.25 MHz design frequency can be calculated using [34]-[35],

$$f_a = \frac{\bar{v}_l}{2t_c} \quad (10)$$

which sets the anti-resonance frequency, f_a of the composite given the composite longitudinal velocity $\bar{v}_l$ and the thickness, t_c . For low k materials (10) is frequently used as an approximation for the resonance frequency, f_r [35], [23]; however the high k value for PIN-PMN-PT makes (10) appropriate for f_a for this design. The analytical model given by (1)-(8), predicts a composite speed of sound of 3665 m/s, which for 6.25 MHz and (10) corresponds to a composite thickness of 290 μm .

Fig. 4 shows a plot of KLM model (PiezoCAD, Sonic Concepts, Bothell, WA) and measured results for the transmit electrical impedance, Z , in air for the composite design described above. This composite measured 11 mm $\times$ 5 mm $\times$ 0.29 mm and was fabricated according to the process outlined in Section IV below. The plotted data compare KLM results, Z_m , given measured parameters for an actual fabricated composite (dashed lines) and measured impedance data, Z_d (solid lines) from a representative fabricated composite sample. As can be seen in Fig. 4, we obtained excellent agreement between the KLM model and measured data.

The coupling factor, $\bar{k}_t$, of the fabricated composite was determined from the measured data by [35],

$$\bar{k}_t = \sqrt{\frac{\pi f_r}{2 f_a} \tan\left(\frac{\pi f_a - f_r}{f_a}\right)} \quad (11)$$

where f_a is the anti-resonance frequency and f_r is the resonance frequency and was found to be 0.77 after poling which was close to that predicted by the analytical model (0.8). The density of the composite was calculated by measuring the volume and mass and found to be 5100 kg/m³.

A two matching layer system was used to optimize the bandwidth of the array. The impedance of these materials can be determined by [36],

$$Z_{m1} = \left(Z_p^4 Z_l^3\right)^{1/7} \quad (12)$$

$$Z_{m2} = (Z_p Z_l^6)^{1/7} \quad (13)$$

where, Z_p is the acoustic impedance of the composite (20.8 MRayls predicted by the analytical design), and $Z_l = 1.50 \text{ MRayls}$ is the acoustic impedance of water. Z_{m1} and Z_{m2} are the acoustic impedance values of the first and second matching layers respectively and can be computed from (12)-(13) as 6.74, and 2.18 MRayls respectively.

Using a widely available database [37] of acoustic parameters for various materials, we selected the second matching layer material to be Acrylonitrile Butadiene Styrene (ABS) with $Z = 2.2 \text{ MRayls}$. The first matching layer was a silver epoxy mixture consisting of 2-3 μm sized silver particles in Insulcast 501 that has a reported acoustic impedance $Z = 7.3 \text{ MRayls}$ [38]. Material parameters for these matching layers are listed in Table 4. We used 70 μm thickness for the first matching layer and 75 μm for the second matching layer in a KLM model for the complete acoustic stack. The final fabricated matching layer thicknesses were 55 μm and 85 μm for the first and second matching layers respectively. These values have been summarized in Table 3.

The backing thickness was chosen such that the roundtrip attenuation would be greater than -40dB . The material used for this design was E-Solder 3022 which has attenuation between 13 dB/cm/MHz and 37 dB/cm/MHz, depending on whether or not it is centrifuged [38]. For this design, the E-Solder was centrifuged; however it is also part of an acrylic matrix in the backing interposer (described in Section IV below), and we therefore expect the final attenuation to be lower than reported in the literature. For the purpose of design, we used a nominal value of 20 dB/cm/MHz as an initial starting point. We calculated the required thickness of the backing by assuming -20 dB attenuation in one direction at 2.5 MHz, which results in a minimum backing thickness of 0.4 cm.

Results for the KLM model of the acoustic stack will be presented in Section V below and compared to the final measured data.

IV. Fabrication

Fabrication of the acoustic stack for the modular prototype was done in a batch process, starting with a larger grouping of 2D array elements which was later diced into smaller sub-arrays for assembly to the ASIC. This process [Fig. 5(a)-(g)] includes fabrication of the interposer, the composite, 2D dicing of the assembled acoustic stack and lamination of multiple matching layers. The final acoustic sub-array module for ASIC assembly had 5×6 acoustic transducer elements, and the batch array had a grouping of 3 of these smaller sub-arrays. While the ASIC used implements a 5×8 array, we reduced the final acoustic aperture in elevation to avoid overlapping and potentially damaging the bond wires near the top of the ASIC assembly [Fig. 7 (a)]. In this section, fabrication of the 1×3 grouping of sub-arrays will be described.

