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An evaluation of PZT5A, PIN-PMN-PT Single Crystal, and High-Dielectric PZT for a 5mm x 5mm Histotripsy Transducer

Jeffrey Woodacre
Department of Biomedical Engineering
Dalhousie University
Halifax, Canada
jwoodacr@dal.ca

Jeremy Brown
Department of Biomedical Engineering
Department of Electrical Engineering
Dalhousie University
Halifax, Canada
j.brown@dal.ca

***Abstract*—Three 5 MHz, 1-3 piezoelectric-epoxy composites with a volume fraction of approximately 40 percent were fabricated using the dice-and-fill technique. The composites, made from PZT-5A, single crystal PIN-PMN-PT, and CTS 3257HD, a high-dielectric piezoelectric, were cut to 5 mm x 5 mm a mounted to an aluminum lens of the same dimensions with a 5 mm focus, and the focal pressure as a function of drive voltage was measured using a 40 um needle hydrophone from Precision Acoustics while driving the transducer to steady-state using a custom, in-house adjustable voltage pulser with a peak voltage of 600 V. The focal pressure for each device was found to increase as, 6.6, 8.6, 9.0 MPa/100V for the PZT-5A, PIN-PMN-PT and CTS 3257 HD, respectively. It is expected that the CTS 3257 HD and PIN-PMN-PT should be capable of generating cavitation within the range of the current pulser, while we expect the PIN-PMN-PT could generate more pressure with higher voltages, but a new pulser would be required. The PZT-5A composite has been shown to reach its saturation limit at 500 V (1.5V/ µm) and, at this voltage, may not always be capable of generating cavitation consistently.**

Keywords—histotripsy, single crystal, ultrasound, high-intensity, composite

I. Introduction

Histotripsy is a tissue ablation technique where tissue is targeted with short, high-intensity ultrasound bursts to induce cavitation, ablating and leaving a mixture cellular remnant. Due to the tight margins of the ablation region and lack of thermal damage, histotripsy shows promise as a neural ablation technique for tumor resection in burr hole surgeries where it is critical to minimize damage to surrounding tissue. To perform burr-hole surgery using histotripsy, a device with an endoscopic form factor is needed. Previously, a 1 cm diameter circular histotripsy device using an aluminum lens has been shown to successfully ablate tissue using a 5 MHz, PZT-5A 1:3 dice-and-fill composite as the piezoelectric element [1]. This design and frequency ensure a tight focus and, therefore, small ablation zone measuring less than 1 cubic millimeter. Further reduction of the device to 5 mm by 5 mm square was done and shown to be capable of generating a bubble cloud in water [2] and is, therefore, likely also capable of ablating tissue.

The small 5 mm x 5 mm form factor is designed for use in burr-hole surgeries, however, it was found that driven single-ended at 5 MHz, PZT-5A composite may be near saturation at a drive voltage of only 400 V. To provide an increase in the overhead of these 5 mm x 5 mm devices, it is necessary to explore alternative designs for the piezoelectric element, the lens, and potentially the matching layers. This work focuses on the piezoelectric element.

The objective of this work was to design and build three, 5 mm by 5 mm, histotripsy devices based on 5 MHz, 1:3 composites of PZT-5A, single-crystal PIN-PMN-PT, and high-dielectric PZT (3257HD from CTS Corp.), and examine the focal pressure per input volt of each to determine the feasibility of each for histotripsy, specifically with respect to how much additional pressure can be achieved above the cavitation threshold. The transducers are all focused using an elliptical aluminum lens with a quarter-wavelength matching layer of parylene-C on the surface. The lens and matching layers are all kept the same for each device, such that only the composite effects the output.

In Section II of this proceedings the fabrication steps in the creation of each composite and transducer are described along with electrical impedance curves after poling and after lens bonding. In Section III, we show the pressure measured by the hydrophone as a function of drive voltage and an initial measurement of the saturation voltage for the PZT5A and CTS 3257 HD composites. Finally, in Section IV, a discussion of how the results will guide future work and conclusion summarizing the key findings.

