Pad-printed thick-film transducers for high-frequency and high-power applications

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ABSTRACT

High-frequency-ultrasound transducers are widely used but are typically based either on planar piezoceramic sections that are lapped down to smaller thicknesses or on piezopolymers that may be deformed into more complex geometries. Piezoceramics then require dicing to obtain arrays or can be fractured into spherical geometries to achieve focusing. Piezopolymers are not as efficient for very small element sizes and are normally available only in discrete thicknesses. Thick-film (TF) transducers provide a means of overcoming these limits because the piezoelectric film is deposited with the required thickness, size and geometry, thus avoiding any subsequent machining. Thick-film transducers offer the potential of a wide range of geometries such as single-elements and annular or linear arrays. Here, a single-element focused transducer was developed using a piezoceramic composition adapted to high-power operation which is commonly used at standard MHz frequencies. After fabrication, the transducer was characterized. Using specific transmit-receive electronics and a water tank adapted to high-frequency devices, the transducer was excited using a short pulse to evaluate its bandwidth and imaging capabilities. Finally, it was excited by a one-period sine wave using several power levels to evaluate its capacity to produce high-intensity focused ultrasound at frequencies over 20 MHz.

Keywords: Piezoelectric thick films, high-frequency ultrasound, medical imaging, HIFU

1. INTRODUCTION

The drive for developing PZT thick-film (TF) transducers has been miniaturization, integration and low cost for mass production and several applications have been suggested [1, 2]. As the PZT TF technology evolves, other applications have emerged. This is especially true for high-frequency (HF) acoustic applications (> 20 MHz) because several properties desirable for HF applications are inherent features of the PZT TF [3,4]. As the thickness of the TF lies in the region of 10-100 μm, the resonance frequency of such a structure can reach 20-60 MHz, which is well suited for high-resolution medical imaging. The intrinsic porosity of the thick film is also favorable for medical imaging applications as it reduces the acoustic impedance and, thus, enhances the acoustic power transfer from ceramic to tissue and vice versa. Consequently, this has become a promising field in the development of PZT TF. Here, the fabrication of the TF structure is first described, then the transducer is characterized in pulse-echo mode and its ability to perform images is evaluated. Finally, the transducer is excited by a one-period sine wave at its centre frequency for increasing voltages and the pressure is measured at its focal point in order to evaluate its potential for high-frequency HIFU applications.

2. THICK FILM TRANSDUCER MANUFACTURING

The basic structure of the transducer is depicted in Figure 1a and a cross section of the active structure is seen in Figure 1b. The transducer consisted of a backing material that was machined into a cylinder with one end spherically curved in order to define the focal length of the transducer. Top and bottom electrodes and the active film were deposited using pad printing on the curved face of the cylinder and contact electrodes were added along the side of the cylinder using screen-printing. A thorough description of the manufacturing method can be found in [5].
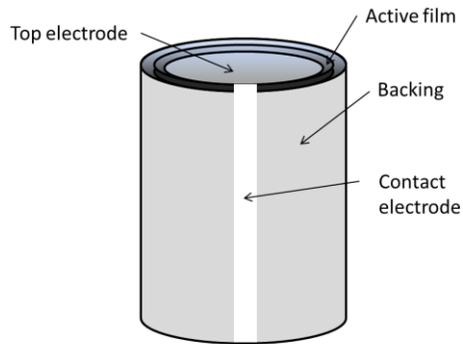

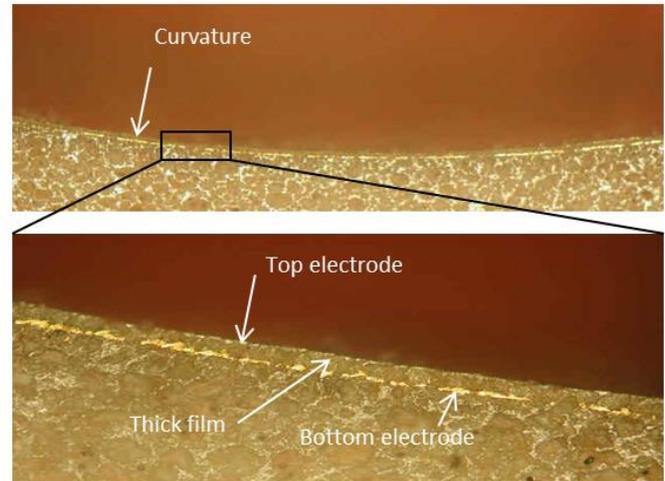Figure 1a. Basic structure of the transducer.

