Optimization of Single Crystal Composite Arrays for Harmonic Imaging

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Abstract— **The design concept for a single-active layer ultrasound transducer array for simultaneous sub- and second-harmonic imaging of contrast agents was tested for feasibility. Using PMN-PT single crystal in a 1-3 composite, multiple matching layers and a back plate, a design for imaging at 2, 4 and 8 MHz was implemented in a series of transducers. The effects of array pitch and piezocomposite thickness were examined. Transmit and receive sensitivities show the pitch and piezoelectric thickness can vary effects across the passband by more than 10 dB for different transducer parameters. Maximum transmit sensitivities of 230 dB re 1 uPa/V at 1 mm were achieved for the arrays. Contrast agent testing using Definity® showed the second harmonic could be detected. The sub-harmonic was not detected, and could be due to a low peak pressure from the unfocused array sub-aperture.**

Keywords- harmonic imaging, single crystal, PMN-PT, subharmonic, ultrasound , array

I. INTRODUCTION

In recent years, the use of nonlinear contrast imaging methods in ultrasound, such as second harmonic imaging, have achieved significant clinical significance. Tissue harmonic imaging (HI) has found success in research due to its increase in resolution, contrast and depth of penetration [1], though in applications of vascular identification and classification HI has proved a complicating factor.

Injected microbubbles have proved a significant benefit in highlighting vasculature, due to their high nonlinear behavior. The second harmonic generation from these bubbles is greatly enhances the intensity of Doppler signals, which allows for ultrasonic detection of low blood flow or capillary flow. As this signal passes through tissue, however, the signal can mix with second harmonic generation from the tissue, reducing the contrast between the blood and tissue.

The high energy spectrum of the microbubbles also includes lower frequency emissions, providing another means of detection. Subharmonic imaging (SHI) has recently become a viable alternative since subharmonics are not significantly generated in tissues, allowing for a more targeted approach for vascular discrimination. Because this mode is generally much weaker than the second harmonic, it would be desirable to include detection capability for both modes in a single transducer. Currently, the bandwidth of transducers is limited; commercial devices may achieve one harmonic mode, but do not have adequate bandwidth to achieve both. This is due to both the limited electromechanical coupling of the devices and the difficulties with acoustically and electrically matching the transducer over such a large spectrum.

Multi-resonant ultrasound arrays have successfully recorded both the sub- and second-harmonic signals [2], though a singly-resonant device could allow for easier integration into current ultrasound systems. Single crystal materials such as PMN-PT or PZN-PT provide a very high electromechanical coupling ($k_{33} > 92\%$ compared with 75% for PZT ceramic) and are ideal for providing high sensitivity, high bandwidth transducers [3]. By utilizing these materials in a composite form, the full benefit of the high coupling can be realized. The relatively high clamped permittivity also aids in increasing the capacitance of small elements in arrays. However, though bandwidths near 150% have been achieved with some transducers [4-5], significant design considerations must still be made to achieve that bandwidth in an array.

The goal of this work was to evaluate a set of varying design criteria to determine the optimum characteristics for a single crystal PMN-PT composite transducer array that could transmit on one frequency and receive on both the subharmonic and second harmonic frequencies. In this work, the authors explored multiple matching and backing layer schemes to increase sensitivity at desired frequency bands, as well as varying composite thickness and array pitch. Both the transmitting and receive sensitivities were evaluated, as well as characteristics of the impedance spectra. Transducer response to sub and second harmonics was tested by exciting Definity® contrast agent with the transducer's fundamental frequency.

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II. EXPERIMENTAL METHODS

A. *Array Design and Fabrication*

In order to achieve sufficient energy at three distinct frequency ranges (2.0/4.0/8.0 MHz) with a single resonator, a high electromechanical coupling or low mechanical Q is not enough. Passive materials selection is critical in modifying frequency content and electrical impedance matching becomes important in such a range. Pulse-echo predictions were made using 1-3 piezocomposite with PMN-PT. Bulk properties of the composite, summarized in Table I, were measured and used in the KLM equivalent circuit model. Predictions of this model showed that by utilizing three matching layers and a thin backplate behind the piezoelectric, energy of specific frequency ranges could be increased, as illustrated in Figure 1. The impulse response shows a notch in the spectrum, however, this is between bands of interest and could be shifted depending on what harmonic criteria is necessary. This suggested that the sub- and second-harmonics could be preferentially selected. Increasing the array pitch increased bandwidth and sensitivity, though the model could not accurately determine spatial effects of the pitch or coupling between elements that could affect the array.

