Broad Band Single Crystal Transducer for Contrast Agent Harmonic Imaging

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Abstract – **A broadband single element transducer was constructed from single crystal PMN-PT and tested to determine the feasibility of using this material for simultaneous sub-harmonic and second harmonic imaging. The transducer consisted of a 1-3 PMN-PT/epoxy composite with two quarter wave matching layers and a backing. The transducer face was spherically curved to yield a 53 mm focal point. The transducer's impulse response had a center frequency of 5.2MHz and -6 dB bandwidth over 130%. The transmit response for tone burst excitation indicated a shift in center frequency to 6.5 MHz and a -6dB bandwidth of 100%. Receive sensitivity was high at the lower end of the band and decreased with increasing frequency; this behavior was probably due to electrical impedance mismatch. Contrast agent testing using Sonazoid® showed that the second harmonic could be easily detected. The sub-harmonic was not detected due to the center frequency shift under tone burst excitation. Simultaneous sub and second harmonic testing could probably be accomplished with a lower center frequency and better electrical impedance matching.**

I. Introduction

There are a broad variety of clinical benefits that can be gained by using ultrasonic harmonic and sub-harmonic resonances generated from tissue or contrast agents. These include significantly enhanced resolution for vascular imaging, targeted imaging of specific organs, and targeted imaging of tumors. The second harmonic generated by a contrast agent at twice the fundamental transmitted frequency is used to enhance imaging of blood flow over that of soft tissue. Second harmonic signals from contrast agents compete with harmonic generation in the soft tissues, but this is not the case for sub-harmonics at ½ the fundamental so that simultaneous sub and second harmonic imaging can be used to subtract tissue generated artifacts for more detailed blood perfusion images. In addition, the sub-harmonic can be used for deeper tissue scans because of its lower frequency and resulting reduced absorption loss.

Implementation of harmonic imaging requires very broad bandwidth ultrasonic transducers. For example, a transducer that detects both sub-harmonic and 2nd harmonic resonances from contrast agents would need a 2-octave bandwidth (150% for a 3.5 MHz transmit frequency). Currently the design of very broadband transducers requires use of high coupling coefficient $Pb(Zr,Ti)O_3$ (PZT) based piezoelectric ceramic transducers, multilayered and/or graded matching layers, and high attenuation backing layers [1]. Further bandwidth improvements can be made by using 1-3 PZT-polymer composites to maximize coupling coefficient [1]. Use of 1-3 composites and high impedance backings result in reduced signal to noise ratio and high insertion losses, respectively, and thus trade-off bandwidth for sensitivity. Use of multilayer (> 2 matching layers) or graded matching layers adds significant cost and complexity to the transducer fabrication process. Other methods that have been investigated to get around these problems typically involve multilayer transducers [2]. This is a fairly complex engineering solution that is difficult to implement for array transducers.

A more attractive solution to the problem is to use a piezoelectric material with higher electromechanical coupling coefficient such as PMN-PT single crystals to provide a transducer with inherently more bandwidth. PMN-PT crystals exhibit an extremely strong piezoelectric effect with electromechanical coupling coefficients (k_{33}) in excess of 92% (compared to 75% for PZT ceramic) [3]. Simple ultrasound transducers have been constructed from crystals exhibiting bandwidths of 100% and insertion losses less than similarly constructed PZT transducers with only a 70% bandwidth [4]. In addition use of high impedance, backing layers have resulted in bandwidths as high as 140% [5].

To test the feasibility of using PMN-PT crystals for broadband imaging transducers, a single element transducer was constructed from a 1-3 PMN-PT/epoxy composite with 2 matching layers and a heavy tungsten-epoxy backing. Transducer response to sub and 2nd harmonics was tested by exciting Sonazoid® contrast agent with the transducer's fundamental frequency.

II. Experimental Procedure

Single element transducer modeling and fabrication was described in Ref. [6]. Two single element transducers were fabricated each with an 18mm diameter circular aperture and ~ 50mm spherical focus. This was done to conform to the contrast agent test fixture at Thomas Jefferson University. The transducers were constructed from 1-3 crystal-epoxy composites with a 4.6 MHz thickness mode resonance frequency. The composites piezoelectric volume fraction was 56%. Two matching layers were bonded to the transducer face. The matching layers were designed for optimum acoustic impedance matching at the composite resonance frequency. A backing layer was cast to the back of the composite. The backing had the same acoustic impedance as the composite. A schematic of the transducer construction is shown in Fig. 1.

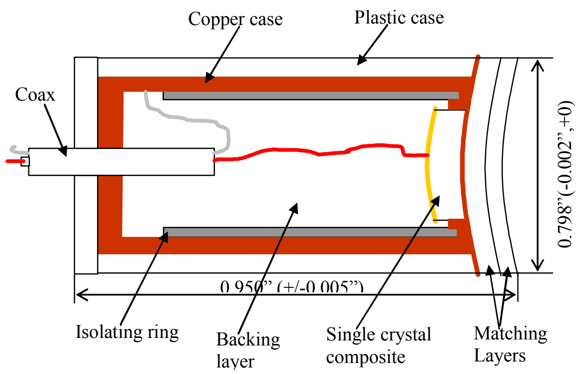

Figure 1: Transducer schematic.