Figure 1b. Cross section of the transducer. Thick film and top and bottom electrode is clearly seen.

The backing material (InSensor® SU37) is based on Ferroperm composition Pz37, a porous engineered structure version of PZT. The thick film InSensor® TF2100, is a NAVY type I powder modified for TF manufacturing and formulated into a pad printable paste. The bottom and top electrode and their contact electrodes were gold and silver, respectively. The silver contact electrode is seen in Figure 1a while the gold electrode was printed on the opposite side of the backing cylinder.

3. PULSE-ECHO CHARACTERIZATION

A thick film transducer with a center frequency of 20 MHz, a 15 mm radius of curvature and 2.5 mm aperture was mounted between the electrodes of a BNC connector, soldered in place, and then embedded in a non-conductive epoxy (Fig. 2a). The pulse/echo response was characterized by placing a glass plate at the geometric focus of the transducer in a plane normal to the acoustic propagation. The transducer was excited with a pulser/receiver (Panametrics 5900, Olympus NDT Inc., Waltham, MA) using the lowest energy setting for the excitation. The resulting time- and frequency-domain waveforms (Fig. 2b) revealed a -6 dB bandwidth of 135% and a center frequency of 19.5 MHz.
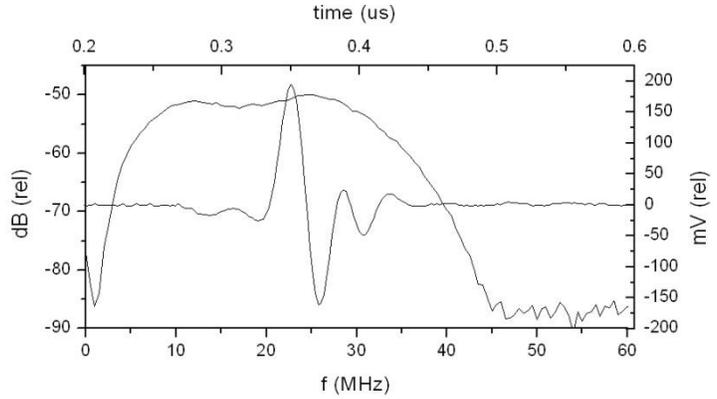
Figure 2. a) Transducer mounted in a BNC conductor and encased in epoxy. b) Glass plate pulse/echo response revealed a center frequency of 19.5 MHz and -6 dB bandwidth of 135%.

4. TRANSDUCER PERFORMANCE EVALUATION

4.1 Phantom imaging

Before performing animal imaging, a high-frequency phantom [6] was used to estimate the 3D resolution performance of the transducer. The phantom consisted of slabs of tissue-mimicking material with each slab containing a random distribution of uniform-diameter anechoic spheres. The phantoms allow for a quantification of the minimum feature size that can be resolved by a transducer. The feature size resolution is related to the 3D beam properties of the focal zone. The transducer was mounted to a motorized stage and then radio-frequency data were acquired as the transducer was laterally translated across the phantom.