II. Design and Fabrication

In Figure 1, we present the basic design of our transducer stack, where a 1-3 piezoelectric-epoxy composite is bonded to a 6061-T6 aluminum elliptical curvature lens with a quarter-wavelength parylene-C matching layer deposited on the top. The composite is air-backed within a 3D printed plastic casing.

The composites made from TRS PIN-PMN-PT, a single-crystal relaxor material and CTS 3257HD, a high-dielectric piezoelectric, were created using the dice-and-fill technique on a Disco DAD3220 dicing saw with Epotek 301 as the kerf fill. The CTS 3257 HD composite, with a thickness of 310 µm, has pillars measuring 92 x 92 µm with kerfs at 50 µm resulting in a 15 MRayl composite, while the single-crystal composite, with a thickness of 213 µm, has pillars measuring 83 x 83 µm with kerfs of 39 µm, giving a 17 MRayl composite. The composite volume fractions were made to closely match the acoustic impedance of aluminum as best as possible given the dicing blades available,

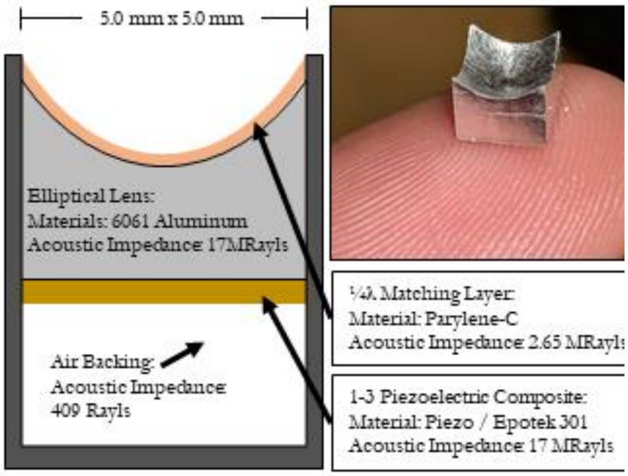

Fig. 1. A cross-sectional view of the transducer design shows a piezoelectric compsite, bonded to an aluminum lens with a parylene quarter wavelength matching layer deposited on top. The lens can be seen in the top-right.

and the thicknesses were chosen to achieve a 5 MHz resonance. The PZT-5A composite, 330 µm thick, had pillars measuring 100 x 100 µm with 60 µm kerfs, giving a 15 MRayl acoustic impedance. Air loaded electrical impedance measurements of the composites were made after poling but before mounting to the lens for the purpose of checking the resonance frequency, the overall resistance at resonance and the phase to ensure poling was adequately performed. These impedance measurements can be seen in Figure 2.

The impedance measurements show that the minimum impedance of each composite to be between 4.9 and 5.1 MHz, as per the design, where additionally the inset image show the minimum impedance values to be 8.5, 2.7, and 1.5 Ohms, for the PZT5A, 3257HD, and PIN-PMN-PT respectively. We expect the pressure generated by each transducer to increase, with decreasing minimum electrical impedance as a lower impedance will draw more power, however, determining an exact ratio of pressure output based on impedance ratios is not expected due to fabrication variations in composite, lens, and overall transducer stack.

The composites were bonded to the lens using Epotek 301 cured over 24 hours at room temperature. The bonding was done under pressure to create a thin, even layer of epoxy between composite and lens. The lens itself, machined from 6061-T6 aluminum, has an elliptical curvature to avoid any spherical aberrations which might affect the focal pressure for transducers below f-number 1. For this lens, the focal point is designed to be 5 mm from the lowest point of the lens curvature, or roughly 3 mm away from the points of the lens. After mounting the composites to their lenses, the impedance was again measured and is shown for each composite in Figure 3.

The zero phase crossings of both the CTS 3257 HD and PIN-PMN-PT composites occur between 6.0 and 7.0 MHz, which is also the drive frequency at which we expect the maximum output pressure to occur. Within the 6.0 to 7.0 MHz band, we also see that the impedance magnitude for the lens-bonded CTS 3257 HD and PIN-PMN-PT composites is four to five times lower than the PZT-5A composite. It has been shown previously that bonding a lens to composite increases overall impedance while removing the strong anti-resonance peak [1], however, there is typically still evidence of the anti-resonance if the epoxy bonding layer between lens and composite is thicker than 10 – 20 µm, so it is believed that both the CTS 3257 HD and PIN-PMN-PT composites have epoxy bonding layers above 20 µm, which may slightly degrade the overall pressure output.