A. Interposer backing

The interposer was fabricated by a hybrid process which uses a 3D printed acrylic grid as a mold for conductive backing material (Fig. 6). The mold becomes part of the final interposer and serves to electrically isolate the channels from each other and also increases structural integrity and dimensional stability of the pillar array.

It is possible to fabricate an interposer pillar array by dicing a solid block of backing material; however the aspect ratio for the isolating walls by dicing cannot be made greater than 20:1, due to the limitation of the maximum blade exposure. For the tall backing required (e.g. 4000 μm), this results in isolation walls that are almost as wide as the element pitch itself ($4000/20 = 200 \mu\text{m}$). Therefore, the advantage of using 3D printing is the ability to produce backing stacks which have very high VF for the acoustically attenuating material (E-Solder 3022) vs. the grid matrix (acrylic). This allows for a sharper pulse/echo response and therefore improved -20 dB pulse width (due to reduced ringing), which in turn improves the axial resolution.

The interposer grid frames [Fig. 6(a)-(b)] were printed using a ProJet 3500 HD printer (3D Systems, Inc., Rock Hill, SC, USA) in XHD mode using VisiJet M3 Crystal acrylate material. The printer has a published resolution of 750 DPI (34 μm) in the X and Y dimensions parallel to the printing platen and 1600 DPI (16 μm) layer thickness. Fig. 6(a) shows an example grid printed by this process for the direct assembly array. The pitch for the interposer is designed to match the ASIC which also matches the transducer composite pitch, being 340 μm in azimuth and 275 μm in elevation. To maximize the volume of backing material contained in the grid holes, the walls were designed to be printed at the minimum feature size of the printer. In this case, the best resolution of the printer should be used in the elevational dimension since the elevation pitch is finer than the azimuthal pitch. This was achieved by rotating the part in the design to orient the elevation direction parallel to the printing platen. The achieved wall thicknesses were 30 μm in elevation and 100 μm in the azimuthal direction.

After printing, the grid holes contained a sacrificial layer of a wax-like vendor-proprietary material which must be cleared. We attempted to clear the wax using solvents including alcohol, acetone, trichloroethylene, and the manufacturer's own proprietary liquid. Cleaning with the solvents resulted in the fine walls of the grid being significantly damaged. The most effective method to clear the wax was found to be a combination of heat (75 $^{\circ}\text{C}$ oven) and capillary action (Kimwipes, McMaster-Carr Supply Company, Santa Fe Springs, CA, USA). An important issue with the finely printed interposer grids for the arrays is the presence of pin-holes in the very thin walls between interposer channels [Fig. 6(e)-(f)], which lead to shorting between the elements due to E-Solder bridging through the holes. After clearing the wax, the walls of the interposer were inspected for these holes and grids with obvious defects were discarded.

The grids were filled using the following process: First, a 3D printed acrylic containment dam was glued to a 2" $\times$ 2" piece of carrier glass and filled with E-Solder 3022 conductive adhesive (Von Roll Isola, New Haven, CT, USA). This assembly was then centrifuged before applying the grids. E-Solder is known to increase its acoustic attenuation after centrifugation

[38]. This can only be accomplished before the grids have been filled, since the E-Solder does not migrate once it is contained in the grid, and the excessive force damages the fine structures in the interposer.

In the next step, the grids were forced down into the centrifuged uncured E-Solder material which was contained by the dam. To minimize wasted material due to squeeze out, the dam was designed to be as close as possible to the size of the grid itself. In addition, the grids were surrounded by a thick border which provided structural stability to the fragile grid frame.

After filling, the interposers were cured overnight at room temperature and then post-cured at 45 °C for 2 hours the next day. Once cured, the interposers were polished on both sides to remove excess cured material and expose the tops and bottoms of the interposer pillars for assembly [Fig. 6(c)]. The completed interposer backing array had a fill factor of 63% and separation wall aspect ratios of 133:1 (4000 μm /30 μm) in the elevational dimension, and 40:1 (4000 μm /100 μm) in the azimuthal dimension [refer to Fig. 5(g) for an illustration of these dimensions].

B. Composite, and Matching layers

To create the composite, bulk PIN-PMN-PT material was lapped to a thickness of 280 μm and diced with a 30 μm kerf in X and Y dimensions at half the element pitch resulting in pillars that were 140 μm wide in azimuth and, 108 μm wide in elevation. The kerfs were left to soak in DI water to clear debris and were then dried and filled with de-gassed EPO-TEK 301 as kerf filler. After cure, both sides of the composite were polished and sputtered with 500 Å of Chromium and 1000 Å of Gold.