The results of imaging the tissue-mimicking phantom using the transducer with a 15 mm radius of curvature and 2.5 mm diameter are shown Fig. 3. The phantom images showed that the transducer was able to resolve the 825 μm (Fig. 3a) and 530 μm diameter anechoic spheres (Fig. 3b) but not the 400 μm diameter anechoic spheres (Fig. 3c). The slab with no anechoic spheres (Fig. 3d) showed a similar speckle pattern to the slab with 400 μm spheres, providing further evidence that the 400 μm spheres were not resolved. The phantom results were consistent with the theoretical lateral beam width of approximately 0.5 mm.
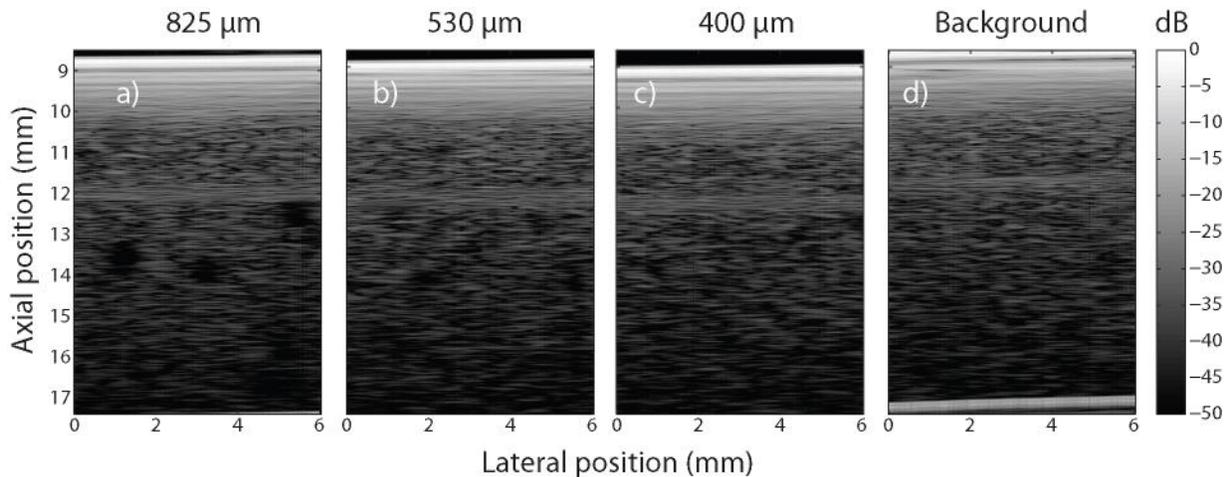

Figure 3. Sequence of images showing visibility of the anechoic spheres within the tissue-mimicking material as a function of sphere diameter. The a) 825 μm spheres were resolved as were the b) 530 μm spheres. The c) 400 μm spheres were not resolved and the background material with no spheres (d) showed a speckle pattern similar to the 400 μm sphere case.

