2D Arrays Performances Optimization to Address High Quality Volumetric Imaging

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Abstract— 2D ultrasonic array techniques let expect exciting perspectives for volumetric or multiplane imaging in medical applications. However, 2D array design is very challenging to achieve acoustical performance comparable to 1D imaging state of the art. The present work relates to the optimization of the acoustic stack. Arrays with different active layers are manufactured with bulk ceramic and piezocomposite microstructures. Once the arrays are packaged and interconnected, they are fully characterized by measuring pulse-echo response and directivity pattern. All results are analyzed and design routes are proposed. Finally, the optimized 2D array is benchmarked with a configuration previously presented in 2002 IEEE symposium and compared to a 1D standard Phased-array.

I. INTRODUCTION

Over the past decade a lot of advanced studies were performed on 2D arrays from modeling, acoustic design to interconnect technologies both on sparse and fully populated configurations [1,2]. The main technological issues were interconnecting 100% of the thousands active elements and the beamformer development. Still, it is essential for 2D arrays to achieve performances at the same level than current state of the art 1D phased array.

In this work, we focus on the array acoustic optimization. To illustrate this we have manufactured sub-apertures of 2D array with 2.5 MHz center frequency, 64*64 active elements and 300µm pitch. The 8*16 elements sub-apertures are composed of an active layer, 2 matching layers, a backing module, and a flexible interconnect circuit designed to plug the array to a 128 coaxial cable. We manufactured arrays with different active layers, from bulk ceramic to piezocomposite microstructures. Once the arrays are packaged and interconnected, we fully characterize them by measuring pulse-echo response and directivity pattern. All results are analyzed and design routes are proposed. Finally, we benchmark an optimized array with a configuration previously presented [3] and compare also performances to a 1D standard Phased-array.

II. PROCESS FLOW

Before describing the optimization of the acoustic stack, we first detail the process flow of 2D array transducer manufacturing. The objective of this process flow is to provide industrial compatible processes, in order to produce reliable, and 100% connectivity without any trade-offs on acoustic performances. The process of our 2D array is based on an integrated backing connector [4], which supports the acoustic stack and provides fully functional connectivity to flex or PCB type conventional interconnect. The purpose of this backing is to embed two functionalities: an acoustic function and an electrical function. For the acoustic backing function, the medium exhibits an acoustic impedance of 5 MRayls comparable to impedances commonly used in 1D array designs, attenuation is set sufficiently high to limit parasitic echoes from the back of the structure, finally the backing anisotropy generates limited cross-coupling in the back area of active elements. Thus the backing module is also an electrical conductor that transfers the contact of each elements from the back of the active layer to the back face of the assembly. Then all type of interconnect can be used, such as flex circuits, PCBs or flip-chipped on dedicated ICs. Electrical performances of the backing layer are suitable to high performance arrays: low resistivity (<0.5 Ohms), very low capacitance (<1pF) and highly reproducible contacts. The backing module does not impact acoustic performances and provide 100% connectivity.

Once the backing module is prepared for the transducer assembly (surface polished, cleaned, and patterned), the process flow can be applied through these seven different steps:

1. Bonding of piezocomposite or piezoceramic plate on backing layer
2. Dicing of elements 300µm*300µm
3. Kerf filling
4. Front electrode
5. Bonding of matching layers
6. Dicing of matching layers
7. Matching layer kerf filling

Figure 1 displays the main process flow steps, for the manufacturing of complete 2D transducer array.

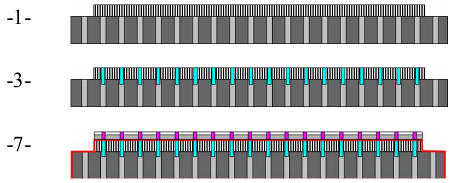

Figure 1 : Main process flow steps.

