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PIN-PMN-PT Single Crystal High Frequency Ultrasound Transducers for Medical Applications

Q. F. Zhou,[1] B. P. Zhu,[1] D. W. Wu,[1] C. H. Hu,[1] J. M. Cannata,[1] J. Tian,[2] P. D. Han[2] and K. K. Shung[1]

[1]NIH Resource on Medical Ultrasonic Transducer Technology, Department of Biomedical Engineering, University of Southern California, Los Angeles, CA 90089

[2] H. C. Materials Corp., 479 Quadrangle Dr., Suite E, Bolingbrook, Illinois 60440, USA

Abstract: High frequency ultrasonic transducers were fabricated using lead indium niobate-lead magnesium niobate-lead titanate (0.24PIN-0.44PMN-0.32PT) as the active piezoelectric material. The measured center frequency and bandwidth of the device were 35 MHz and 48 % respectively. The electrical impedance magnitude was 71 Ω and phase was - 38°. Insertion loss was measured to be 15 dB. A phantom which consists of 20-μm tungsten wires was imaged to assess spatial resolution of the transducer.

I. INTRODUCTION

Medical imaging transducers usually utilize a piezoelectric material as the active element to transform the electric input into a mechanical wave propagating into the imaging target and transform the echo back into electric output signal. Recently, superior piezoelectric properties have been discovered for relaxor-based PZN-PT and PMN-PT single crystals (d_{33}=2000-3000 pC/N, k_{33}=85-95%). Currently, PMN-PT single crystals have been commercialized in advanced medical ultrasound imaging system. However, for binary PMN-PT crystal, the coercive field (2.5 kV/cm) has been found to be low for high drive applications, and the low depoling temperature ($T_{R/T}$ ~ 75-95 °C) leads to undesirable changes in properties and performance with temperature. Thus, exploring new single crystals with higher coercivity and improved good thermal stability for ultrasound transducer application are warranted. Nowadays, the addition of lead indium niobate PIN to PMN-PT crystals for higher transformation temperature has received much attention [1-4]. The ternary PIN-PMN-PT single crystal, due to its high coercivity and high depoling temperature, is a promising material for high frequency ultrasound transducers in medical imaging applications.

II. MATERIAL PRAPARATION AND CHARACTERIZATION

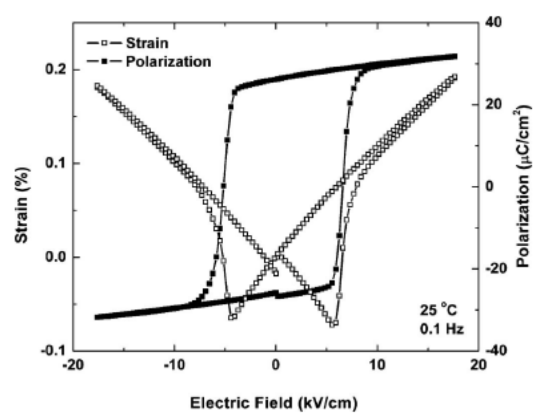


Figure 1. Piezoelectric strain and ferroelectric hysteresis for PIN-PMN-PT.

A ternary PIN-PMN-PT single crystal with (011) seeding was grown by a modified Bridgman method. High-purity (99.99%)

oxide powders of PbO, In_2O_3, Nb_2O_5, MgO, and TiO_2 were mixed stoichiometrically and ground using an attrition mill to reduce particle size. The resulting powder was pressed and sintered into ceramic forms before loading into a platinum crucible with a (011) oriented seed crystal affixed in the base. The crucible was sealed and packed within an alumina tube and placed inside a furnace. The charge was heated up to 1370 °C and the melt was equilibrated for 10 h before the crucible was lowered at 0.3–0.8 mm/h for seeded crystal growth [4].

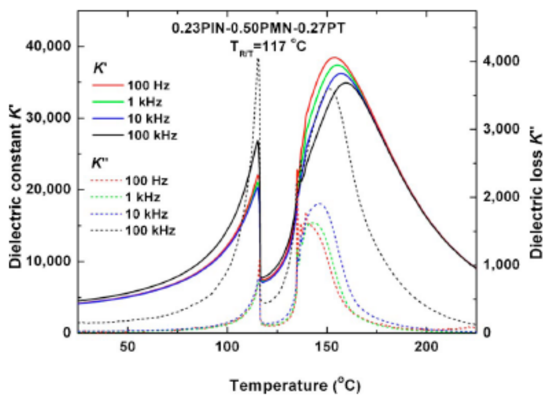


Figure 2. Temperature and frequency dependence of dielectric constant.

