Focused 20 MHz single-crystal piezocomposite ultrasound array

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Abstract— **Lead-based piezoelectric single crystals such as PZN-PT and PMN-PT have been first developed for under water applications by the U.S. Navy. Their outstanding piezoelectric properties (d33 as high as 2000pC/N and k33 > 90%) make them valuable for high-end ultrasound transducers. Thus, they have been successfully used and commercialized in medical field mainly for cardiac imaging (2-5MHz) but manufacturing such a probe is critical since single crystal structures are more sensitive to thermal and mechanical stresses induced by standard micromachining process.**

We propose in this paper to manufacture a high frequency ultrasound probe (15-20MHz) based on very thin 1-3 single crystal composite materials (<70µm thick) using low-stressing machining process and exhibiting improved electroacoustical performances. This paper presents the acoustical design, fabrication and evaluation of an ultrasound array based on single crystal piezocomposite. The array specifications were a 3mm elevation, 100µm pitch, 20MHz center frequency.

We demonstrate the feasibility to produce a PMN-PT single crystal probe with suitable performances for high resolution imaging. A complete electro-acoustical characterization has been done: bandwidth, directivity and pressure performances are then discussed and compared to classical PZT probes with the same specifications. Performances are compared to those obtained with state-of-the-art piezocomposite transducers, achieving competitive bandwidth and an improvement of +6dB in sensitivity.

I. INTRODUCTION

High frequency ultrasound probes are nowadays being developed for dermatologic [1], ophthalmologic and small animals applications. Single element transducers mechanically driven are already used but recently multi elements arrays have been commercialized specially for small animal imaging. Development of multielement probes will improve image quality.

Achieving improved image resolution and penetration depth requires the development of transducers with enhanced bandwidth and sensitivity. Due to its high coupling coefficient and high permittivity single crystal is the perfect active material to meet these requirements for arrays with small element size.

Up to now, different type of active materials were used to manufacture high frequency probes (>20 MHz) : ceramic based piezocomposites ([2], [3]), PVDF, sol-gel deposition ([4]),cMUTs... For single crystals, new techniques coming from semiconductor industry were used to develop PC-MUT 1-3 composites [5].

We propose to focus on the design of a 20 MHz probe of 100µm pitch, 3 mm elevation with 1-3 single crystal PMN-PT composite using fabrication methods based on the dice and fill technique. Main issue is the mechanical aspect of this material which is very difficult to process. It is well reported that it is very breakable during dicing and lapping. It can also be very easily depolarized during probe manufacturing because of its low morphotropic phase boundary (MPB) temperature with regards to PZT ceramic. One can imagine that it is even more difficult for high frequency applications because of reduced size of elements and thickness.

In order to improve image resolution we chose to give a geometric focalization by a radius of curvature of 15mm. The first part of the article will be devoted to description of single crystal properties. Then we will present the manufacturing process of the composite and transducer and related challenges. The characterization of the complete probe will follow. Results will be compared to those obtained with piezoelectric ceramic based composite.

II. SINGLE CRYSTAL PROPERTIES

PMN-PT and PZN-PT single crystals were first developed for naval applications for their high saturation strains, low losses and piezoelectric factors greater than 0.90 [6]. Reduced size and properties inhomogeneities from crystal to crystal associated with high costs limited first the large use of single crystal into ultrasound transducers for medical imaging.

Recently advances in crystal growth and homogeneity have been reported [7]. Indeed there was an important variation of piezoelectric properties between production batches. In 2002, Michau [8] evaluated variations of ε_{33}^T and k_T for 5 pieces of the same crystal grower at 30%. We performed the same study on current batch of 30 pieces and found properties variations of less than 10% which is a more acceptable tolerance for transducer manufacturing. Moreover the size of PMN-PT and PZN-PT plates is getting even bigger so we can currently produce multielement probes.

Single crystal exhibits high coupling coefficient (see Tab 1) which improves penetration depth and signal to noise ratio compared to classical PZT based transducer. Its high dielectric permittivity enables to design probes with smaller element pitch and so considerably enhance the image contrast.

