Piezocomposite 30MHz linear array for medical imaging: design challenges and performances evaluation of a 128 elements array

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Abstract— **The range of applications demanding the development of high frequency ultrasound imaging is very broad, from dermatology and ophthalmology to intravascular and small animals imaging, to improve the resolution of the images over a small penetration depth. However the manufacture of such imaging systems remains very challenging from both transducer manufacture (small dimensions of the elements, thin layers materials properties control) and associated electronic system perspectives.**

This article extends the current state of the art limited at 20MHz for fully operational array devices and presents the acoustical design, manufacture and evaluation of a 128 elements 30MHz ultrasound array based on the 1-3 piezocomposite technology, with a 100µm pitch and a 2mm elevation aperture. Electro-acoustical characterisation of the full array will be reported (in terms of bandwidth, pulse duration and homogeneity performances) as well as electrical characterisation (impedance and cross-coupling measurements).

I. INTRODUCTION

The need for improved image resolution in medical imaging for specific applications has triggered numerous R&D efforts to manufacture high frequency ultrasound transducers above 20MHz. A large range of applications, from dermatology, ophthalmology, intravascular to small animals imaging, is requiring this level of image resolution over a small penetration depth. First ultrasound systems above 20MHz relied on single element transducers that are mechanically moved. Array manufacture faces indeed several challenges that have to be overcome to replace single element technology.

From transducer manufacturer perspective, these challenges are mainly related to the small dimensions and thicknesses targeted for the high frequencies. Some R&D teams have developed and evaluated innovative techniques to manufacture this type of array from PZT ceramics: Ritter ([1], thin ceramic plates coated with epoxy mixed with polystyrene micro-spheres, then diced into 2-2 composites); Hackenberger ([2], tape casting technology), Liu ([3], manufacture of composites through interdigital pair bonding method)…

It is one of the objectives of this paper to demonstrate the feasibility of array transducers working at 30MHz through advanced manufacturing processes based on dice and fill technique for the piezocomposite preparation. The design and manufacturing processes have been optimized to provide high performances transducers. This work is a continuation of our previous publications related to high frequency transducers development. (Nguyen-Dinh [4] and Lacaze [5]).

This article presents the acoustical design and manufacture of a 128 elements ultrasound array based on the 1-3 piezo-composite technology with a 30MHz center frequency. We will first describe the acoustical design of the probe with regards to the targeted performances. The manufacturing process of such transducers, very close to standard manufacturing process applicable to lower frequencies arrays, will then be detailed and a complete set of characterization measurements will be performed on the complete probe to assess its performances.

II. DESIGN CHALLENGES AND RULES

High frequency arrays manufacturing remains very challenging as small dimensions for all transducer layers are required. As an example, matching layer thickness can range from less than 10µm to 30µm that is at least one tenth of the thicknesses achieved on a standard 3MHz abdominal probe. In addition, small capacitances measured on these small elements lead to electrical impedance mismatch with the ultrasound imaging system: this will require specific piezocomposite design.

To meet the demands to higher frequency arrays we set the following specifications for our transducer:

<u>Specifications of the transducer:</u>
Center frequency: 30MHz
Type of array: linear **Number of elements**: 128
Pitch: 100µm
Elevation: 2mm
Focus distance: 10mm
Bandwidth: > 50%
Cross coupling < -30dB