Three transducer arrays of 12 elements each were fabricated, using single crystal PMN-30%PT 1-3 composite as the piezoelectric. The composite was diced using a Thermocarbon dicing saw, resulting in kerfs of 25 microns and a volume fraction of 52%. A summary of composite properties is shown in Figure 1. The array elements were patterned such that each array consisted of two sub-apertures of six elements each. One sub-aperture maintained a pitch of 260 microns (two posts in the width) and the other was 390 microns (three posts). These corresponded to a one wavelength pitch or smaller. The composite thicknesses corresponded to center frequencies of 3.8, 4.6 and 5.2 MHz. The electromechanical coupling of the composite was not significantly affected by the different aspect ratios of posts for the designs, as the height/width ratio was kept above two. A summary of the transducers is shown in Table II.

Many factors could be varied for optimization of properties for an array; in this work, the array pitch and piezoelectric thickness were varied while maintaining the same matching and backing scheme. Each array utilized three acoustic matching layers; the acoustic impedances of the outer to inner layers were 2.25, 4.5 and 9 Mrayls, and each was one quarter wavelength at 4 MHz. A PZT backplate of one-eighth wavelength thickness at 4 MHz was bonded to the back of the transducer, and an alumina-loaded epoxy served as the backing. A flex circuit was bonded to the front of the array, and 75 ohm coaxial cables were soldered to the flex circuit. The elements were separated by scratch dicing the electrodes. The composite was poled at 5 kV/cm at room temperature. The array was potted in a housing, and is shown in Figure 2.

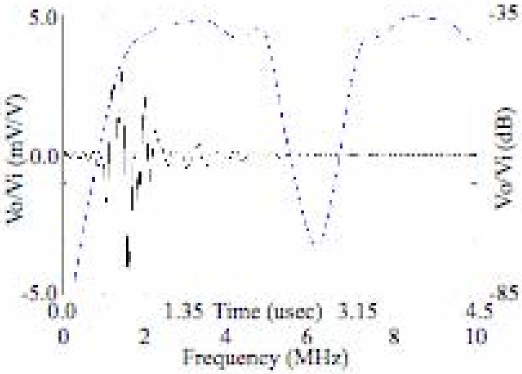

Figure 1. Response of composite transducer in KLM model showing good sensitivity at 2.0/4.0/8.0 MHz. Graph represents volts received on echo (Vo) per drive voltage (Vi).

TABLE I. 1-3 PMN-PT COMPOSITE PROPERTIES

Property	Value
$\varepsilon^S/\varepsilon_0$	390
Density (kg/m^3)	4750
Velocity (m/s)	3300
k_{eff}	0.84
Q	40

TABLE II. PARAMETERS OF SUB-ARRAYS

Array	Sub-array	Pitch (um)	Piezo Thickness (um)
A	1	260	225
	2	390	225
B	1	260	250
	2	390	250
C	1	260	275
	2	390	275

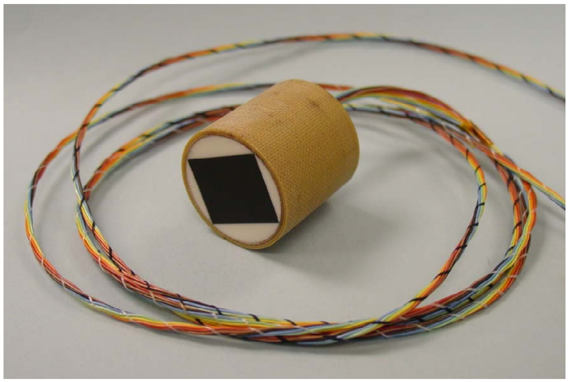

Figure 2. Finished array in housing.