On the curved face of the lens is a quarter-wavelength acoustic matching layer of Parylene-C, which is deposited to a thickness of 82 µm, corresponding to a match of 6.5 MHz between aluminum and water. As mentioned above, it has been shown in our previous work that the addition of an aluminum lens to composite shifts the maximum transducer pressure output up to a higher frequency than the composite alone. For

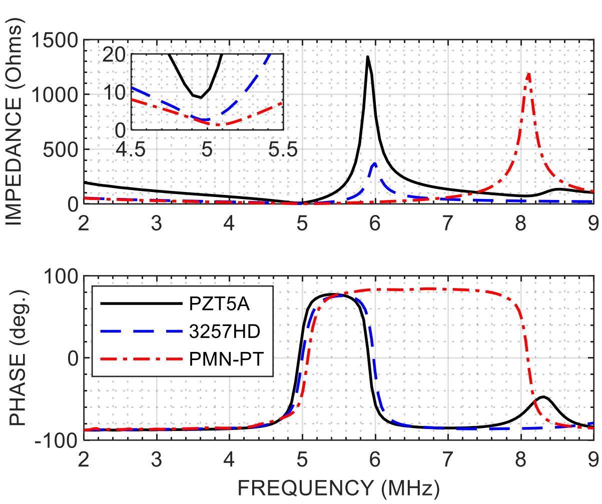

Fig. 2. The impedance and phase of the PZT-5A, CTS 3257HD, and PIN-PMN-PT composites are shown, with an inset of the composite resonance minimums shown in the top left of the magnitude curve.

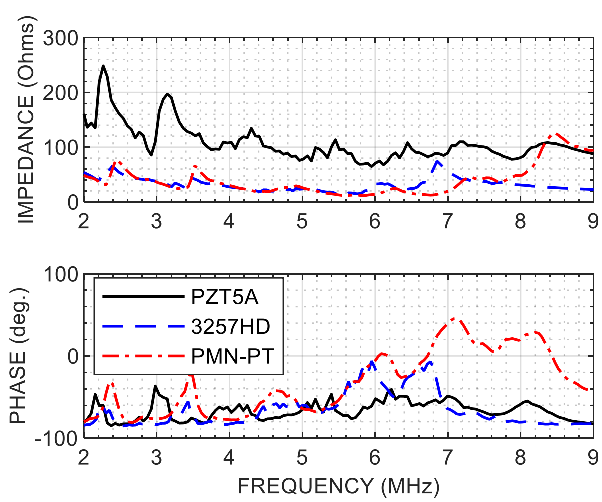

Fig. 3. The impedance and phase of the lens-mounted PZT-5A, CTS 3257 HD, and PIN-PMN-PT composites are shown, wh

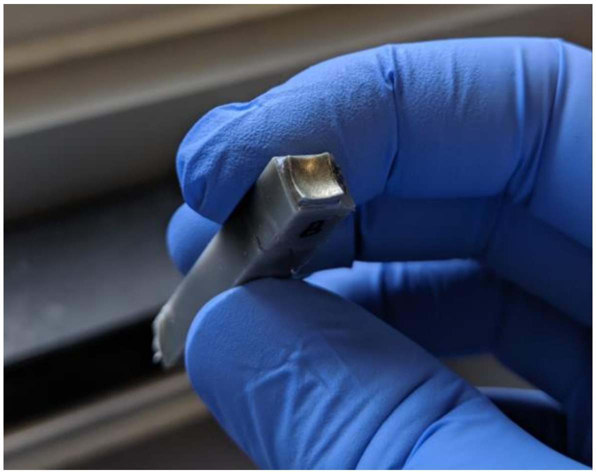

Fig. 4. The final transducer is shown here set in a 3D printed casing. The overall face including casing measures 8 mm x 7 mm, however this size could be reduced.

the devices in this proceeding, although the maximum output frequency can vary depending on thickness of the epoxy bonding layer between composite and lens, 6.5 MHz was found to be a good matching layer frequency for each composite.

