Lead-free high-frequency linear-array transducer (30 MHz) for *in vivo* skin imaging

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Abstract— **This work presents the fabrication of a 30 MHz, linear-array transducer based on a KN, 1-3 piezocomposite. Performances of the transducer were characterized and compared to a PZT-based linear array with similar structure. The composites were designed to minimize lateral modes of vibration which can severely degrade imaging performances. Fabrication steps were optimized to achieve a 40 MHz resonant frequency in air with a composite thickness of 69 microns. The measured thickness coupling factor was around 50 %. A 128-element, linear array was then fabricated with 100 µm pitch and 1,5 mm elevation aperture. The structure of the transducer (backing, matching layers, and electric components) was optimized to deliver good fractional bandwidth and sensitivity. The final probe was integrated in a prototype, real-time, 128-channel scanner to acquire high-resolution images of the human skin *in vivo*.**

Results showed that, compared to PZT ceramics, KN single crystals provide low density and high acoustic velocity, both highly desirable for the manufacturing of HF transducers. The central frequency of the linear-array transducer was 30 MHz despite the KN composite being 20% thicker than equivalent PZT-based composites and the relative bandwidth was about 50%. High-resolution images of the human skin were acquired. A large ultrasound penetration due to good signal sensitivity was obtained and detailed features could be visualized.

Keywords: lead-free, 1-3 piezocomposite, linear array, high frequency, in-vivo skin imaging

I. INTRODUCTION

Over the last decades, lead zirconate titanate (Pb(Zr, Ti)O_3, PZT) based ceramics and single crystals (PMN-PT) have been extensively used to manufacture high-frequency (HF, > 20MHz) ultrasound transducers for medical imaging as they have high piezoelectric coefficients and high dielectric permittivity.

Due to health and environmental concerns, the European legislation recently adopted the RoHS (Restriction of the use of certain Hazardous Substances in electrical and electronic equipment) directive that requires lead-based components to be substituted by safer materials in most electrical devices.

Even though medical devices are exempted from this legislation for the moment, it is necessary to look for new, safer piezoelectric components. For the past ten years, a lot of effort has been put into the development of lead-free piezoelectric materials that provide high performances and are suitable for industrial manufacturing [1]. Shrout et al. [2] classified lead-free materials in three groups: BaTiO3, (Na,Bi)Ti-BaTiO3-(K,Bi)TiO3 (BNBK), and (K,Na)NbO3 (KNN) and several lead-free materials (ceramic and single crystal) were already tested for high-frequency transducer applications [3-5] and compared with lead-based transducers [6]. In 2012, Zhou et *al.* [7] fabricated a 1-3 lead-free piezocomposite (NBT-BT/epoxy) for single transducer and linear array in the frequency range 3-5 MHz.

Potassium niobate (KN) single crystal (KNN group) was identified as a good alternative to PZT because of its high thickness coupling coefficient [8] Nakamura et al. [9-10] showed that a piezoelectric coupling coefficient of up to 69% can be achieved for specifics cuts and orientations of the KN crystal. Other interesting properties of KN are its relatively low mechanical impedance compared to PZT, for better impedance matching to tissues, and a high phase transition temperature (225°C) suitable for industrial processing and imaging applications.

One drawback of single crystals is that they are usually more brittle than lead-based ceramics, which makes conventional processing such as dicing and lapping more difficult. In previous work [11] we demonstrated the feasibility of a 20 MHz, linear-array probe based on a single-crystal (PMN-PT), 1-3 piezocomposite.

Here, a 30 MHz, 128-element probe was manufactured using a KN, 1-3 piezocomposite. The composite and the final probe were characterized, and in-vivo images of the human skin were acquired using a real-time, high-resolution imaging system developed at Tours University [12] .

II. ARRAY DESIGN AND CHARACTERIZATION

A. KN piezocomposite

Large polydomain plates, cut at 45° from an as-grown, [001]c-oriented KN crystal, were used to fabricate a 1-3 piezo-composite with fine structure. The composite was designed to minimize lateral modes of vibration which can severely degrade imaging performances. Previously, spatial homogeneity (of initial plate sample) of the electromechanical properties and as a function of the frequency was measured [13].