B. *Array Charcterization*

The in air impedance spectra of the arrays and coaxial cables were obtained using an HP4194A impedance analyzer. The acoustic transmit pressure was measured using a calibrated needle hydrophone (Precision Acoustics, Inc., Dorchester, UK) in degassed water at 23°C. Measurements were taken at 10 mm. A programmable function generator (Wavetek) provided a 20-cycle toneburst that was swept through the band of interest

(1-10 MHz), and amplified using a 25 dB RF power amplifier. The hydrophone's integrated preamplifier was connected directly to a digital oscilloscope.

The transmitting response per volt (TRV) was then calculated using the relation:

$$TRV = \frac{V_h}{V_{in}} \cdot \frac{TL}{RS_h} \qquad (1)$$

where V_h is the output hydrophone voltage, V_{in} was the driving voltage, RS_h was the calibrated hydrophone sensitivity and TL was the one-way transmission loss.

The receive response sensitivity (RRS) was calculated by measuring the pulse-echo voltage using the same excitation method and a stainless steel plate (perfect reflector) in place of the hydrophone. The receive signal was range gated. The RRS was calculated by inserting the data into the relation :

$$RRS = \frac{V_r}{V_{in}} \cdot \frac{2 \cdot TL}{TS \cdot TRV} \qquad (2)$$

where V_r is the received voltage of the array element, TS is the target strength of the reflector, and the other variables are as described above. Measurements were taken with single array elements, both on end and central elements, and using two or four array elements connected in parallel for Array 3. This was done since multiple elements were to be used during contrast agent experiments.

The crystal arrays were tested with Definity® (Bristol-Myers Squibb) contrast agent in vitro. This agent consists of lipid stabilized suspension of octafluoropropane with a mean diameter of 1.1 to 3.3 um. The product produces a homogeneous dispersion of microbubbles.

The testing was performed within an acoustic window (latex, 12 micron in thickness) on the wall of a 100 ml test chamber. The saline in the chamber was kept in circulation with a magnetic stirrer. For each measurement, 0.6 ml of reconstituted Definity® was injected into the chamber. A transmit/receive switch was used to separate transmit and receive signals. The received signals were amplified with a low noise RF amplifier (Model 5052 PR) and digitized with a LeCroy oscilloscope. An average signal was obtained with 64 sequences of scattered signals, and the FFT spectrum was analyzed in the oscilloscope.

III. RESULTS AND DISCUSSION

A summary of representative electrical impedance profiles are shown in Figure 3. With the coaxial cable, all elements are well matched to 50 ohms. The elements in Array B are slightly higher than the others, and the phase angles are different. Though this could be due to the change in thickness of the piezoelectric, it is more likely to be caused by the coaxial cable or fabrication differences.

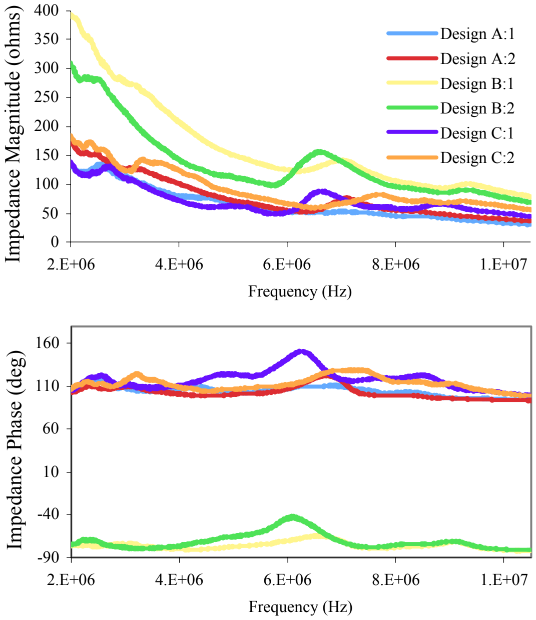

Figure 3. Impedance profile of representative individual elements from each array design. The coaxial cable is included during measurements.