4.2 Imaging performance

After the phantom experiments, the transducer was used to image an *ex vivo* rabbit eye, an *in vivo* adult mouse heart, an externalized *in vivo* mouse embryo, and an *in vivo*, *in utero* mouse embryo. Examples of animal imaging using the above transducer are shown in Fig. 4. Figure 4a shows an image of an *ex vivo* rabbit eye with the key anatomical features indicated. Figure 4b shows an externalized, *in vivo* mouse embryo with the embryo, umbilical vessels, and placenta visible. Figure 4c shows another image of a mouse embryo, this time with the embryo *in utero*. The acoustic attenuation within the dermis of the mother reduces signal strength but the embryo was still visible as was the uterus. Finally, Figure 4d shows the left ventricle of an adult mouse heart. Again, the dermis reduced signal strength and it was difficult to see the walls of the heart chamber in a static image. However, a dynamic series of images (not shown) revealed the movement of the heart. The imaging examples show that the TF transducer used in these studies was capable of delivering the single-to-noise ratio necessary to perform HF imaging. However, the high F-number of 6 for the transducer made it less than ideal for pure imaging applications due to the lateral resolution being on the order of 0.5 mm. Typical high-frequency imaging transducers at these frequencies have lateral resolutions on the order of 100 to 200 μm. Nevertheless, these initial imaging studies show that thick-film transducers are able to generate acoustic signals sufficient for imaging applications.
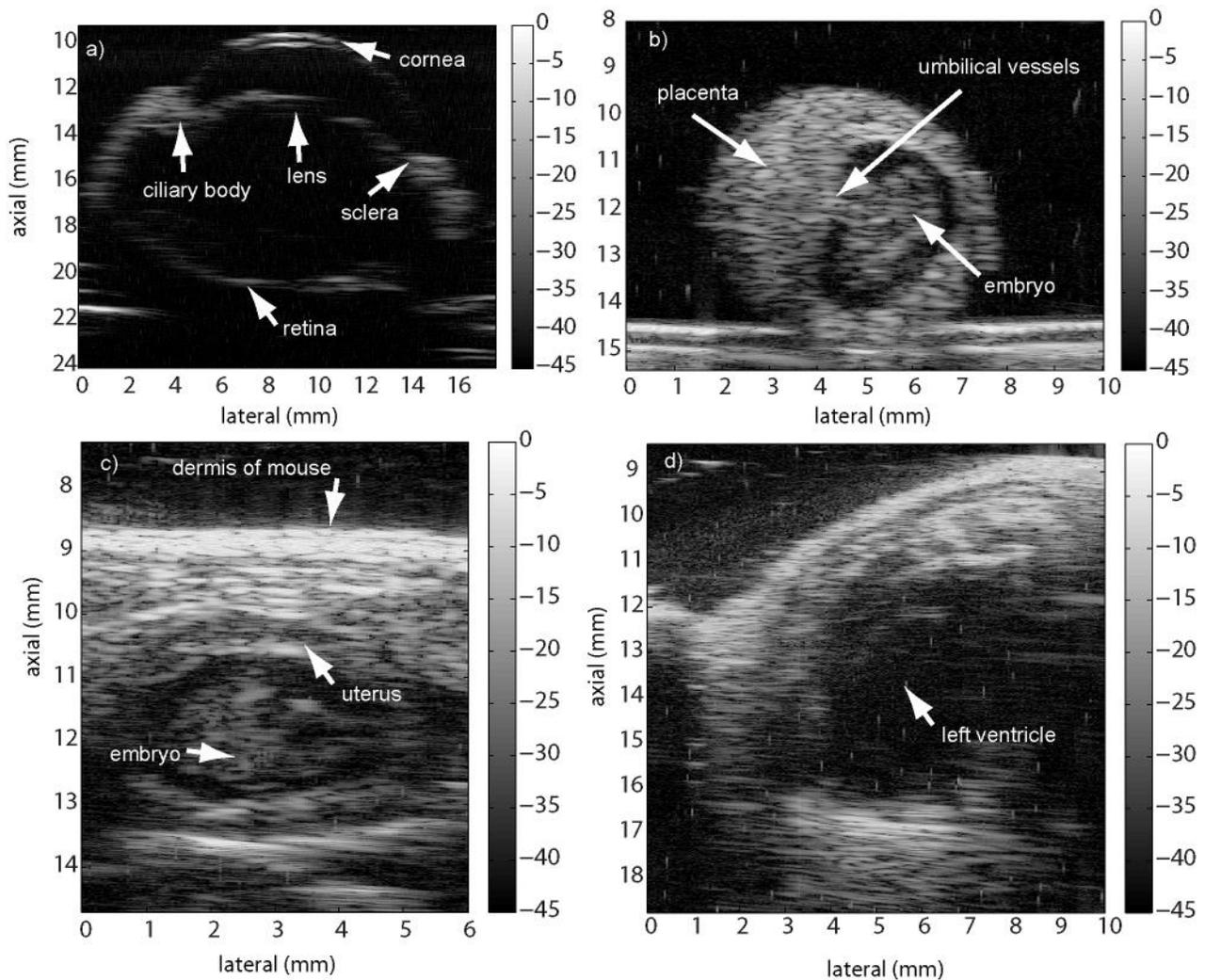

Figure 4. Imaging examples using the 15 mm focal length and 2.5 aperture 20 MHz transducer; a) *Ex vivo* rabbit eye, b) externalized *in vivo* mouse embryo, c) *in vivo* and *in utero* mouse embryo, and d) *in vivo* adult mouse heart.