The pitch may be considered as large (it corresponds to two wavelengths at 30MHz in water) but it is compatible with the ultrasound system that will be used for image evaluation.
The manufacturing of a 128-element array will allow us to perform this evaluation on a commercial high frequency imaging system. Transverse beam focusing is achieved with an acoustic lens placed on the front face of the transducer. The focus distance was determined by clinical requirements to optimize resolution and beam penetration and was set to 10mm.
The most important design work performed for this high frequency array was devoted to the design of the piezocomposite configuration adapted to the application. Design parameters for the piezocomposite include : starting ceramic material, polymer phase and dicing characteristics (pitch and kerf).
Adapted ceramic shall be selected to comply with these fine scales. Fine grain ceramic, with suitable machining behavior was selected to suppress cracking and inhomogeneities during the dicing process. High dielectric constant ceramic is also needed to improve the electrical impedance matching with the ultrasound system.
Another concern for piezocomposite design is to evaluate the frequency position and amplitude of the lateral mode. This spurious mode within a 1-3 piezocomposite is a consequence of the periodic structure of the composite. Its characteristics depend on the properties of the polymer phase and of the ceramic and on the kerf width. As we have already set the selection of the ceramic, polymer phase and kerf width characteristics were designed to push the lateral mode out of the operating frequency range. This requires the selection of a hard resin with high velocities for the polymer phase and dicing width less than 12µm, which is very challenging. It shall be pointed out that the accuracy is also a key parameter, both in the dicing kerfs and in the thicknesses of all the layers.
Based on all these considerations the 1-3 piezocomposite configuration was designed with a ceramic volume fraction of 51% and with a dicing width less than 12µm. Final piezocomposite thickness is 47µm. We have reported in Figure 1 the real and imaginary parts of the electrical impedance measured on the piezocomposite alone. These graphs show the suitability of this composite for 30MHz applications. Measured values from the impedance:

- Fa= 37.3MHz anti-resonance frequency (maximum of the real part of impedance)
- thickness coupling coefficient kt=0.57
- dielectric constant: Eps33S=920

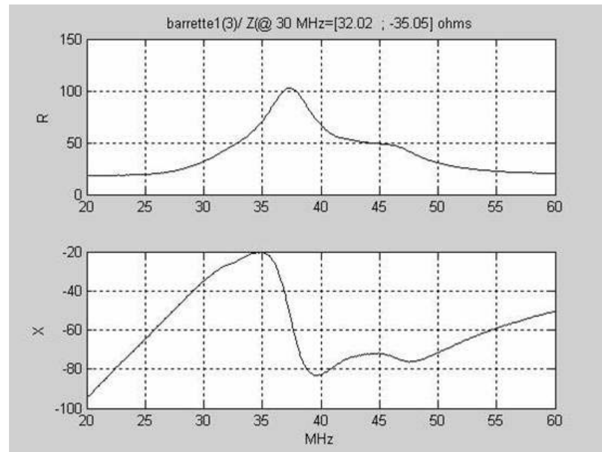


Figure 1 :.real and imaginary parts of the electrical impedance of the 1-3 piezocomposite

For the complete array we have set the following design rules to make the manufacture easier:

- 1-3 piezocomposite as piezoelectric material
- one matching layer with following properties: Z=3MRayls, thickness 9µm
- focusing in elevation ensured by an acoustic lens

The figure 2 summarizes this acoustical stack (flexible interconnection is not represented on this drawing).

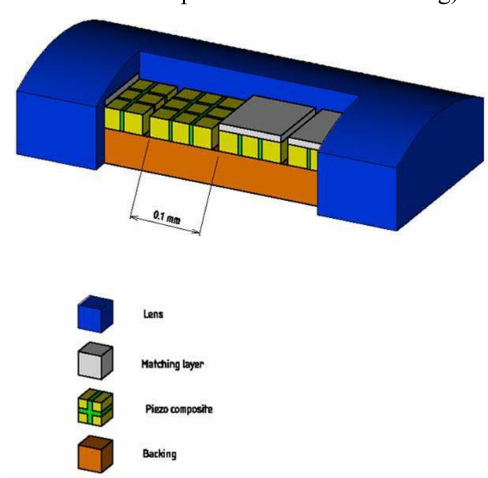


Figure 2: Schematic drawing of the acoustical stack

III. MANUFACTURING PROCESS

The small dimensions of all components of the transducer require specific provisions in terms of composite processing and matching layer fabrication. As emphasized before, only a tight control of the dicing parameters can lead to suitable piezocomposite. In addition a precision lapping process was developed in the course of the project. Nevertheless, it shall be noted that the manufacturing process for this high frequency transducer remains compatible with standard manufacturing process for probes with lower center frequency, as the steps are as follows:

- Piezocomposite preparation
- Lapping to final thickness
- Electrodes sputtering
- Acoustical stack assembly

Figure 3 is a picture of the acoustic head of the probe and its dimension is compared to a 1 eurocent coin.