The completed composite [Fig. 5(b)] was next waxed to glass and a silver-loaded epoxy was mixed in the lab and cast in place using a dam and centrifugation to provide the first matching layer. The epoxy used was Insulcast 501 (Insulcast, Montgomeryville, PA), loaded with 2-3 μm silver particles (Sigma-Aldrich Inc., St. Louis, MO, USA) at a ratio of 8 gm silver to 2.825 gm mixture of Insulcast 501 and Insulcure 9. This ratio is higher than previously reported for high frequency probes [38] and is necessary to obtain the required performance for our low frequency elements. After overnight cure and 45 °C post-cure for 2 hours, the matching layer was lapped to the design thickness. The samples were then perimeter diced to remove them from the glass.

The composite with the first matching layer was next assembled to the completed interposer using a purpose-built positioning system with X, Y, Z and Theta micrometers coupled to a positioning stage. The system incorporates a clamp to apply pressure after assembly. Alignment was monitored using a USB microscope (Dino-Lite, AnMo Electronics Corp., Hsinchu, Taiwan) positioned to view from the side. The composite kerfs were lined up with the interposer grid frame in order to reduce the overlap of piezo material with the acrylic frame to minimize ringing. The interposer was mounted to a glass slide and positioned using the micrometers, with the exposed pillars facing up. The composite was mounted to a glass chuck using 60 °C wax and was secured to the bottom of the clamp and held in place above the interposer. A thin layer of uncured E-Solder was spread on the interposer top surface,

and the composite was lowered down to contact the interposer. Some squeeze out of the conductive adhesive occurs in this process, and it is later removed with the dicing saw after post-curing.

Pressure was applied with the clamp by hand and the clamp locked in place and the assembly was then cured overnight in the dry-box and post-cured the next day at 45 °C for 2 hours. At the end of the post-cure, the oven temperature was increased to 65 °C so that the composite and matching layer stack could be released from the glass chuck on the clamp by melting the wax seal.

The elements were next singulated to create the 2D array in a two-step process [Fig. 5(c)-(d)]. In the first step, the elements were diced along the azimuthal dimension at the element pitch using a dicing saw (Tcar 864-1, Thermocarbon, Casselberry, FL, USA). In the second step, after kerf fill and cure, the elements were diced in the elevational dimension and filled. This two-step process is critical to ensure high yield of the elements since the small amount of E-Solder under each pillar must be supported by kerf fill to prevent pull-out of the 2D elements during dicing.

The dicing kerf for the 2D element singulation was 55 μm wide and the depth was chosen to go through the first matching layer, the composite, the uniform E-Solder connection layer and finally penetrating slightly into the interposer grid frame. While the composite itself had 30 μm kerfs, the wider 55 μm kerf was necessary to avoid fracturing the blade for the deeper cuts. The final dicing depth was > 400 μm and is critical to ensure that the elements are electrically separated from one another and not shorted in the interposer backing. Alignment of the dicing saw was done from above using grid markers in the interposer [Fig. 5(c)]. After dicing, the kerfs were baked at 45 °C to clear the water and were then filled from the side using capillary action with EPO-TEK 301 and allowed to cure overnight. The tops of the elements were inspected, and any residual kerf filling epoxy left on the first matching layer removed with a sharp blade.

The top surfaces of all of the elements were linked together by sputtering a uniform layer of 500 Å Chromium and 1000 Å Gold [Fig. 5(e)]. The second matching layer (ABS plastic) was next laminated to the top surface of the acoustic stack under pressure using a clamp. A high viscosity epoxy resin (DER-332, Sigma-Aldrich Inc., St. Louis, MO, USA) cured with a curing agent (Versamine C31, BASF Corp., Florham Park, NJ, USA) was used for the lamination of the second matching layer [Fig. 5(f)]. To ensure no bubbles in the adhesive bond line, the uncured epoxy was de-gassed and dispensed using a 0.2 μm PTFE filter (VWR International, Radnor, PA). Fig. 5(g) shows a photomicrograph cross-section of a representative completed sub-array acoustic stack illustrating the layers in the stack-up as described in this section. The second matching layer glue line was cured overnight under clamped pressure and then post-cured in the oven at 45 °C.

