40 MHz piezo-composite linear array for medical imaging and integration in a high resolution system

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Abstract—**Evolution of high resolution ultrasonic imaging is widely dependent on the development of efficient high frequency piezoelectric transducers. Nowadays, efforts are focused on the fabrication of linear arrays in the 40-50 MHz frequency range for dermatology, ophthalmology and small animals imaging. At these frequencies, technological aspects are predominant at several stages of the array fabrication due to typical dimensions of the constitutive elements (few tens of micrometers). Moreover, the development of the imaging system and associated beamforming specifically adapted is of primary interest to optimize the use of the corresponding array and consequently image quality.**

A new fully operational 40 MHz 128 elements 2mm elevation linear array was manufactured using micromachined 1-3 piezocomposite: fabrication rules of low frequency probes were extended and adapted to the design of this high frequency probe. Matching layers, backing and interconnect method are used to finalize the internal structure of the array.

A complete set of measurements show that a center frequency at 40 MHz is delivered with a relative bandwidth over 70%. All the 128 elements of the probe are active and very good sensitivity homogeneity along the probe is measured. Crosstalk between adjacent elements is also evaluated and the corresponding value is around -37 dB.

A specific high resolution real-time ultrasonic imaging platform, called ECODERM developed by the INSERM Imagerie et Cerveau laboratory, with 128 channels using impulse electrical excitation and 100 MHz bandwidth in reception is used to perform human skin images.

The very good performance of the new HF40 MHz linear array coupled with the developed imaging system result in high resolution images of the skin.

Keywords : Micromachining 1-3 piezocomposite, linear array, high resolution real-time ultrasound scanning system, skin images

I. INTRODUCTION

For a few years high frequency transducers are required for different kind of applications such as dermatology, ophthalmology and small animal imaging. Several adapted ultrasound systems are commercialized. Most of them are using single element mechanically driven from 20 to 50 MHz. The major drawback of this type of transducers is the fixed focus which is geometrically performed and which limits the depth-of-field. The mechanical scanning is also a limitation for the imaging frame rate.

Multielement probes were developed to allow electronic focus and to enhance image resolution. The only high resolution imaging system with multielement transducers commercially available was developed by VisualSonics (Toronto).

Fabrication of high resolution probe remains difficult because of technological aspects such as small dimensions of the array elements, very thin layers for active and passive parts and microinterconnection.

A specific real-time imaging system also has to be developed to optimize the use of the probe in this range of frequencies.

This paper will present works performed to manufacture a 128 elements 40MHz 2mm elevation aperture probe and the real-time imaging system necessary to monitor it and to generate skin imaging.

First part will focus on the description of the design and the characterization of the array. Second part will describe the architecture of the high resolution system. Finally this paper will end up with the evaluation of high frequency skin images.

II. ARRAY DESIGN AND CHARACTERIZATION

A. Array specifications

Many research teams all over the world have worked on the development of arrays in high frequency field. This is very challenging since every element has to be miniaturized as compared to standard probe. For example matching layers thickness at 40 MHz can range from 10µm to 20µm and microconnections with element pitch less than 50µm. But most of all, the active material is the key point to design multielement high resolution array because it is very thin (less than 40µm) and very fragile.

R&D efforts were made on different kind of innovative techniques such as thin film deposition [1], deep-reactive-ion-etching to develop PC-MUT [2], laser micromachining [3],

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interdigitally bonded piezocomposite [4], photolithography to separate array elements [5].
In this paper the choice was made to enhance 1-3 micromachined piezocomposite to adapt it to high frequency applications.

The 40 MHz array specification was defined in agreement with the imaging system: a 128 element probe, a 2mm elevation and a pitch of 50µm. For skin images to visualize dermis structure the exploration depth is 6mm. A bandwidth of more than 70% is required to have a good pulse length @-20dB and be able to distinguish skin fine structures.

B. 1-3 piezocomposite

A specific 1-3 piezocomposite was designed to vibrate at 40 MHz in water or human body, which means that because of attenuation in front materials like matching layers and in water composite resonance frequency in air has to be around 60 MHz. This observation tends to reduce even more the active material thickness which has to be around 30µm and makes it very fragile.