Both transducers were tested for impulse response by placing them in a water tank with a steel target located at the transducer focal length. An 110V unipolar voltage pulse was applied to the transducer, and the receive pulse reflected off the steel target was recorded with an oscilloscope.

Transmitting and receiving sensitivities were measured according to the general procedures described in Ref.'s [7-9]. A programmable function generator (Hewlett Packard Model 8116A) produced 16-cycle tone bursts for transmission. The frequency of the transmit signals was varied from 1.0 to 15.0 MHz and then amplified in a broadband 50 dB RF power amplifier (ENI, Model 325LA) before being supplied to the crystal transducer. The transmitting sensitivity of the transducer was measured at one field point (57 mm) in water using a 0.5 mm broadband acoustic needle hydrophone (Precision Acoustics, Inc.), which has an excellent sensitivity over 1 to 20 MHz. The hydrophone was connected directly to a digital oscilloscope (LeCroy, Model 9350AM).

The Transmitting Sensitivity (*TRS* - unit: kPa/Volt) at 1 mm from the face of the transmit element was computed as [9]:

$$TRS = (V_r / V_{in})\ (TL / RRS_{cal}) \qquad (1)$$

where V_r (unit: Volt) is the output voltage of the hydrophone at the given field point, *TL* is the total one-way transmission loss from the sub-array to the field point (a dimensionless number ≥ 1 which is a function of ultrasonic absorption and spreading losses with distance), RRS_{cal} (Unit: Volt/kPa) is the sensitivity of the hydrophone and V_{in} (unit: Volt) is the driving voltage applied to the transducer, which was obtained by scaling the output of the amplifier with the transducer impedance (4.95 Ω∠63.84°) relative to the expected impedance (50 Ω DC).

The receiving sensitivities were measured with a 'perfect' reflector (a flat steel plate) placed at the mechanical focus (at 54 mm parallel to the transducer) as a function of frequency (1 – 11 MHz). Sinusoidal, 64 cycle, 4.50 MHz tone bursts were generated by the 8116A Hewlett Packard function generator at a pulse repetition frequency (PRF) of 10 Hz with the timing controlled by a timing modulus (actually a pulse generator, Avtech Electrosystems, AV-1023-C). Tone bursts were supplied *via* the broadband 50 dB RF power amplifier (ENI 325LA) to the crystal transducer. A Transmit/Receive switch (Ritec, Model RDX-6) was employed to separate transmit and receive signals. Crosstalk from the transmit signals was eliminated with a double-mixer range gate. The received signals were amplified with a low noise RF amplifier (Parametrics, Model 5052 PR) and acquired at a sampling frequency of 25 MHz using the LeCroy digital oscilloscope.

The Receiving Sensitivity (*RES*; unit: mV/kPa) is defined as [9]:

$$RES = (V_r / V_{in})\ (2TL / [TS \times TRV]) \qquad (2)$$

where V_r (unit: Volt) is voltage received (output of the probe) and *TS* is the target strength of the reflector (scaled by echo strength at the air/water interface). As a first approximation the *TRV* (*TRS* at 1.0 mm from the transducer face) was calculated as the *TRS* approximately 1.0 cm from the transducer face. Spreading losses (assuming spherical spreading from 1.0 cm to 5.7 cm) were included in this approximation as:

$$TRV = 5.7\ TRS \qquad (3)$$

and the *TL* was assumed equal to 5.4 (again assuming spherical spreading losses).

The crystal transducer was tested for harmonic imaging with Sonazoid® (also known as NC100100; Amersham Health) *in vitro*. Sonazoid is a robust ultrasound contrast agent with excellent harmonic response to ultrasound pulses [10,11]. This agent consists of a lipid stabilized suspension of perfluorobutane microbubbles with a median diameter between 2.4 and 3.5 µm. The finished product of Sonazoid is a powder for reconstitution before injection. After addition of 2 ml of sterile water for injection and gentle shaking by hand the product is easily reconstituted and produces a homogenous dispersion of microbubbles.

The mechanical focus for the test was approximately 2 mm within an acoustic window (latex, 12 micron in thickness) on the wall of a 100 ml test chamber. Isoton II saline in the test chamber was kept in circulation with a magnetic stirrer. For each measurement, 0.6 ml of reconstituted Sonazoid was injected into the test chamber. Sinusoidal, 64 cycle, 4.50 MHz tone bursts were generated by the 8116A Hewlett Packard function generator with a 5 % duty cycle (controlled by the Avtech pulse generator) and supplied via the RF power amplifier (ENI 325LA) to the transducer.