C. Assembly to ASIC

Assembly of the interposer to the ASIC is a potential source of electrical shorts and opens which will reduce element interconnect yield. A low temperature process in this step is critical due to the presence of acrylic material in the interposer grid frame, and epoxy

matching and bonding layers, all of which have glass transition temperatures below 150 °C and high coefficients of thermal expansion (CTE). Elevated temperature is also undesirable due to the possibility of de-poling of the piezo material. For these reasons, a low temperature cure conductive adhesive process was developed for assembly of the acoustic stack to the ASIC.

The ASIC was direct-mounted to the module PCB and wire-bond connections performed to link the I/O pads to the board [Fig. 7(a)] by a vendor (Chip Targets, Richardson, TX, USA). The PCB was processed for ENIG surface finish beforehand to enhance wire-bonding reliability (Superior Processing, Placentia, CA, USA). Gold stud bumping of the ASIC transducer pads was used to break the aluminum oxide barrier layer that forms on the pads to create an inert and ohmic electrical connection point for the interposer pillar terminals and the conductive adhesive.

Prior to assembly, the acoustic stack was flipped over to expose the bottom side of the interposer pillars. The interposer was diced along the grid frame using the dicing saw to a depth of 200 μm [Fig. 7(b)], exposing the pillars which form terminals for direct connection of the interposer to the surface of the ASIC.

To reduce the chance of opens and ensure high yield of the connections, conductive epoxy was used for assembly of the interposer and acoustic stack to the surface of the ASIC. This process differs from standard ultrasound transducer to flex attach in which nonconductive epoxy (e.g. EPO-TEK 301) is used to form the bonds between the flex circuit and the acoustic stack [39]-[40]. The conductive epoxy is meant to take-up variation in surface planarity to increase assembly yield. The wire-bonded ASIC module was positioned on the clamp system micrometer stage for alignment to the interposer and acoustic stack using the side-looking USB microscope camera. Electrostatic Discharge (ESD) precautions were used throughout the process to protect the ASIC.

The interposer was waxed to a glass assembly fixture (using 60 °C wax) and suspended above the ASIC module for the alignment. Prior to final alignment, the interposer bottom terminals were lowered down into a 25 μm thin layer of conductive adhesive (E-Solder 3022) that was spread out on a glass slide. A uniform layer of the adhesive was obtained by spreading using a sharp blade supported by a brass ring glued to the surface of the glass slide which had been previously lapped to 25 μm thickness. Shorting is critical and it is prevented by ensuring that the backside of the interposer is diced to form terminals [Fig. 7(e)]. The terminals are far enough apart, and the gaps between them deep enough such that when the part is lifted out of the uniform adhesive layer only the terminals themselves retain the adhesive material [Fig. 7(e)]. For these very closely spaced terminals, some bridging is occasionally observed (e.g. center of [Fig. 7(e)]), and this was removed by hand with a needle prior to assembly. This “stamping” method is similar to other stamping techniques proposed [41]-[42] and provided a uniform distribution of adhesive volume at the bottoms of the pillars with one single action [Fig. 7(e)].

Adhesive uniformity and squeeze-out were evaluated by lowering the interposer down to the surface of a test (non-functional) ASIC and printing a grid of adhesive dots [Fig. 7(d)] which

demonstrated acceptable adhesive volume for assembly. Adhesive was again applied, and the ASIC was then positioned for the final alignment underneath the interposer [Fig. 7(f)]. The aligned interposer was lowered to the surface of the ASIC and clamp pressure applied by hand [Fig. 7(g)]. This action forced the gold stud bumps into the bottoms of the interposer pillars and at the same time also caused the conductive adhesive to spread out and form a uniform bond between the ASIC and the individual interposer terminals. The combined action of the gold stud bumps being forced into the bottom surface of the interposer pillars, as well as the intervening E-Solder layer is meant to ensure high yield of the assembly by taking up any gaps due to coplanarity variation in the interposer. The clamp fixture was cured at room temperature overnight, post-cured at 45 °C for 2 hours the next day and released by increasing the temperature to 65 °C for 15 minutes. A dam was applied and filled with EPO-TEK 301 dispensed for hermetic seal of the wire bonds and the acoustic stack assembly [Fig. 7(h)]. The current version of the ASIC does not have a dedicated pad for ground connection to the interposer; instead a ground wire was applied by hand and connected with silver epoxy to the top electrode of the acoustic array. This wire contacted the PCB which then connected to the ASIC ground using a bond wire.

Table 4 summarizes the various materials used in the acoustic stack and their relevant properties.

V. Results

The fully assembled ASIC/transducer prototype module was tested electrically and acoustically and was interfaced to the Verasonics Vantage 128 system for water tank testing and imaging experiments using a purpose-built wire-target phantom.