The ferroelectric and dielectric properties were shown in figure 1 and figure 2, respectively. The E_C of ternary PIN-PMN-PT crystal was 6 kV/cm, more than double that of binary PMN-PT. In addition, compared with binary PMN-PT, the ternary PIN-PMN-PT crystal had improved linear strain response over a larger field range. Compared with binary PMN-PT, the thermal stability of ternary PIN-PMN-PT crystal is also improved. The depoling temperature T_R/T, which denotes the upper temperature limit for piezoelectric crystal applications, is increased to 117 °C which is 20 °C higher than binary PMN-PT (85-97°C)

III. ULTRANSOUND TRANSDUCER FABRICATION AND CHARACTERIZATION

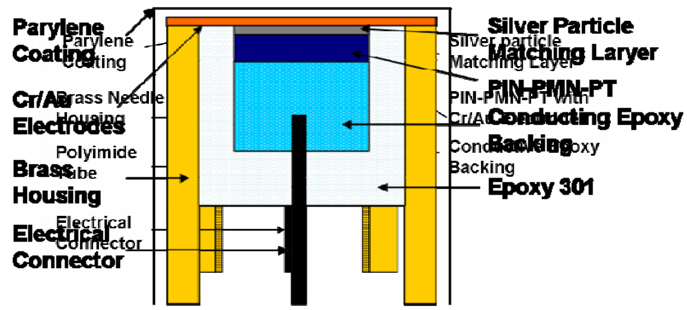


Figure 3. Design cross section of a transducer. The electrical connector was fixed to the conductive epoxy backing. The device was electrically shielded by a brass housing connecting a sputtered 1500 Å chromium/gold layer to silver particle matching layer.

A 500 μm thick PIN-PMN-PT piece (HC Materials Corp., Bolingbrok, IL) piece was lapped to 55 μm. A matching layer made of Insulcast 501 and Insulcure 9 (American Safety Technologies, Roseland, NJ) and 2-3 μm silver particles (Sigma-Aldrich Inc., St. Louis, MO) was cured over the PIN-PMN-PT and lapped to 12 μm. A conductive backing material, E-solder 3022 (VonRoll Isola, New Haven, CT), was cured over the opposite side of the PIN-PMN-PT and lapped to under 3 mm. Active element plugs were diced out at 0.6 mm aperture (0.6 mm x 0.6 mm) and housed using Epoxy 301 (Epoxy Technology Inc., Billerica, MA) once an electrical connector was fixed to the conductive backing using a conductive epoxy. An electrode was sputtered across the silver matching layer and the housing to form the ground plane connection. Vapor deposited parylene with thickness of 15 μm was used to coat the aperture and the needle housing. A cross section of the transducer is shown in Figure 3.

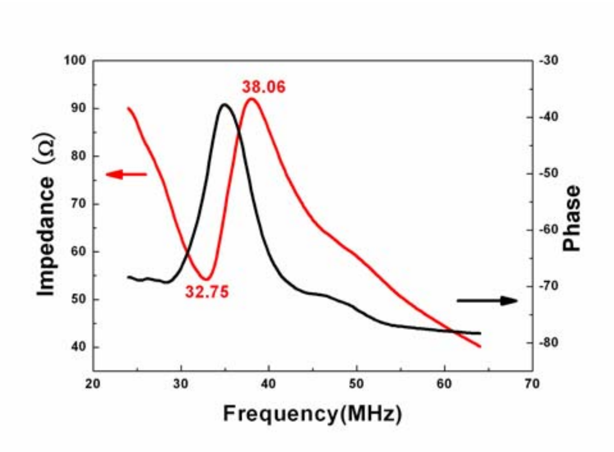


Figure 4. Electrical impedance magnitude and phase plots for an air resonating, 0.6mm aperture, 35MHz PIN-PMN-PT transducer.