But main issue of piezocomposite at this frequency is lateral modes that are very difficult to minimize [6]. It is needed to perform very small resin kerfs: for a 40 MHz 1-3 piezocomposite, kerf width has to be no more than 8µm.
Resin choice is also important to put lateral modes outside the composite operating frequencies: a hard resin with high velocities is needed.
For ceramic plots design, a trade-off has to be found between a high ceramic volume fraction and lateral modes position that can be influenced by the plots width.
As composite thickness is quite low and ceramic plots are narrow, during dicing damages on the ceramic often happen and cracks between ceramic grains can occur. Low grain size ceramics are more desirable for high frequency applications as grain size shall be almost 10 times smaller than ceramic plots in composite.
A high permittivity ceramic is also needed to match the electrical impedance between transducer and ultrasound system.
Based on all these considerations and by taking specific provisions on the manufacturing process, the 1-3 piezocomposite was fabricated through dice-and-fill with a volume fraction of 58%, a dicing width of less than 8µm and final thickness of 25µm.

Electrical, acoustical and electromechanical parameters of the thickness mode were extracted using a method based on measurement of the complex electrical impedance according to frequency Ze(f) around the fundamental thickness-mode resonance. The experimental set-up was composed of an HP4395 spectrum analyzer with its impedance test kit and specific spring clip fixture. An equivalent electrical circuit scheme was used (KLM model [7]) for the corresponding modeling. Figure 1 shows the experimental and theoretical impedance obtained by a fit process to deduce the effective thickness coupling factor, the dielectric constant (at constant strain), longitudinal wave velocities and losses. Measurements were realized on a 1-3 piezocomposite surface of 2x6mm² before elements singularization.
It can be seen that the resonance frequency in air in over 60MHz. The thickness coupling factor deduced is 0.45 and dielectric constant ε_{33}^{S} is 105.

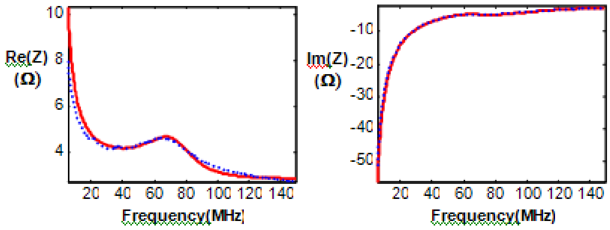

Figure 1 : complex electrical impedance of 1-3 piezocomposite measured in air (dotted line : experimental; solid line : theoretical)

C. Probe manufacturing

Before connecting the head of the probe to coaxial cable a measurement of the capacitance of each element of the array was performed (see Figure 4). This measurement shows that elements of the array are very homogeneous as the capacitance difference between them is +/- 1.2 dB which is very good for such a high frequency composite. It shows that the manufacturing process is controlled and well defined for this type of array.

A new formulation of the matching layer was achieved with very small grain size powder to avoid grain size to be in the range of the acoustical wavelength.
The manufacturing process at low frequency was extended and adapted to those very small and fragile materials.
The head probe was then connected to a 80 ohms coaxial cable (Figure 2).

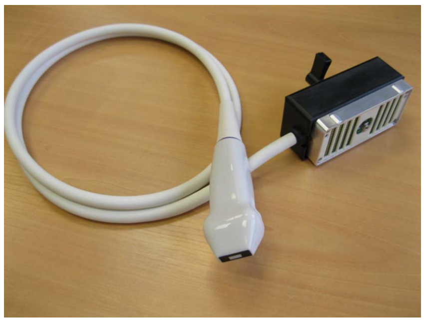

Figure 2 : Photography of the complete 128 elements array

D. Electro-acoustical characterization

The electro-acoustical properties characterization of the complete array was performed. A Panametrics 5073R high frequency pulser/receiver was used to excite each element with 20dB gain on receive. The probe was placed in a water tank in front of a flat stainless steel at the distance of 4mm. Typical measured pulse and spectrum responses (Figure 3) are reported below.