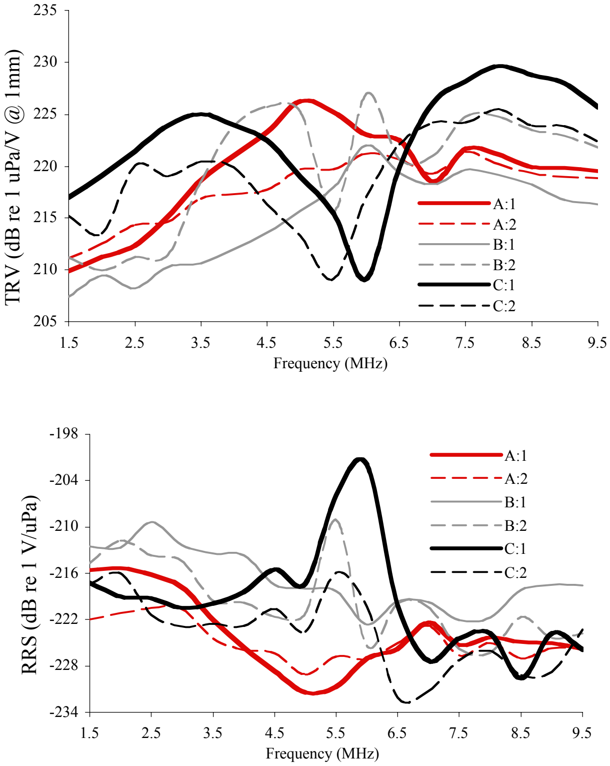

Figure 4. TRV and RRS for individual representative elements of arrays. Element data are from elements in Figure 1.

Transmit sensitivity for the three transducer arrays as measured, is shown in Figure 3. As expected, there was a notch in the band for Array C. The difference in the notch frequency could be due to the variance in electrical impedance. The notch separated the sub- and fundamental frequencies from the second harmonic, but had similar TRV values for all three ranges. The corresponding RRS for Array C showed a nearly 10 dB increase at 2 MHz than at 8 MHz, which is desirable due to the low sub-harmonic resonance of the contrast agent. The

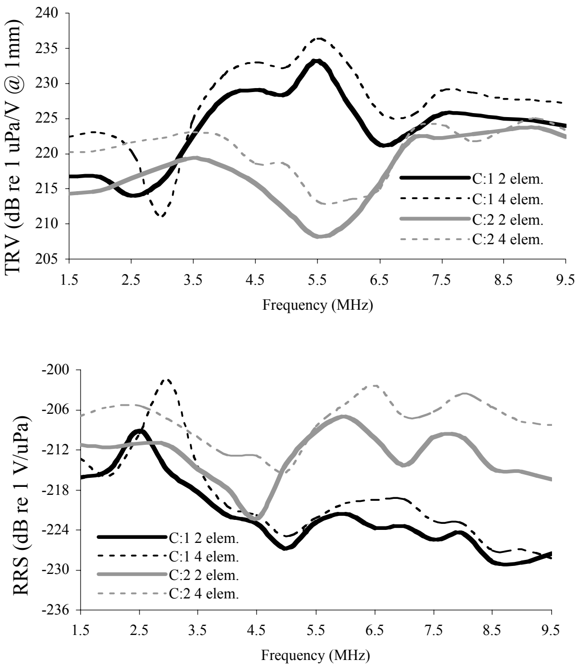

Figure 5. TVR and RRS for multiple elements of Array C.

other two arrays showed less of a notch in the frequency response. The lower transmitting response of Array A is most likely due to the higher resonance frequency from the thinner piezoelectric.

The response of using either two or four elements from Array C are shown in Figure 4. The notch is evident in design 2 for the array, however, it is not evident in design 1. This could be due to electrical impedance, however, since the electrical impedance is nearly identical for the elements, interactions between the elements could also be a factor. Since the pitch is different there may be crosstalk effects between elements.

The averaged spectrum from the Definity yielded the second harmonic, however, the sub-harmonic was not detected. The array was not focused, and therefore the signal was most likely not strong enough to achieve a good sub-harmonic signal. The pressure was not high enough to generate the signal. Further tests are being continued with biasing the elements to allow for a much higher signal. By increasing the excitation by approximately 10 dB, a detectable sub-harmonic is expected to be generated.

Six linear array sub-apertures were fabricated, and the lowest resonance frequency array shows promise for simultaneous sub- and second harmonic imaging. The pitch is important for providing enough sensitivity at the fundamental frequency, though focusing shows to be a significant factor in generating the sub-harmonic.

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