4.3 HIFU performance

A second experimental set-up was used to measure the acoustic pressure at the geometric focus of the transducer. A high voltage, one-period sine wave was generated and amplified. The corresponding peak-to-peak voltage at the transducer leads was measured and then the pressure generated at focal depth was plotted versus this voltage. Figure 5 shows photographs of the experimental set-up.
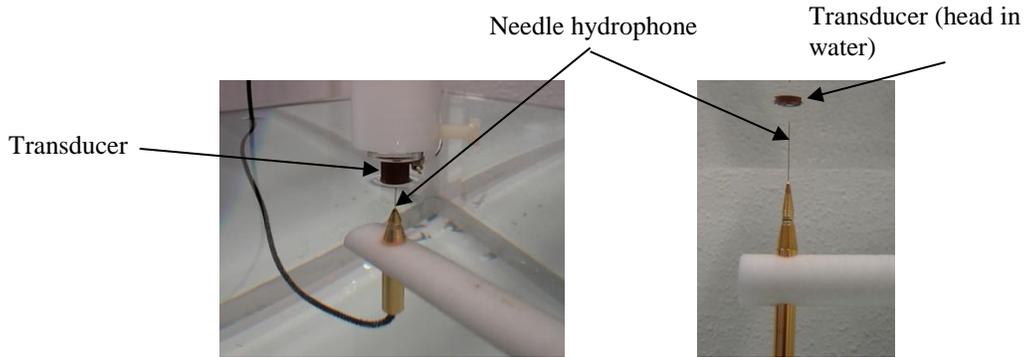

Figure 5. Photographs of the experimental set-up for pressure measurements at the focal distance.

A 200 µm aperture needle hydrophone (Precision Acoustics, Ltd., Dorchester, Dorset, UK) calibrated to slightly above 20 MHz was used. The results obtained are presented in Figure 6. The piezoelectric thick film transducer delivered high-pressure values over 3 MPa for an input voltage of 140 V_{pp}. In this study, the thickness coupling factor was not evaluated, but previous publications have shown that this value is similar to that of the same composition in bulk form (close to 50%). Here, 140 V_{pp} was the maximum voltage that could be produced by our experimental set-up. A fairly linear pressure versus voltage curve with no saturation was observed. Considering that the thickness of the film was around 30 µm, the corresponding electrical field was around 5 kV/mm.
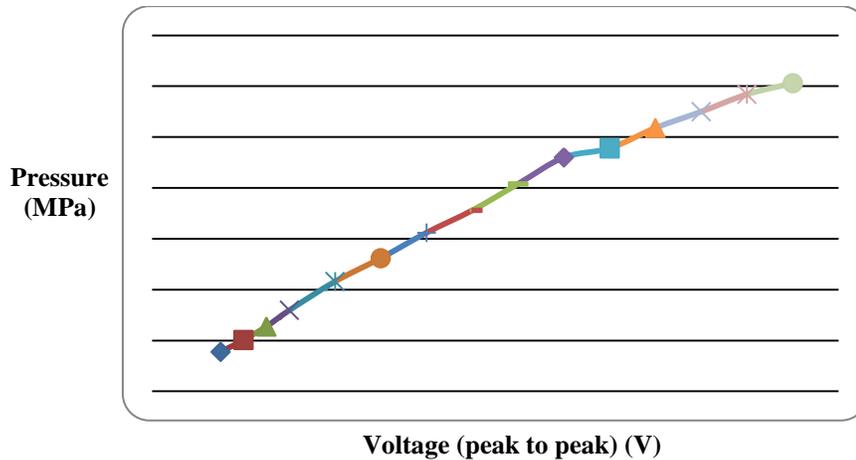

Figure 6. Pressure (peak to peak) measured at the focal distance (11 mm) as a function of the voltage (peak to peak) applied to the transducer ($\approx$ 15% error as specified by NPL).

5. CONCLUSIONS

Thick-film technology has been shown to be suitable for high-resolution medical imaging in many publications. Here, this technology, in particular pad printing of low-loss PZT, has been evaluated. Results demonstrate that focused thick film transducers are capable of combining reasonable imaging performance and high-intensity generation. Despite a relatively high F-number, a peak-to-peak pressure of 3 MPa (corresponding to an intensity of 150 W/cm^2) was measured for a peak-to-peak input voltage of 140 V at frequencies close to 20 MHz. This opens the way to applications of high-frequency HIFU. The flexibility of the technology allows for further improvement through design optimization such as electrode/transducer configuration and alternative backing selection.

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