Measured values for element 64:

Fc=38 MHz	LCF@-6dB=21.5 MHz
BW@-6dB=87%	HCF@-6dB=54.4MHz
Pulse duration@-20dB = 86ns	

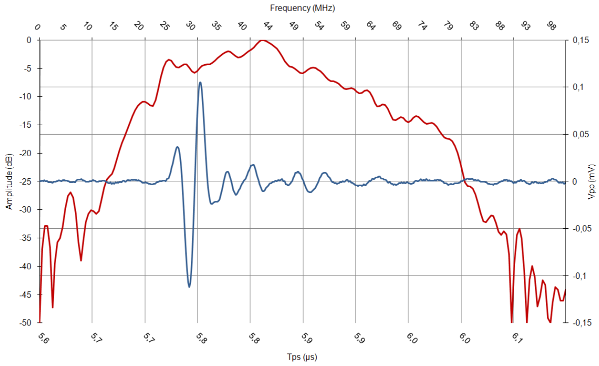

Figure 3 : Typical measured time and frequency responses for the final transducer

The large bandwidth allows a large frequency operating range from 21MHz to 54 MHz.

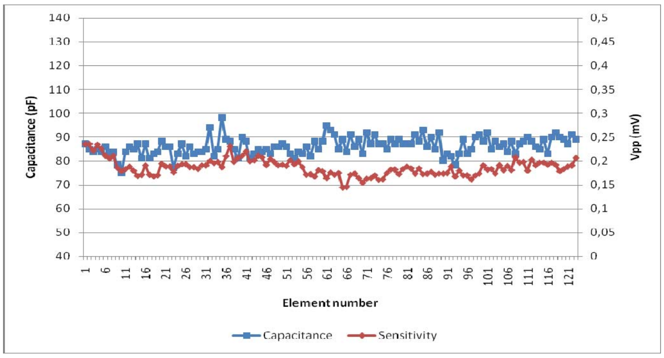

Figure 4 : Capacitance and sensitivity homogeneity between elements

A complete characterization of the transducer was performed in conditions described before. All 128 elements of the probe are active and the sensitivity homogeneity between elements is very good for such frequency: +/- 2,1 dB (Figure 4). It shows that the manufacturing impact is quite low comparing capacitance homogeneity of the array and sensitivity homogeneity of the complete probe.

E. Beam

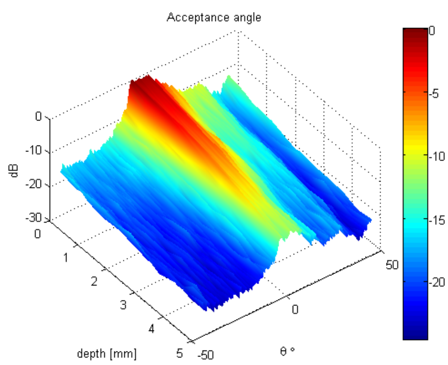

Figure 5 : Representation of beam measurement

A measurement of directivity diagram was also performed in water using a 200µm diameter wire at different depths from 1mm to 5mm in two ways. The array was excited with the Panametrics 5073R high frequency pulser/receiver with 30dB gain on receive. Results are presented in Figure 5.
The experimental aperture angle is around 20° (at –6dB) at the distance of 1mm.

F. Crosstalk

Cross-coupling measurement between adjacent elements (elts 63-64) was done with a network analyzer 4294 on the final probe (Figure 6). The average value of cross-talk on the whole transducer bandwidth is -37dB which is in agreement with the experimental acceptance angle value and will be a real benefit for electronic beam forming.