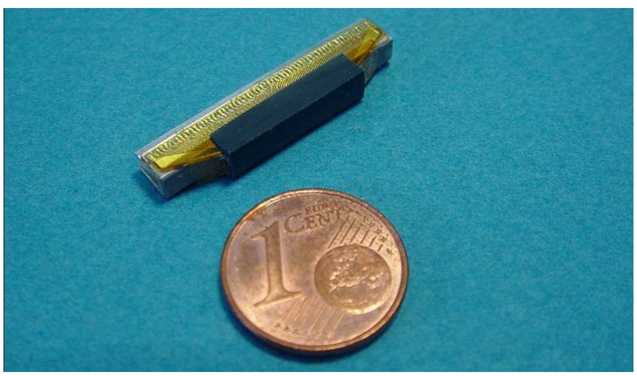


Figure 3: 30MHz linear array acoustic head

This acoustic head is subsequently integrated into an housing and interconnected to a coaxial cable. This cable has a 85 Ohms impedance and its length was defined at 2m. An ITT Cannon standard connector was mounted on the cable for interconnecting with the imaging system.

IV. CHARACTERIZATION

A complete set of measurements were performed on the final transducer. Main results and measurement conditions are displayed in this article: electro-acoustical properties, electrical impedance and cross-coupling measurements.

Electro-acoustical measurements:

<u>*Conditions:*</u>

<u>Pulser/Receiver</u>: Panametrics 5073PR

Damping: 50Ω / Energy: 1 / Gain +20dB / Filter: none

<u>Propagation medium</u>: water, 20°C; <u>Target</u>: Flat stainless steel target placed at the focal distance.

Typical measured pulse and spectrum responses are reported in figure 4.

Measured values for element 64:

Fc = 28.1MHz; LCF(@-6dB) = 17.9MHz ; HCF(@-6dB) = 38.2MHz ; BW(@-6dB) = 73% ; AxR(@-20dB) = 97ns

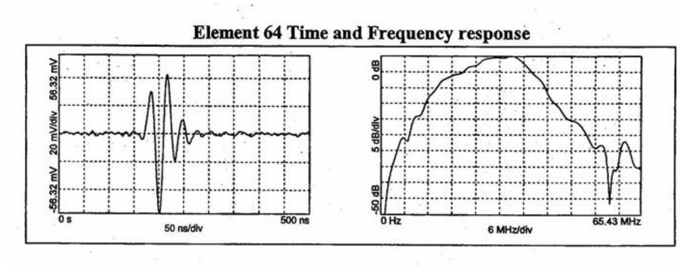


Figure 4: Typical measured time (first curve) and frequency (second curve) responses for the final transducer

The large bandwidth allows a large frequency operating range as the frequencies corresponding to -6dB sensitivity range from 18MHz to 38MHz.

In addition, a complete characterization of the probe was performed, as for standard probes, by measuring the time and frequency responses for each of the 128 elements. All 128 elements of the probe are active. The figure 5 presents the sensitivity homogeneity along the probe.