Unfortunately single crystal shows a temperature limitation related to a low morphotropic phase boundary (MPB) temperature that could lead to the depolarization of the crystal during probe manufacturing process if heating during the process.

PMN-PT material also has a low frequency constant. This implies that it has to be thinner than PZT ceramic for a same frequency. Moreover as it is not a polycristalline material it is even more breakable especially during manufacturing process where thickness is reduced to less than 100 µm. But its monocrystalline property provides the advantage in the high resolution domain where PZT ceramic begins to be limited by grain size and porosity. These features are in the same range as transducer's elements size and active layer thickness.

Using bulk single crystal for this configuration would lead to undesirable radiated modes. Therefore we chose to manufacture transducer based on 1-3 single crystal piezocomposite structure fabricated from same techniques as those used with PZT ceramics. This implies of course more stress induced to the crystal due to dicing and a smaller thickness due to the decrease of the celerity in a composite.

Specific process provisions should be taken to overcome these challenges and to produce a high resolution probe.

Materials	PZT5H Ceramic	PMN-PT 30-32%
Orientation	Multi-grain	<001>
K_3^T	3400	5500-7500
Z (Mrayls)	30	28
Tanδ	0.02	0.015
T_{DP} (°C)	195°C	70-95°C
k_{33}	0.72	0.91-0.94
d_{33} (pC/N)	650	1500-2600
N_T (Hz.m)	1900	1600

Tab 1 : Material properties of PMN-PT compared to PZT5H [9]

III. DESIGN CHALLENGES AND TRANSDUCER MANUFACTURING

First challenge in the design of the 20 MHz 1-3 piezocomposite is the lateral mode resonance. This is a frequency limitation determined by the shear wave velocity of the filler material, the kerf width and the microstructure dimensions. For a 20 MHz composite made with an epoxy resin kerf width has to be less than 10µm inducing the first lateral mode frequency at 39 MHz.

Specific nature of the single crystal requires the use of specific dicing tools and adapted dicing speeds.

Because of its low celerity PMN-PT 1-3 composite has to be thinner than PZT 1-3 composite. For 20 MHz targeted active material thickness is around 60µm. No breakage was observed and the thickness target was obtained. Kerf measured after lapping meets requirements (Figure 1).

Gold electrodes are sputtered then transducer assembly steps are realized:

- Polarization of the sample.
- Backing and matching layers assembly. Considering single crystal thickness and frequency range specifics matching layers were developed, processed in thin thickness and tightly controlled.
- Mechanical deformation of the active and passive layers.
- Flexible printed circuits soldering

Those process steps are totally compatible with our standard probe manufacturing process.

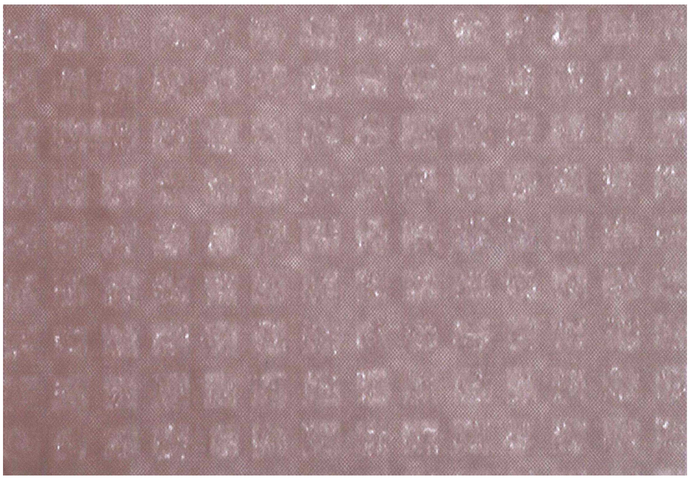

Figure 1 : Photographs of PMN-PT 1-3 composite after lapping

Poling experiment:

As said earlier polarization issues are very important in the single crystal behaviour. A poling study was conducted to evaluate performances evolution when using different polarization voltage. Tests were done on single crystal probe elements: different polarization cycles were applied to a zone of elements of the probe and low frequency capacitances of each zone were measured. In our case, low frequency capacitances reflect sensitivity values of the final probe.