With this process flow, fully connected arrays can be manufactured with reliable interconnect technology compatible with industrial process. Moreover connectivity is 100% and yield is comparable with 1D array technology.

With a reliable process flow, we can focus on the enhancement of electroacoustic and acoustic performances of the array stack.

III. ACOUSTIC STACK OPTIMIZATION

Backing module is as explained previously important to provide fully connected arrays, but the "motor" of array transducers is the acoustic stack. Its optimization implies the definition of several key parameters of the active layer and the front matching. This work will mainly focus on the active layer design, the piezoelectric element and the interelement structure. The piezoelectric element can be bulk piezoceramic or piezocomposite with different volumic fraction and the interelement structure is defined by the kerf width and filler material. On the front face, the matching layers with adequate impedances, kerf width and filler material can produce broadband electroacoustic response.

To optimize the active layer (which will determine the final electromechanical and acoustical behavior), we explore the 50% to 100% volumic fraction range and various configuration of filler materials. We manufacture 3 prototype arrays (128 elements, 8*16 active elements, 300µmx300µm pitch). They are set without matching layers, in order to see only performances of active layer. We investigate 3 different volumic fractions (50%, 75% and 100%, corresponding to a bulk piezoceramic element) while fixing other adjustable parameters: piezoceramic type (High permittivity), low acoustic impedance filler material and kerf width set to 60µm.

Figure 2 displays the typical pulse-echo response obtained from the 3 arrays. The arrays are immersed in water handled by a tilting – translating mechanical system. A 2.2m, 50Ω, 110pF/m, 128 elements coaxial cable is connected between the arrays and a 192 channels multiplexing electronics that allows the switching of excitation between the probe elements and the panametrics 5072PR pulser-receiver. Arrays are positioned geometrically and acoustically in front of a flat steel target. Then, all pulse-echo signals are acquired and stored. We calculate all fundamental electroacoustic parameters (center frequency, high and low cutoff frequencies, fractional bandwidth and pulse duration) and reported them in Table 2.