Dicing conditions had to be finely tuned because the KN material has a higher Young's modulus than conventional lead-based single crystals, and it breaks more easily. However, the superior hardness of KN is an advantage when it comes to high frequencies due to the higher sound velocity in the crystal, allowing for high resonant frequencies to be achieved with relatively thick KN plates. The 1-3 piezocomposite had a kerf of about 10µm, a volume fraction of 64%, and a 69 µm thickness (Fig. 1).

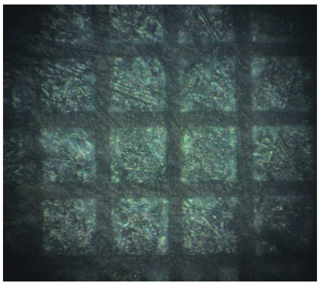

Fig. 1 : Photograph of the KN single crystal 1-3 piezocomposite

The piezocomposite plate was machined to fabricate a linear array made of 128 elements. The complex electrical impedance of each element was measured using a HP4395 spectrum analyzer with its impedance test kit and specific spring-clip fixture. An equivalent electrical circuit scheme was used (KLM model [14]) to model the electrical behavior of the piezocomposite elements around their thickness-mode resonant frequency, and deduce their electrical, acoustic and electromechanical properties. Fig. 2 : shows the experimental impedance curve and the numerical fit used to determine the effective thickness coupling factor, the dielectric constant (at constant strain), the longitudinal wave velocity, and the electrical and mechanical losses. The resonant frequency in air was around 36MHz and the thickness coupling factor was 0.47. A low relative dielectric constant of 14 was obtained, which is likely due to a degradation of the crystal integrity during the dicing and lapping processes.

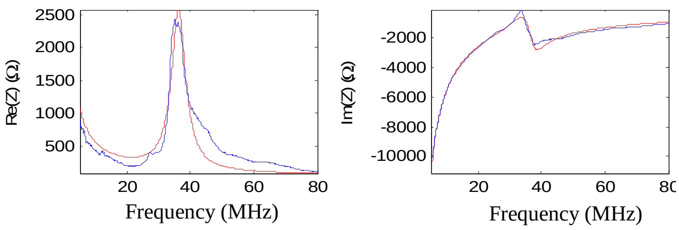

Fig. 2 : complex electrical impedance of 1-3 piezocomposite measured in air (blue line : experimental; redline : theoretical)

B. 30 MHz, 128-element, lead-free probe

A 128-element probe was manufactured using the KN-based 1-3 piezocomposite and the same processing steps than described in [15] The tip of the probe was sealed by an acoustic lens providing an elevation focusing of 8 mm.

Specifications of the transducer:

Center frequency: 30MHz

Type of array: linear **Number of elements**: 128

Pitch: 100µm

Elevation: 1.5 mm

This acoustic head was integrated into housing and interconnected to a coaxial cable. This cable had 80 Ohms impedance and its length was 2 m (Fig. 3). A connector was mounted on the cable for interconnecting with the imaging system [12] The 128 elements were functional.

Fig. 3 : Photograph of the complete 128 elements array

1. Electro-acoustic characterization

The electro-acoustical properties of the complete array were characterized. A Panametrics 5073R pulser/receiver was used to excite each element using 50Ω settings with 20dB total gain on receive. Pulse-echo measurements were performed in water using a stainless steel, planar reflector positioned 4 mm away from the probe. The measured pulse-echo and corresponding spectrum of one element is shown in Fig. 4.

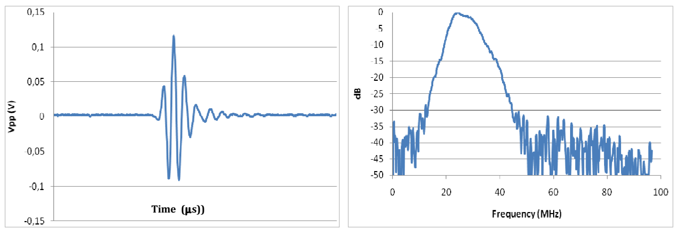

Fig. 4 : Typical measured time and frequency responses of one element of the final transducer.