We first increased voltage from 30V to 50V to 100V considering active layer thickness. Capacitance values before and after polarization were compared. Then we decided to increase voltage to 150V, 200V and 250V. We obtained a maximum of capacitance gain at 150V (Figure 2). Above this voltage, capacitance value decreased due to overpoling phenomena.

We used this electrical field value for the entire study.

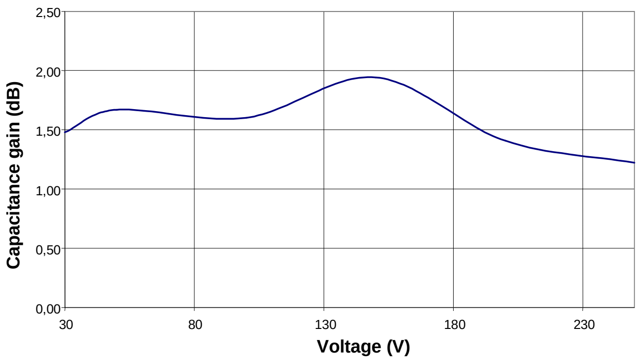

Figure 2 : Capacitance gain on a single crystal aperture when increasing polarization voltage

IV. CHARACTERIZATION

A complete set of measurement were performed on the final transducer.

Electro-acoustical measurements

A measurement of the pulse echo response on a flat stainless steel target in water was done using the Panametrics 5900 pulser-receiver with 20dB total gain, energy setting 4µJ and no frequencies filter. The plane target was set at the focal distance of 15mm. The probe was connected using a 2m coaxial cable (50pF/m).

Typical measured pulse and spectrum responses are reported in Figure 3 and Figure 4.

Corresponding values are as follows:

Center frequency (@-6dB): Fc = 18.1 MHz;

Sensitivity = 1,3V ;

LCF (@-6dB) = 12.3 MHz; HCF (@-6dB) = 24 MHz;

Bandwidth (@-6dB) = 65%.

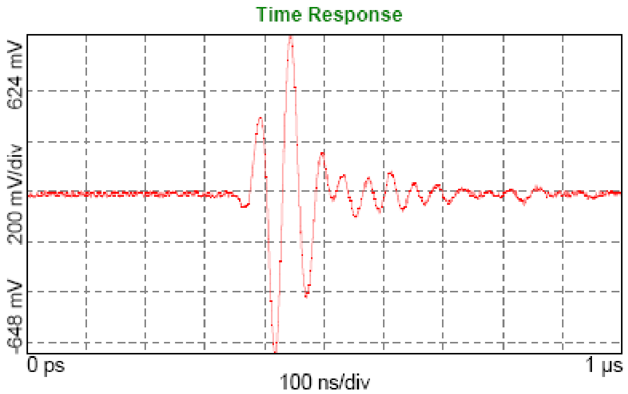

Figure 3 : Typical time response for the final transducer measured at the focal distance

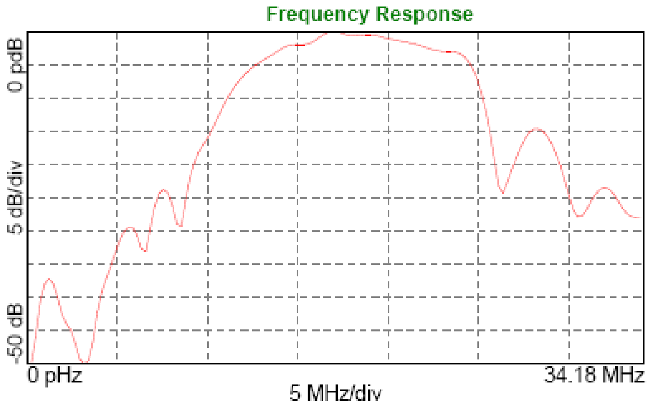

Figure 4 : Typical frequency response for the final transducer measured at the focal distance

Performances were compared to those obtained with a probe manufactured with a PZT ceramic 1-3 piezocomposite. Bandwidth values are very close but main benefit is sensitivity which is more than 6dB in crystal's favour.