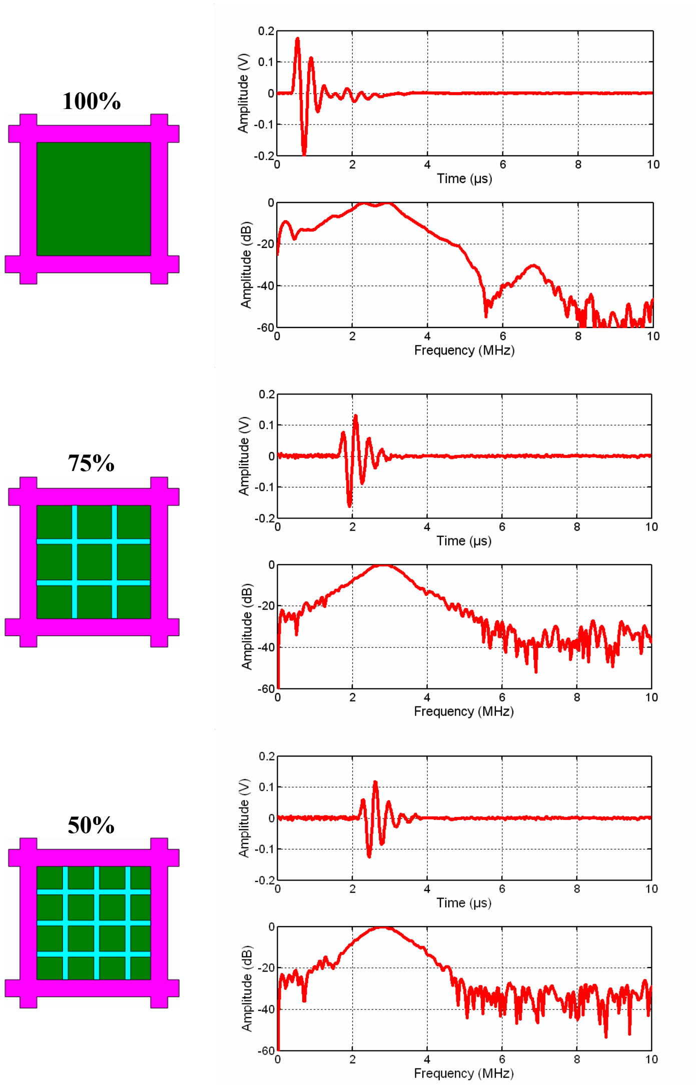

Figure 2 : Pulse-echo time and frequency response of piezocomposite based 2D array elements without matching layer (100%, 75% and 50% volumic fraction).

We can first observe on the 100% configuration response the broadband behavior as compared to other configurations, but the ring down that appears after the first oscillation periods indicates clearly that parasitic electromechanical modes exist. For the two other configurations the vibration seems to be very homogeneous and the result of single vibration mode (length thickness extensional mode).

Volumic fraction	Sensitivity	Bandwidth @-6dB	Acceptance angle
100%	0dB	"61%"	51°
75%	#-2dB	40%	56°
50%	#-6dB	46%	59°

Table 1 : Influence of volumic fraction on 2D array elements electroacoutic and acoustic performances.

One can determine from these results the well-known sensitivity-bandwidth trade-off driving 1D array design. The bulk configuration (100%) is the reference for sensitivity as compared to piezocomposites ones, but parasitic behavior artificially creates the wide bandwidth by creating phase-shift in the temporal response. This multi modal vibration will decrease the final performances and image quality.

Piezocomposites configurations (50% and 75%) seem to be good candidates for 2D arrays active layer, but sensitivity is mandatory for 2D arrays, then the 75% volumic fraction exhibits the best sensitivity, bandwidth and acceptance angle trade-off.

The other important component in the active layer is the filler material that will fill the gap between elements after dicing of the piezocomposite plate. For filler evaluation, we fixed all other parameters: piezocomposite and kerf width. Tested materials are characterized by their acoustic impedance. Results of electroacoustic and acoustic characterization are displayed in the table below.

	Sensitivity	Bandwidth @-6dB	Acceptance angle
Filler 1	0dB	Ref	Ref
Filler 2	#+3dB	Ref+5%	Ref-8°

Table 2 : Influence of interelement kerf filler material on 2D array elements electroacoutic and acoustic performances.

Filler #2 with higher impedance provides improvement on the sensitivity and the damping. In the other hand, the acceptance angle value is low. Filler materials are essential to manage trade-offs and must be taken into account during optimization.

In summary, we have emphasized the impact of constitutive materials of the active layer on the performances of 2D array elements. For the next step, we manufacture a complete configuration including matching layers.

IV. COMPLETE ARRAY CHARACTERIZATION

The complete array is made off the 75% piezocomposite plate, the kerf width is set at 60µm and filled with the filler #2. A double matching layer is bonded and diced (Z = 8 Mrayls & Z = 2 MRayls). The number of active element is 8x16 = 128 corresponding to a sub-aperture of a fully connected 64x64 array.

We will first compare the performances of array presented in 2002 [3] to current results and then benchmark the 2D array with a standard 1D phased array for external cardiac imaging.

A. Comparison with 2002 2D array

To compare the two 2D arrays we use the same measurement protocol previously described, results obtained are displayed in the following figures and table.

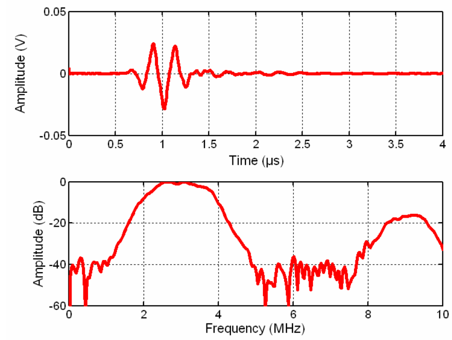

Figure 3 : Pulse-echo time and frequency response of 2002 2D array.