The characteristics deduced from the electro-acoustic response of one representative element (element 64) are summarized below:

F_c=27 MHz	LCF@-6dB=20.3 MHz
BW@-6dB=48.5%	HCF@-6dB=32.3MHz
Pulse length@-20dB = 143 ns	

F_c: center frequency; BW@-6dB: fractional bandwidth at -6dB; LCF:lower frequency; HCF: higher frequency at -6dB

Considering those measurements, it was estimated that the signal sensitivity was more than sufficient at 30 MHz to obtain a good penetration on in-vivo images.

2. *Impedance measurement*

Electrical impedance of the final transducer without the cable was measured using an Agilent E5100A impedance analyzer. Fig. 5 shows the real and imaginary parts of the impedance for element 64. Measured values at 30MHz (R+jX with R=144 Ohms and X=-460 Ohms) were less favorable than those of a PZT-based probe previously reported in [15]. This result is a direct consequence of the low permittivity of the KN, 1-3 piezocomposite.

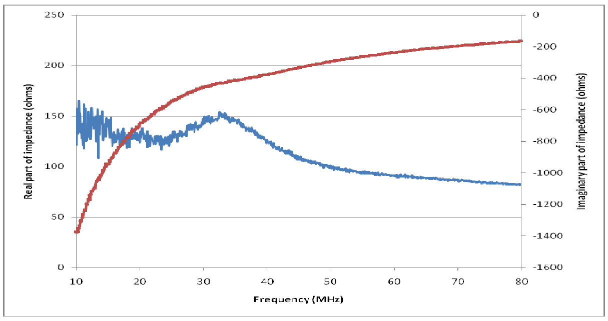

Fig. 5 : Real and imaginary parts of electrical impedance for element 64

3. *Acoustical field measurement*

A measurement of the acoustic field was performed in water using a 240 µm-diameter steel wire mounted on 2-axes, motorized stage. A representative element was excited using a 5900 Panametrics pulser-receiver with 40dB gain in receive. Results are presented in Fig. 6 and confirm that good sensitivity was achieved over a large depth-of-field.

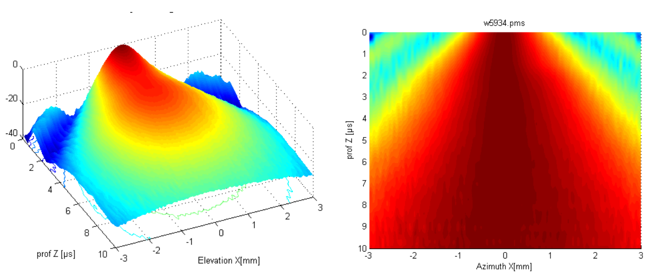

Fig. 6 : Radiation pattern with an excited representative element

III. IN-VIVO SKIN IMAGING

A custom, multi-channel, real-time, imaging system (ECODERM [12]) was used to perform *in-vivo*, high-frequency imaging of the human skin. Linear scanning was performed using 15 elements in transmit and 32 in receive. A fixed focus at 8 mm was used in transmit. A frame-rate of 40 Hz was achieved with this configuration. A 20 MHz PZT-based probe was also used for comparison. The 20 MHz probe had identical element count, pitch and kerf, and the same beamforming configuration was used.

Fig.7 shows images of a human forearm skin performed successively with the two probes. First, one can see that image resolution of the PZT probe was lower than that of the lead-free probe, which is mainly due to its lower central frequency. The higher resolution of the 30 MHz probe allowed for clearly distinguishing the inner wall of the artery. A large depth-of field of over 6 mm could be obtained with the 30 MHz probe.