Measurements were also realized after 24 h and 48h aging. No performances loss was observed which means that the crystal phase was not damaged by fabrication process and poling.

Elementary directivity diagram

A measurement of directivity diagram was also performed in water using a 3 mm diameter rod at a distance of 30 mm in two ways. Results are presented in Figure 5.

The experimental aperture angle is 34.3° (at –6dB) which is totally comparable to the aperture angle of the PZT composite probe. The theoretical value for one element is 43°.

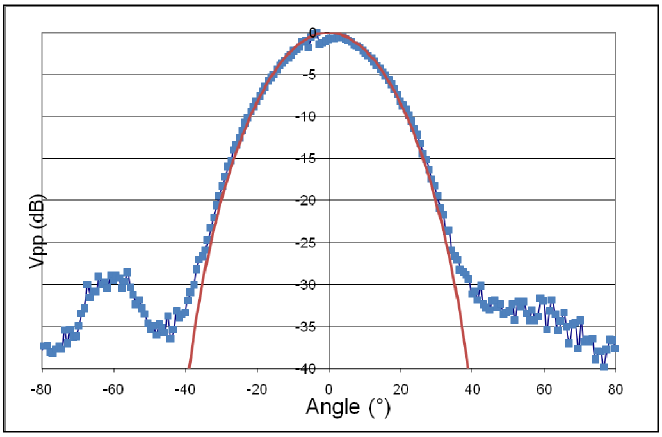

Figure 5 : Directivity diagram response : measured values (dash) and fitted values (solid).

Pressure measurement

In this experiment, one element of the array is excited through an arbitrary waveform generator (Vpp = 10 V, F = 18 Mhz). The excitation is not continuous, but consists of small sinusoidal pulses (12 cycles) to limit heating.

A hydrophone (Precision Acoustic Ltd ®) is mounted on a two axis motorized support to scan a portion of the plane 44 mm from the array (beyond the far field limit). A 28x12 mm rectangle is swept (<0.5 mm step).

The recorded signal is treated to extract only the steady state information, overpassing the transitory phase. Using the vendor's hydrophone (and booster amplifier) calibration data, the peak-peak voltage is converted into acoustic pressure values, giving a 2D map of peak harmonic pressure field value (Figure 6). At focal distance (15 mm) and normally to the element, a peak pressure value of 230 kPa is recording, corresponding to a acoustic power flux of 444 mW/cm². The total energy emitted by the transducer (integrated over the scanned area) is 3.3 mW.

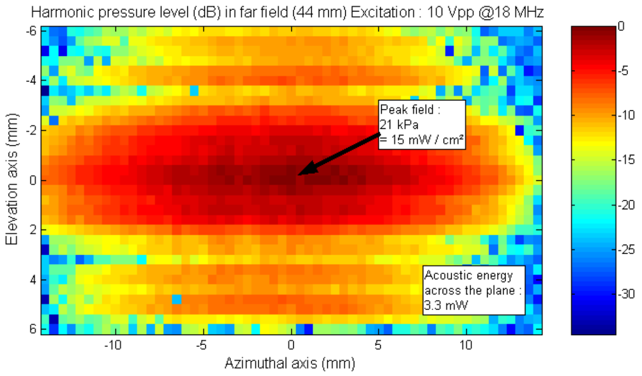

Figure 6 : Harmonic pressure level in far field (44mm)

V. CONCLUSION

This article demonstrates the feasibility of a 20MHz ultrasound array based on 1-3 single crystal piezocomposite. Specific process provisions using a dice and fill technique for piezocomposite manufacture allow us to overcome the main manufacture challenges (small thickness and mechanical and temperature behavior of the crystals).

We have achieved array transducers with high performances: bandwidth comparable to standard PZT based piezocomposite and improved sensitivity (+6dB). Considering the process used the realization of a 128 elements or higher element count probe will give same results all along the transducer.

Next steps will require the image evaluation of this ultrasound array and its comparison with standard probe to assess the final interest of including piezoelectric single crystal into high frequency ultrasound transducers.

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