A. Acoustic Stack Evaluation

Prior to assembly of the acoustic sub-array to the ASIC module as described above, the large 1×3 grouping of subarrays was tested by micro-probing to evaluate the performance of the acoustic stack prior to assembly. The array impedance was tested using a probe needle visualized under a bifocal microscope and applied to the backside of the interposer and an impedance analyzer (HP 4294A, Agilent Technologies, Santa Clara, CA, USA).

For test purposes, a 3×5 grouping of 2D array test elements was created by shorting backside terminals with E-Solder. This grouping provided a lower electrical impedance than the very small individual 2D array elements, facilitating measurement and matching of data to the KLM model. Fig. 8 shows the measured transmit electrical impedance of the 3×5 grouping along with the KLM model results for comparison. A 3.6 pF parasitic capacitance for the interposer was calculated based on geometry and the assumed dielectric constant of the 3D printed acrylic. This value was added to the model to account for electrical loading in the backing.

The 1×3 macro-array was suspended above a quartz target in a water tank and the probe needle was used to scan all of the elements in the array. X- and Y-axis micrometers were used to translate the array relative to the needle for fine accuracy of positioning. A pulser/receiver (Panametrics 5900PR, Olympus NDT Inc., Waltham, MA, USA) connected to the

probe needle was used to acquire pulse-echo responses from the array with an oscilloscope sampling the data. Fig. 9 provides maps of the normalized sensitivity (a), center frequency (b) and fractional bandwidth (c). The additional tested columns shown in Fig. 9 between the sub-arrays were later removed during dicing to singulate the arrays for assembly. The mean and standard deviation for these measured data can be found in Table 5.

Based on the acquired acoustic data, the center sub-array in the 1×3 lot grouping had the highest FBW among the 3 subarrays and was therefore selected for assembly to the ASIC as described in the previous section. An earlier fabrication lot also yielded a single array for assembly. Two ASIC/Acoustic assemblies were fabricated and tested using these available arrays.

B. Test Setup and Electrical Interface

Following the fabrication steps described in Section IV above, the completed arrays were interfaced to the Verasonics Vantage 128 system for detailed acoustic testing with the combined ASIC and transducer array and imaging. The pulse-echo and imaging test setup included multiple power supplies to power the ASIC and the FPGA, including logic (+3.3 V), ground (0 V) and positive and negative high voltage supplies (+/-20 V). These supplies feed into the distal probe board PCB which houses the ASIC module connector, a connector for a CMOD 7 Artix-7 FPGA (Digilent, Pullman, WA, USA) acting as the ASIC control board, as well as a card edge connector that interfaces directly to a modified L7-4 probe cable assembly (Philips, Bothell, WA, USA) that was purchased second-hand and had the original transducer array removed. This L7-4 cable assembly is convenient for connection to the Verasonics system since it houses both the 260P ZIF connector on the proximal end of the cable for interface to the Verasonics system, as well as a simplified card-edge connector interface on the distal end which accepts purpose-designed PCBs very easily. The L7-4 product probes were not muxed, and we therefore modified our second-hand cable to reroute signal coaxes for some system channels to make the mux control data lines available at the distal end of the cable. The fabricated transducer/ASIC module was plugged into the distal-end probe PCB and then the entire assembly including the distal cable housing was attached to a positioning system which allowed them to be lowered into a water-tank for acoustic testing.

C. Pulse-echo Testing

Initial acoustic testing was performed using a quartz target positioned in front of the array for pulse-echo mapping of the elements. We later used a wire-target assembly fabricated in our lab, comprising 20 μm tungsten wires (California Fine Wire Co., Grover Beach, CA, USA) spaced at 1.5 mm distance on a metal frame for resolution imaging tests.

Pulse-echo testing with the system was performed on multiple elements to assess the yield and uniformity of the fabrication process. For imaging the elements were grouped in elevation which created a 1×5 element 1D linear array. These linear array grouped elements were also evaluated for pulse-echo response with the system. Fig. 10 compares time and frequency domain pulse-echo data for the previously discussed 3×5 grouping of 2D elements (solid black line), a grouped 1D element with ASIC buffering (dotted grey line) and the

KLM model using measured acoustic parameters (dashed gray line). As is evident in Fig. 10, the acoustic response after assembly to the ASIC is shifted relative to the original response with no ASIC buffering. The final acoustic response is centered near 4.5 MHz which is the design frequency for the 340 μm azimuthal pitch of the array.