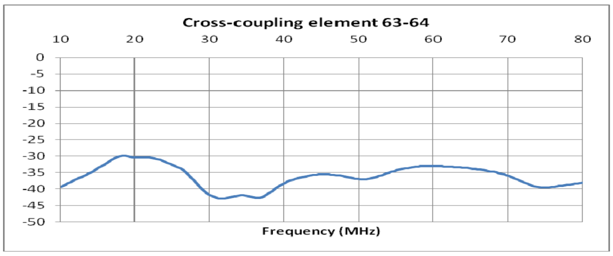

Figure 6 : Cross-talk measurement between elts 63-64

III. HIGH RESOLUTION SYSTEM

A. Architecture

The multi-channel ultrasound scanning real time system, called *ECODERM* and developed by the INSERM Imagerie et Cerveau laboratory, consists of three distinct units: the analogical transmitter /receiver unit, the sampling - beamforming unit and the sync-master unit.
The analogical transmitter-receiver unit is composed of 128 channels (Figure 7a), the connection to the transducer is through a 128 wire coaxial cable (Figure 7b).

Figure 7 : The analogical transmitter-receiver unit and high-resolution ultrasound scanning real time system

The 128 transmitters have individually programmable time delays from 0.5 to 125.5 ns with a step of 0.5 ns. These transmitters can emit a unipolar pulse with amplitude of -100

V and duration of 10 ns, with a bandwidth equal to 150 MHz at -6 dB. The 128 receivers have an individual pre-amplifier with adjustable gain varying from 30 to 75 dB and a bandwidth equal to 120 MHz at -3 dB.

The sampling - beamforming unit is able to sample and process simultaneously 16 analog signals selected through a multiplexer. Each of the input signals is sampled at 200 MHz and 12 bits. The data are then processed in 4 FPGAs (Virtex 6) in order to perform focalization and summation of the sampled signals. The image data are transmitted over a PCI Express bus to a PC processing unit which controls displaying and memorization.

The sync-master unit controls the central timing of the scanning process. Photography of the high-resolution ultrasound scanning real time system is shown on Figure 7c).

B. Beamforming

Imaging with the 40 MHz probe is performed through linear scanning with 15 elements transmission aperture and 32 elements in reception. On transmit, the focal length is fixed to 3 mm. Delaying and summing echo samples from receive channels dynamically allows us to focus received echo signals at every depth. In this configuration, the frame-rate of the scanner is equal to 40 Hz.

C. Skin images

Ecoderm scanner is authorized by French Competent Authority (AFSSAPS) to be used in a clinical trial.

First in vivo images have been performed on human skin.

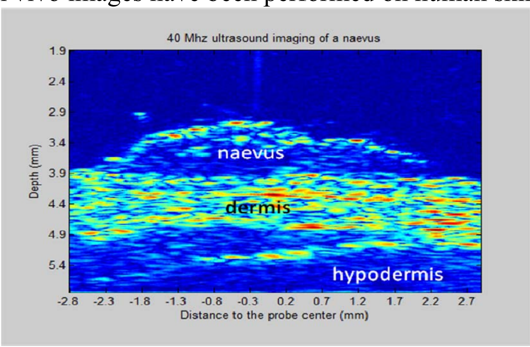

Figure 8 : Ultrasound image of a naevus performed with the 40MHz probe and the ECODERM system

In Figure 8 we show an image of the human skin with a naevus (benign tumor). The image is 4 mm in depth and 5.5 mm in width. The naevus has a thickness of approximately 1 mm, as the dermis, and a width of 4 mm. The limits of the naevus are clearly visible. Below the dermis, the hypodermis is weakly echogeneous.

IV. CONCLUSION

Thanks to appropriate techniques applied to fine thickness materials, a micromachined 1-3 piezocomposite resonating at 60MHz in air was successfully fabricated. A 40 MHz 128 elements linear array was manufactured adapting fabrication process used for standard low frequency probes. A high-resolution ultrasound real time scanner was developed to drive this specific transducer and skin images were obtained that show fine structures of dermis in dermatological field.

In future works, comparative imaging between single element mechanically driven and the new high resolution multi-element scanner *ECODERM* will be done. Further evaluation and studies in beam forming will also be performed to increase the image quality and demonstrate clinical benefits compared to lower frequency ultrasonic imaging and other diagnostic techniques.

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