The final, fully water-tight assembly can be seen in Figure 4, where the housing of the transducer was made using the Formlabs Form 2 3-D SLA printer (Formlabs Inc., Somerville, MA, USA). The electrical connections to the transducer are made using spring-loaded pushpins to avoid damage to the composite from soldering, with a MMCX connector on the back to connect to our custom pulser.

III. Hydrophone Measurements

The focal pressure of each transducer was measured using a 40 µm needle hydrophone from Precision Acoustics (Precision Acoustics Ltd., Dorchester, UK). The transducer is driven using a single-ended 10 Volt square pulse for fifteen (15) cycles at a pulse-repetition frequency of 10 ms while three high-precision linear motion stages were used to precisely position the hydrophone at the transducer focus. Fifteen cycles are used to ensure the transducer pressure reaches a steady state. The transducer voltage is then increase in one (1) Volt increments starting at six (6) volts and ending at a voltage level corresponding to roughly 1.3 MPa, above which pressure causes instability in the hydrophone output. Focal pressure is recoded at each voltage level. A plot of focal pressure versus voltage is shown in Figure 5 for the three transducers.

As expected, due to its higher impedance, the PZT-5A composite transducer gives the lowest pressure per volt with a linearly extrapolated pressure increase of 6.6 MPa/100V, with the next highest being the PIN-PMN-PT at 8.64 MPA/100V and finally, the best performance is given by the CTS 3257 HD composite with a pressure rise of 8.99 MPa/100V. Given the peak-negative pressure needed in water to cavitate is 26.1 – 27.9 MPa at 3 MHz, to a linear approximation these devices should be capable of creating a cavitation event in water at 390 Volts for PZT5A, 300 Volts for 3257HD, and 290 Volts for PIN-PMN-PT.

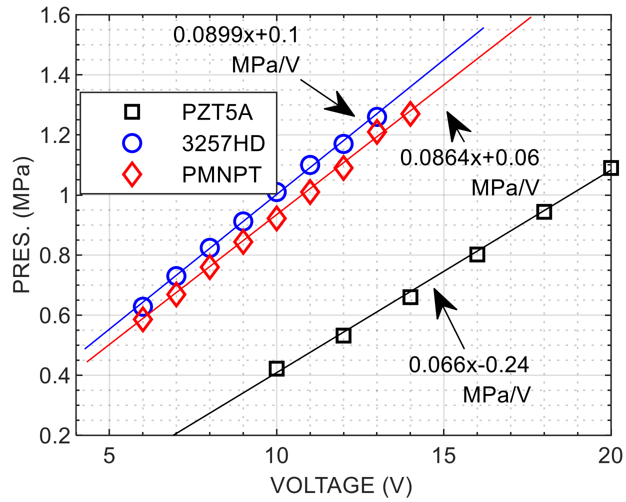

Fig. 5. For low voltages, the CTS 3257 HD and PIN-PMN-PT composite transducers greartly outperform the PZT5A composite, generating more overall pressure per volt, while the rate of pressure gain per volt is also greater, at 8.99 MPa/100V for the CTS 3257 HD and 8.64 MPa/100V for the PIN-PMT-PT compared tot eh 6.6 MPa/100V of the PZT5A.

We expect the PIN-PMN-PT transducer to have a saturation voltage limit that is unreachable given the properties of single-crystal [3] and our current pulser, however, the PZT-5A and CTS 3257 HD may be saturated given enough drive voltage. To test the saturation limit on these composites, air-backed composites of PZT-5A and 3257HD were mounted without a lens or matching layer and pulsed off-resonance at 6.5 MHz in water, while the needle hydrophone was placed off-axis to monitor the increase in pressure as a function of drive voltage. The composites were pulsed off-resonance and off-axis to avoid saturation of the hydrophone. The results are shown in Figure 6.