Data were acquired with the Verasonics system for all 30 of the 2D array elements and all 5 of the grouped linear array elements. The Verasonics script used for pulse-echo testing implemented a wide-bandwidth transmit pulse at 6.25 MHz, and a transmit voltage setting of 11.7 V-peak. The average FBW for the un-buffered acoustic elements as tested with the 50 Ω impedance Panametrics pulse/echo system was 59%. The average FBW increased to 64% for buffered elements driving the Verasonics system and probe cable and an average of 77% when these buffered elements were grouped electronically in elevation to form 1D elements using the ASIC multiplexors. The FBW for the elements without ASICs was low due to the first matching layer thickness being smaller than design (55 μm vs. 70 μm) and will be corrected in future work.

The FBW for the ASIC-interfaced elements benefited from the low frequency bandpass response of the on-chip cable buffer amplifiers which accentuate lower frequencies, shifting the center frequency, F_C , down by approximately 1 MHz as compared to the unbuffered 2D array elements. The absolute bandwidth (BW) changed only slightly, and therefore this lower F_C yielded a higher FBW (BW/F_C) for the buffered elements.

The observed average -20 dB pulse width (PW) for the two modules was 592 ns. These measurements are summarized in Table 5.

The yield for the fabricated ASIC/transducer array modules was evaluated from the system pulse/echo data. There was significant improvement in the interposer fabrication and the assembly processes between the first and second ASIC/array assembly builds with this being reflected in an increase in yield of the 2D array elements from 64% in the first array to 90% in the second array. For a production process we would sort the fabricated assemblies according to image quality criteria for acceptable number of missing elements and reject the individual module assemblies which did not achieve this level. In this way we would expect to achieve high aggregate yield of the completed large array probes.

D. Imaging

Imaging tests for the array module resolution were conducted using the wire-target assembly described above. To evaluate the array performance relative to theoretical expected results, a model of the acoustic beam intensity profile of the device configured as a linear array was obtained using the Field II acoustic simulator [43]. The axial beam plot predicts the natural focus of the array at 2.65 mm. The lateral line spread function (LSF) was used to determine the expected lateral resolution at the natural focus, with a FWHM beam width of 0.66 mm.

To evaluate the expected image quality for this array, we used the built in Verasonics VSX simulator (Verasonics, Inc., Kirkland, WA, USA) to generate simulated wire target images with the small array aperture [Fig. 11(a)]. As is evident in the simulation results, a 5-element array produces still-discernable wire images, but they are not highly focused in azimuth. In

the future, we expect to see improved lateral resolution for a 30-column wide aperture which would be the case for 6 tiled ASIC array modules.

Fig. 11(b) presents an image of wire-targets which was obtained with the small array module operating with the Verasonics system in real-time scanning. The image was obtained by electronically configuring the 2D array elements to form 1D columns which were then connected directly to the Verasonics system for both transmit and receive. The Verasonics script implemented full synthetic aperture with each of the 1D elements transmitting in turn and all of the 1D element receive signals then beamformed in parallel. The transmit frequency was set to 5.2 MHz for 1 cycle, and a transmit voltage setting of 11.7 V_{Peak} was used.

The axial and lateral LSFs for Fig. 11(b) were obtained and used to calculate the observed axial and lateral resolutions, which were 221 μm and 540 μm respectively.

The theoretical Full Width Half Maximum (FWHM) of the lateral beamwidth, w_b , for a focused array can be calculated by [23],

$$w_b \approx f\#\lambda \quad (14)$$

where, for this test, λ is the wavelength in water of imaging (here 344 μm), and $f\#$ Focal Distance / Aperture Width (here 1.5). This gives a theoretical value of 516 μm at the focal point of the array (2.55 mm) which is similar to the observed result of 540 μm .

The expected axial resolution for the array can be calculated by [44],

$$w_{ar} = \frac{C}{2BW} \quad (15)$$

where, for this test, c is 1480 m/s, the speed of sound in water (not tissue) and BW is the average bandwidth of the linear array elements used for imaging (here BW=3.3 MHz). This results in an expected axial resolution of 224 μm , which is close to the observed result of 220 μm .

VI. Conclusions

In this work, a new process for fabrication of a tileable ASIC/transducer array module by direct assembly of the acoustic stack to the surface of the ASIC with a 3D printed backing interposer has been developed and results presented. Multiple individual modules have been completed and tested. A complete tiled array will be the subject of future work.

A single ASIC module was integrated with a 5×6 element 2D array acoustic stack by direct assembly using an interposer backing. A novel 3D printed acrylic interposer grid was used to create a conducting backing array of pillars which serves to link the 2D transducer elements to the surface of the ASIC for electronic connection by direct assembly.