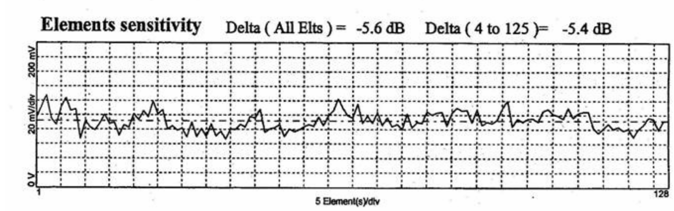


Figure 5: sensitivity homogeneity of the probe

Main results are summarized in table 1, as average values for all elements: (minimum and maximum values for these parameters are also included in the table for the whole array)

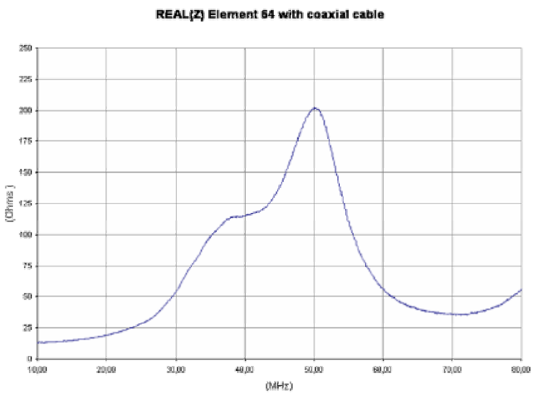
Parameters	Values
Average Center Frequency @-6dB	27.3MHz (min 26.2, max 28.8)
Average Sensitivity	92mV
Sensitivity Homogeneity	5.6dB
Average BW@-6dB	74% (min 58%, max 85%)
Average Pulse Length @-20dB	113ns (min 84ns, max 144ns)

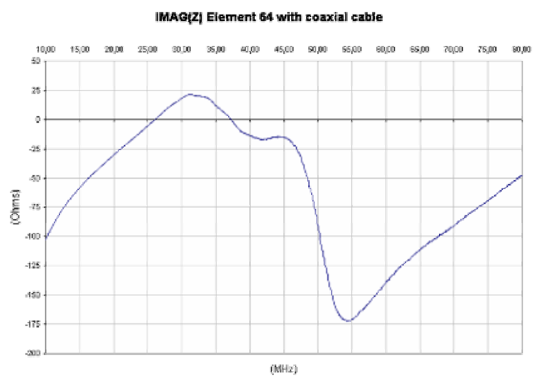
Table 1: measured electro-acoustical properties for the complete probe (128 elements)

Electrical Measurements

Conditions :

Electrical properties are characterized with an Agilent E5100A impedance analyzer with the transducer in its final configuration. Figures 6 and 7 give the real and imaginary parts of the impedance for the element 64. Measured values at 30MHz (R+jX with R=54 Ohms and X=18 Ohms) show a significant improvement in electrical matching with a 50Ohms ultrasound system.





Figures 6 and 7: real and imaginary parts of impedance for element 64 with the coaxial cable.

Another important measurement is the cross-coupling between adjacent elements that was performed on the final probe. The reported cross-talk (fig.8) was measured between two adjacent elements (elt n°31 and 32) and achieved performance (average on the whole bandwidth is 35.3dB) shows promising results for the electronic beam forming.

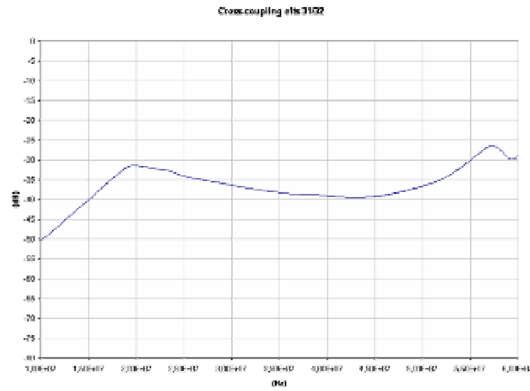


Fig. 8: Cross-talk measurement between elts 31 and 32

V. Conclusion

A high frequency 128 elements array was manufactured with advanced manufacturing processes for the 1-3 piezocomposite configuration. Characterization of the complete probe was conducted, from pulse-echo to electrical characteristics. Further work will include image evaluation on different applications to confirm the design. The performances of this high frequency probe shall likely extend the range of applications to endo and intracavity imaging.

References

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