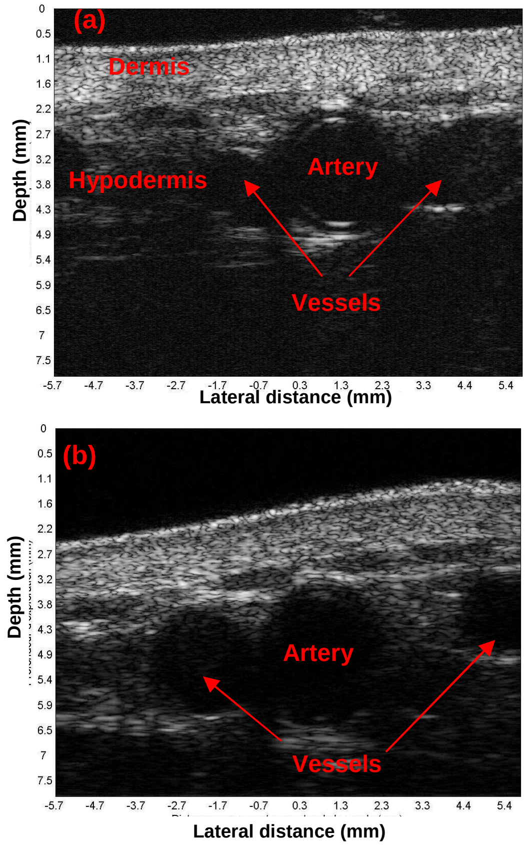

Fig. 7 : Ultrasound image of a human forearm skin performed with (a) 30 MHz lead-free probe and (b) 20 MHz PZT probe

In Fig.8, comparative images of a human skin with a naevus (benign tumor) are shown. The limits of the naevus were clearly defined in both images. Skin structures under the naevus, around 3 mm from the probe, were better defined with the 30 MHz lead-free probe. The high sensitivity, spatial resolution and depth-of-field observed in these in-vivo images confirm the high potential of this new generation of lead-free probes.

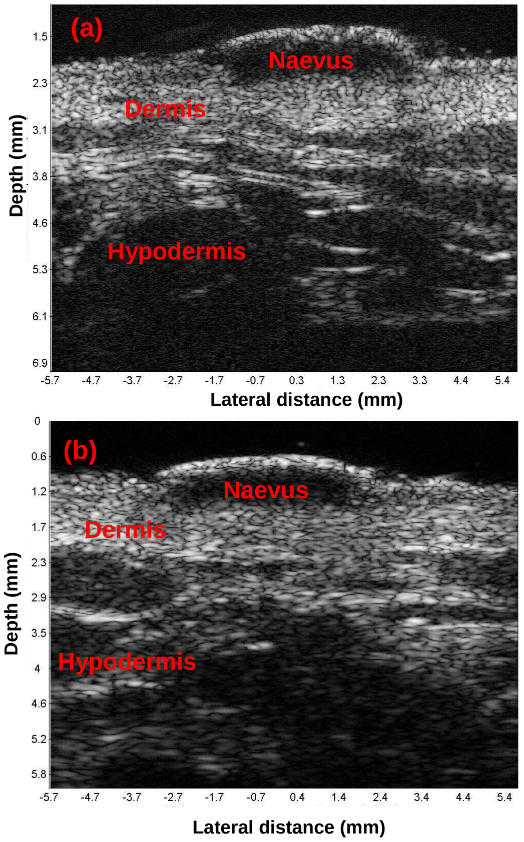

Fig. 8 : Ultrasound image of a naevus (human forearm) performed with (a) 30 MHz lead-free probe and (b) 20 MHz PZT-based probe

IV. CONCLUSION

Lead-free based ultrasound probes are a real challenge for the future to respond to environmental and health concerns. We have shown that KN crystal can be a strong candidate to replace lead-based transducers in high-frequency applications.

The fabrication of a 30 MHz, linear-array transducer based on a KN, 1-3 piezocomposite has been demonstrated and the performances of the final probe were comparable to those of PZT-based array. In-vivo images of human forearm skin were acquired and showed that high resolution and large penetration depth could be achieved.

These promising results should lead to a new generation of “green” transducers that can compete with current state-of-the-art devices.

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