The fabricated prototype transducer arrays had an average center frequency of 4.5 MHz and average FBW of 77% when interfaced to the ASIC by direct assembly. The FBW will be

improved in future work by increasing the thickness of the first matching layer. The transducer/ASIC module was successfully integrated to the Verasonics ultrasound system and images of wire targets were obtained. Using the line spread functions acquired from the wire target images, the measured axial resolution was found to be 221 μm , and the lateral resolution was found to be 540 μm . This agreed well with theory.

In the future, we plan to increase the size of the imaging aperture by increasing the number of tiled 2D array modules, which will significantly improve the ability to focus at deeper depths as well as expand the field of view of the array.

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Fig. 1. Proposed 2D array, showing an array of 26 modules, 2 in elevation and 13 in azimuth, illustrating interconnect of the 2D transducer array elements and ASICs by a highly integrated grid of interposer backing pillars.

Fig. 2.

Schematic cross-section of the acoustic stack assembled to an ASIC substrate, illustrating the interposer with terminals assembled to the ASIC using conducting adhesive and gold bumps, the 3D printed acrylic grid support for the interposer backing pillars, the PIN-PMN-PT composite and dual matching layers. Layer thicknesses are not shown to scale.

Fig. 3. Process flow for fabrication and assembly of the acoustic stack. (a) Assemble the composite with first matching layer to the interposer, (b) dice and fill the 2D array, (c) sputter top electrode for ground, (d) glue second matching layer, (e) flip over stack and dice the bottom terminals for assembly to ASIC, (f) assemble to ASIC.

Fig. 4.

Transmit electrical impedance in air for composite without backing or matching layers showing phase and magnitude of the data with linear axes. Solid lines are for the measured data (Z_d) for an $11 \text{ mm} \times 5 \text{ mm} \times 290 \text{ }\mu\text{m}$ thick composite sample, dashed lines are for the KLM model (Z_m) using final fabricated material parameters.

Fig. 5. Fabrication of multi-array acoustic module, (a) interposer, (b) composite, (c) composite with first matching layer laminated to interposer with dicing along the azimuthal direction, (d) dicing in elevation direction, (e) gold sputtered electrode, (f) Lamination of second matching layer, (g) Cross-sectional view of completed single module acoustic stack; each multi-array module has 3 stacks which are diced out prior to assembly.

Fig. 6.

Interposer fabrication process showing (a) the initial 3D printed acrylic grid with $340\ \mu\text{m} \times 275\ \mu\text{m}$ elements and supporting outer frame, (b) close-up of the acrylic grid with empty tubes that will be filled with conducting epoxy for the backing, (c) completed interposer backing with cured E-Solder conducting epoxy filling the acrylic grid, (d) cross-section of the completed interposer illustrating the high aspect ratio of the pillars and grid walls, (e) close-up of holes in the side-walls of a rejected acrylic grid, and (f) close-up of a similar grid that has been filled with silver epoxy illustrating bridging shorts between adjacent pillars.

Fig. 7.

Assembly process for fabrication of the acoustic/ASIC module, (a) shows the wire-bonded ASIC, (b) shows the diced assembly terminals at bottom of the interposer, (c) shows a close-up of the gold stud bumps on the ASIC for assembly, (d) shows results of the stamp test with the conductive adhesive, (e) shows stamped conductive adhesive at the bottom of the interposer, (f) interposer and ASIC prior to assembly, (g) interposer assembled to ASIC surface, (h) final completed module.

Fig. 8.

Transmit electrical impedance for the completed acoustic stack including backing and two matching layers, showing phase and magnitude of the data with linear axes. Solid lines are for the measured data for a 3×5 grouping of 2D array elements, dashed lines are for the KLM model.

Fig. 9.

Maps of measured acoustic data for pulse/echo testing of the 1×3 module fabrication sample, including a) Normalized sensitivity b) Center Frequency, and c) FBW.

Fig. 10.

Pulse/Echo two-way response for the KLM model and normalized measured data showing time domain and magnitude spectrum results. Dashed line is for the KLM model for a 3×5 grouping of 2D elements, solid line is the measured data for the 3×5 grouping of 2D elements, dotted line is for an ASIC buffered grouping of 1×5 2D elements.

Fig. 11. Image of 20 μm wire targets spaced at 1.5 mm intervals. (a) Simulated results using VSX simulator, (b) Measured data captured using the single array module and the Verasonics Vantage 128 operating at 5.2 MHz center frequency. The red box shows the area used for axial and lateral LSF calculations. All dimensions are in mm, and the images as displayed had a dynamic range of 39 dB.