Here the red curve approximates how the pressure should increase were it linear in voltage. The black curve with square

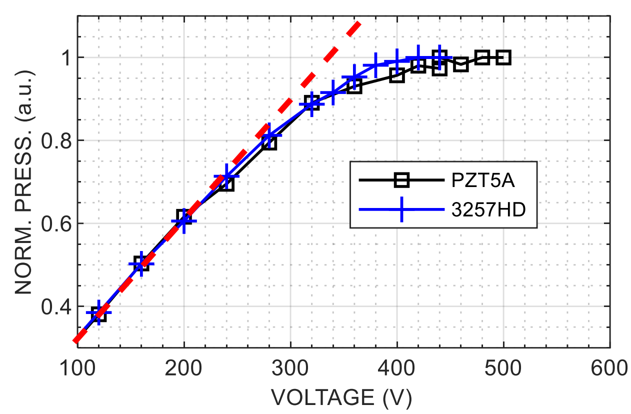

Fig. 6. A pressure vs voltage curve for PZT-5A and CTS3257HD composites driven off-resonance and off-axis shows that, starting between 250 and 300 V, the pressure no longer follows a linear trend as voltage increases, and saturates near 400 V (1.29 V/ µm)for the 3257HD, and gives only small gains above 400 V (1.21 V/ µm) for the PZT5A composite, with saturation at 500 V (1.5 V/ µm). The red-dashed line shows how the pressure should increase were it following the voltage linearly.

markers shows that the PZT-5A composite begins to deviate from linearity between 250 Volts (0.76 V/ µm) and 300 Volts (0.91 V/ µm), and by 400 Volts (1.21 V/ µm) the pressure gains are marginal with increasing voltage. At 500 V (1.5 V/ µm), PZT-5A appears to be saturated. The blue curve with cross markers shows CTS 3257 HD similarly deviates from linearity between 250 and 300 Volts, and has fully saturated just after 400 V (1.29 V/ µm). Given the negligible returns for PZT5A above 400 V (1.21 V/ µm) and the saturation of CTS 3257HD after 400V (1.21 V/ µm), and considering the overall pressure per volts increase from Figure 5, the best option between these two would be the CTS 3257 HD as it should reach cavitation pressure between 300 V and 350 V based on extrapolation of Figure 6, whereas the PZT5A may only reach cavitation pressures under the most ideal circumstances.

IV. DISCUSSION AND CONCLUSIONS

In this work, the ability of lens bonded, 5 mm x 5 mm composites of PZT-5A, CTS 3257 HD, and PIN-PMN-PT were examined for feasibility in generating cavitation events in tissue. It has been shown that a linear extrapolation of pressure versus voltage based on low-pressure measurements cannot be used to determine cavitation for PZT-5A and CTS 3257 HD as there are diminishing returns in their pressure versus voltage curves above 250 Volts. A linear extrapolation of the PZT5A curve from Figure 5 would suggest that 390 V are required to pulse the PZT-5A composite into reaching a peak-negative pressure which would induce the creation of a cavitation event, however we now know that, from Figure 6, the required voltage is likely much greater and, additionally, would be reaching the limits of a PZT-5A based histotripsy device. Based on this current proceedings, previous work which showed that a PZT-5A composite could generate a bubble cloud [2] when pulsed at 570 V was likely the absolute limit of a PZT-5A composite based device under ideal fabrication, and should not be expected to provide additional pressure overhead in future devices.

We know that single-crystal PIN-PMN-PT will maintain linearity at voltages well above both PZT-5A and CTS 3257 HD, and therefore would be a good candidate for future histotripsy composites, however, the fabrication of single-crystal composites is time consuming and more costly in material compared to CTS 3257 HD, and the properties of a CTS 3257 HD composite show promise in generating cavitation in tissue so long as the voltage is kept below 400 V. With that in mind, future work will involve exploration of both PIN-PMN-PT and CTS 3257 HD devices for cavitation of tissue with initial focus on CTS 3257 HD devices due to ease of composite fabrication. An overall focus on improving the maximum reachable pressure per volt for both types of composites will be maintained as future goals involve a stacked, co-registered imaging and ablation device, which will likely require significant pressure overhead.

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