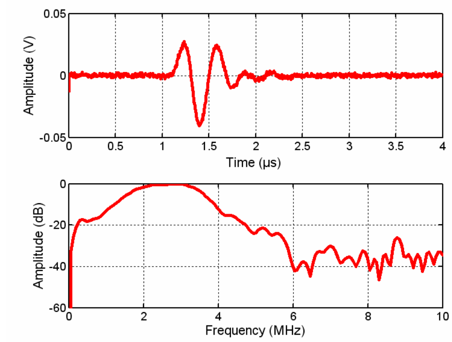

Figure 4 : Pulse-echo time and frequency response of 2005 2D array.

We can observe that all electroacoustic performances are increased with a significant gain: +2dB on sensitivity, 10 percent on bandwidth and increase on the axial resolution of 30%. This demonstrates that the active layer has better performances.

The directivity pattern result exhibits an increase of 6° on the acceptance angle.

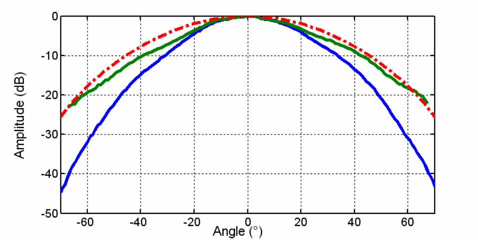

Figure 5 : Directivity pattern of 2D arrays elements: 2005 (green line), 2002 (blue line) and theoretical (red dashed line).

	S	Fc @ -6dB	Ax.R @-20dB	BW @-6dB	Acceptance angle
2002	48.7mV	2.89MHz	1.2µs	58%	49°
2005	68mV	2.5MHz	0.86µs	68%	55°

Table 3 : Comparison of electroacoustic and acoustic performances of 2D array elements.

Optimization of the acoustic stack on the 2005 2D array also contributes to the decrease of the third harmonic level as seen on the frequency spectrum.

B. Benchmarking with 1D Phased Array

The idea in this part of the work is to benchmark performances of conventional Phased array transducer commonly used in external cardiac imaging and 2D arrays. The purpose is to connect in parallel a line of 2D array elements to create an equivalent 1D phased array element. The 1D phased array that is benchmarked is a 64 elements, 0.28 mm pitch lensless array exhibiting a transverse aperture of 10mm. To provide an equivalent array element, then 32 elements of the complete 2D array are connected all together. Thus we have two acoustic apertures with a similar active surface. Using the setups previously described we characterize the two elements in the near field to limit diffraction effects. Electroacoustic and directivity pattern results are reported in the table below.

	S	Fc @ -6dB	Ax.R @-20dB	BW @-6dB	Acceptance angle
1D Phased Array	0dB	2.75MHz	0.8µs	74%	60°
32 //elements of 2D array	-3dB	2.5MHz	0.86µs	70	55°

Table 4 : Benchmarking on electroacoustic and acoustic performances of 1D Phased Array element and 32 parallel 2D array elements.

First we notice that 2D array elements sensitivity is 3dB lower than Phased Array. This was predictable due to the inactive area between array elements that artificially decrease the active surface of the 32 parallely connected elements. Acceptance angle and bandwidth are similar to the ones of 1D array indicating the excellent acoustic behavior of 2D arrays elements. This demonstrates that 2D arrays can be used for conventional 2D imaging and shall reach image quality comparable to 1D standard phased array.

V. CONCLUSIONS

2D arrays performances have been optimized in this work while tuning primarily the constitutive material and design of the active layer.
Results exhibit performances very comparable to 1D phased array transducers and this indicates a promising compliance with imaging system specifications.
Technology can be applied to finer pitch and higher frequencies and future work will be dedicated to new configurations and further optimization of the matching layers.

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