Table 1.**Modular 2D Array Design Goals.**

Parameter	Value
Module Tiling	2×13
Number of Elements	16×65
Aperture Size	$4.5 \text{ mm} \times 22 \text{ mm}$
ASICs Used	26
System Channels (1.5D)	65
Array Module Cells	8×5
Pitch	$275 \text{ }\mu\text{m} \times 340 \text{ }\mu\text{m}$
Module Size	$2.2 \text{ mm} \times 1.7 \text{ mm}$
Center Frequency	4.5 MHz

* All array dimensions are Elevation $\times$ Azimuth

Table 2.

Composite Material Parameters

	Value	Units	Description
c_{11}^E	12.43×10^{10}	N/m ²	Stiffness of PIN24%-PMN-PT <11>
c_{12}^E	10.90×10^{10}	N/m ²	Stiffness of PIN24%-PMN-PT <12>
c_{13}^E	11.02×10^{10}	N/m ²	Stiffness of PIN24%-PMN-PT <13>
c_{33}^E	12.45×10^{10}	N/m ²	Stiffness of PIN24%-PMN-PT <33>
e_{31}	-9.11	C/m ²	Transverse piezoelectric constant
e_{33}	17.60	C/m ²	Longitudinal piezoelectric constant
ϵ_0	8.854×10^{-12}	F/m	Permittivity of free space
ϵ_{33}^S	$\epsilon_0 \times 868$	F/m	Clamped dielectric constant
ρ	8122	kg/m ³	Density of bulk PIN24%-PMN-PT
c_{11}	0.81×10^{10}	N/m ²	Stiffness of EPOTEK-301 <11>
c_{12}	0.46×10^{10}	N/m ²	Stiffness of EPOTEK-301 <12>
ρ^p	1150	kg/m ³	Density of EPOTEK-301
ϵ_{11}	$\epsilon_0 \times 4$	F/m	Dielectric constant of EPOTEK-301

Table 3.

Acoustic and design parameters

Param.	Analytical [Eq. (1)-(8)]	Final KLM Device Model	Description
VF	65%	65%	Volume Fraction
$\bar{Z}$	20.8 MRayls	20.3 MRayls	Composite Impedance
$\bar{k}_t$	0.80	0.68	Electromechanical Coupling Coefficient
$\bar{\rho}$	5682 kg/m ³	5600 kg/m ³	Density
$\bar{v}_l$	3665 m/s	3620 m/s	Velocity
Z_{m1}	6.74 MRayls	7.2 MRayls	ML1 Impedance
Z_{m2}	2.18 MRayls	1.8 MRayls	ML2 Impedance
t_C	290 μm	280 μm	Composite thickness
t_{m1}	70 μm	55 μm	ML1 thickness
t_{m2}	75 μm	85 μm	ML2 thickness
t_b	4 mm	4 mm	Backing thickness

Table 4.

Material properties for the fabricated array

Acoustic Layer	Material	Z (MRayls)	$\bar{\rho}$ (kg/m ³)	$\bar{v}_l$ (m/s)	Attn. (dB/cm/MHz)	Design thickness
Backing Pillars	E-Solder 3022, Von Roll	5.5	2500	2110	13–20	4 mm
Interposer grid	Vero Clear Acrylic, 3D Systems	—	—	—	—	4 mm
Piezo Layer	1-3 Composite: PIN24%-PMN-PT/EPOTEK-301	20.8	5682	3665	—	290 μ m
Matching Layer 1	2-3 μ m Silver particles in Insulcast 501	7.33	3860	1900	—	70 μ m
Matching Layer 2	Acrylonitrile butadiene styrene (ABS)	2.2	1190	1850	—	75 μ m
Substrate	Silicon/CMOS ASIC	—	—	—	—	600 μ m

* Material properties are from [37]–[39] and Eq. (1)–(8)

Table 5.

Measured acoustic results for fabricated arrays and ASIC modules

Parameter	1×3 Lot	AR2	AR3	AR4	3×5 Grouping	AR3/ASIC 2D	AR1/ASIC ID	AR3/ASIC ID
F_c (MHz)	5.4 (0.07)	5.5 (0.03)	5.5 (0.10)	5.2 (0.03)	5.48	4.7 (0.1)	4.5 (0.1)	4.3 (0.07)
FBW (%)	59 (2)	63 (2)	57 (2)	55 (1)	73	64 (10)	78 (7)	76 (3)
PW (ns)							640 (12)	543 (58)

* All data: μ (σ)