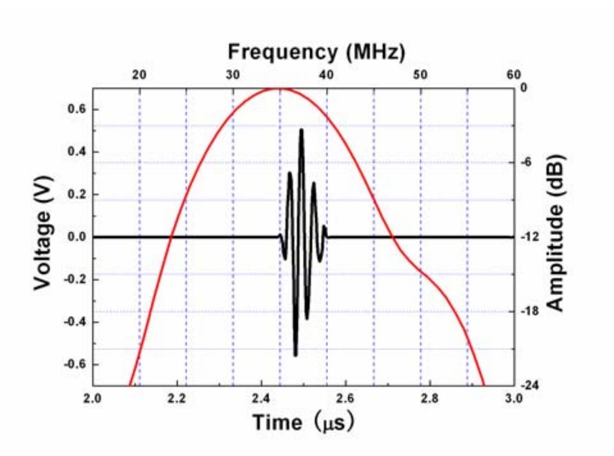


Figure 5. Pulse echo response and spectrum of 35MHz PIN-PMN-PT transducer

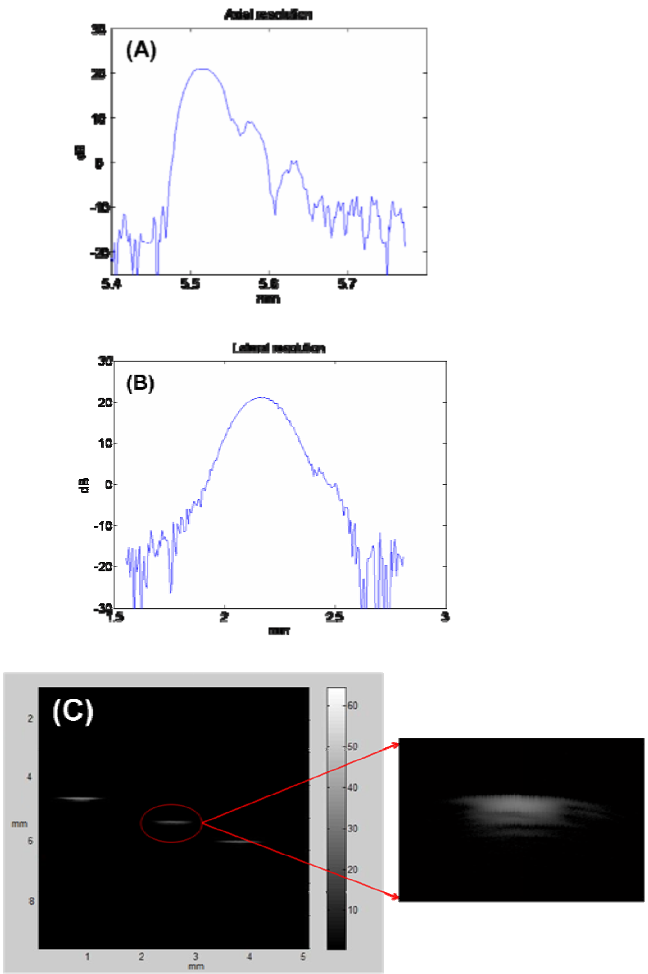
Electrical impedance measurements were taken using an HP4291 impedance analyzer equipped with the HP16194B impedance probe adapter. The electrical impedance magnitude and phase (Fig. 4) were 71 Ω and -38°, respectively. The electromechanical coupling coefficient k_t in the single crystal can be determined from the following [5]:

$$k_t^2 = \frac{\pi}{2}\frac{f_r}{f_a}\tan\left(\frac{\pi}{2}\frac{f_a - f_r}{f_a}\right) \qquad (1)$$

where f_r is the resonant frequency and f_a is the antiresonant frequency, and assume that f_r is frequency of minimum impedance and f_a is frequency of maximum impedance. According to (1), k_t is determinated to about 0.55, which is comparable to that of PMN-PT transducer. [5] The negative phase shows the capacitive nature of the device. The pulse echo analysis consisted of measuring the received echo pulse from the reflection of a quartz target in a deionized water bath. A pulser/receiver (Panametrics 5900 pulser/receiver) was used to excite the transducer and receive the echo waveform which was recorded on a Lecroy LC534 oscilloscope (50 Ω coupling). The center frequency of the device was measured to be 35 MHz, and bandwidth was 48 %. The time domain pulse echo response and normalized frequency spectrum are shown in Fig. 5.

Insertion loss was measured using a several cycle sinusoid pulse produced using a Sony/Tetronix (Beaverton, OR) model AFG2020 arbitrary function generator. The amplitude of the input sinusoid signal was recorded with a 50 Ω coupling on the Lecroy oscilloscope set to 4 V amplitude at the transducer's center frequency. The transducer was then connected to the function generator with the oscilloscope, and the coupling was changed to 1 MΩ. The echo signal amplitude (signal averaging) was measured at 2 μs or 3 mm according to a sound speed of 1500 m/s. This distance was beyond the natural focal point of the transducer due to ringing noise from the function generator. The signal loss from the attenuation in water (2.2 x 10-4 dB/mm·MHz^2) and transmission into the quartz target was compensated in the final insertion loss calculation. Insertion loss was measured to be around 15 dB.

IV. WIRE PHANTOM IMAGE



Figrue 6. Wire phantom image (a), axial sprend function (b) and lateral spread function (c) acquired with the transducer .

A phantom which consists of 20-µm tungsten wires was imaged to assess spatial resolution of the transducer. In the measurement, the transducer was driven by the motor controller (DMC-1802, Galil Motion Control Inc, Mountain View, CA) to linearly scan the wires. A Panametrics 5900PR was used to excite the transducer. The reflected echoes were then digitized by a 12-bit digitizer CompuScope 12400 (Gage Inc. Lockport, IL) at a sampling frequency of 200 MHz. Figure. 6 shows the image, the axial and lateral spread functions of the wires. The axial resolution and lateral resolution estimated from the spread functions were 55 µm and 256 µm, respectively. Further development of a focused transducer will improve the lateral resolution.

V. SUMMARY

The measured center frequency and -6 dB fractional bandwidth of the PIN- PMN-PT transducer were 35 MHz and 48 % respectively. The two-way insertion loss was approximately 15 dB. The out put voltage without external amplifier was 1.0 V around 3 mm reflective distance.

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