The Transmit/Receive switch was again employed to separate transmit and receive signals. The received signals were amplified with the low noise RF amplifier (Model 5052 PR). The amplified signals were acquired at a sampling frequency of 25 MHz using the LeCroy digital oscilloscope (model 9350AM) equipped with mathematical functions. For each measurement, sixty-four 20 µs sequences of scattered signals were first acquired at a PRF of 10 Hz. An averaged spectrum of these 64 data sequences was then obtained using an FFT spectrum analyzer in the oscilloscope with a Hamming window. The averaged spectrum was finally transferred via an IEEE-488 interface to a PC for further analysis. Each measurement took less than 10 seconds. The command delivery to the function generator and the data transfer from the digital oscilloscope was controlled by LabView® (National Instruments).

III. Results and Discussion

Properties for both transducers as determined from the impulse response are summarized in Table I. The transducers exhibited good sensitivity and an exceptionally broadband response. The frequency spectrum for transducer #2 is shown in Fig. 2. The vertical lines correspond to the anticipated transmit and subsequent 2nd and sub-harmonic signals from the contrast agent. The high frequency bulge in the frequency response suggested that the 2nd harmonic might be slightly out of band. If this bulge can be flattened both the 2nd and sub-harmonic should be detectable. The origin of the bulge is unknown, but it may be possible to further optimize the response and increase the bandwidth by sacrificing some sensitivity and choosing matching layers that yield the maximum possible bandwidth.

TABLE I: Summary of Impulse Properties for Single Crystal Transducers

Prototype	Focal Length	Loop Sensitivity	-20 dB Pulse Length	Center Frequency	Fractional Bandwidth
1	53 mm	-31 dB	0.49 µs	5.2 MHz	120%
2	53 mm	-34 dB	0.53 µs	4.9 MHz	132%

Transmit sensitivity for prototype #2 as measured using a hydrophone with a series of tone bursts from 1 to 15 MHz is shown in Fig. 3. As expected from modeling (PiezoCad [6]) the -6 dB bandwidth dropped to 100%. However, the center frequency unexpectedly rose to 6.5 MHz. The cause for this is unknown, but it may be related to the high frequency bulge observed in the impulse response. As shown below, the shift in the center frequency put the 2nd harmonic well within the response band, but left the sub-harmonic out of band. This is the reverse of what was expected from the impulse response.

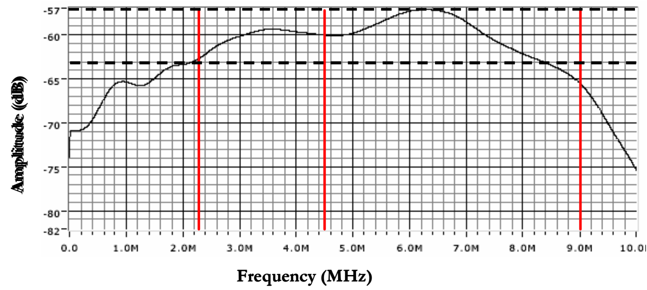

Figure 2: Frequency spectrum from prototype #2 as determined from the transducer impulse response. The dashed lines correspond to the -6 dB bandwidth referenced from the peak response.

For the transmit test of prototype #1 the transducer was driven at a 50% duty cycle with a signal strength of ~ 50 to 60 Vp-p. This caused the transducer to overheat at the solder joint which connected the top electrode to ground. The cause of the overheating was the very low transducer impedance resulting from the large aperture of the single element. Though a problem for the test, such overheating is not expected to be an issue for array transducers where element impedance will be much higher. For the second prototype the duty cycle was reduced to 5% and signal strength to about 30-40 Vp-p.

The receive sensitivity for the prototype #2 is shown in Fig. 4. The response is unusual in that the sensitivity seems to continuously increase with decreasing frequency. This is also believed to be due to the low electrical impedance of the transducer. The impedance mismatch with the 50Ω electronics reduces as frequency decreases increasing the sensitivity. Again this problem will be expected to be much less of an issue for an array transducer.

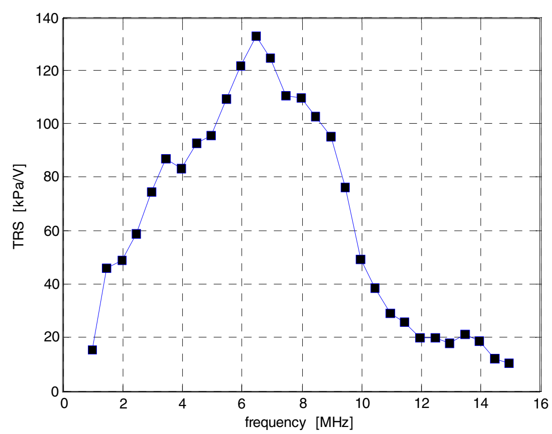

Figure 3: Transmit sensitivity for prototype #2. The center frequency is 6.5 MHz and the -6dB bandwidth from the peak response is 100%.

The averaged spectrum of scattered signals from Sonazoid microbubbles in harmonic imaging mode with the crystal transducer is presented in Fig. 5. The transmitted acoustic pressure amplitude was approximately 2.1 MPa (corresponding to a V_{in} of 23.03 V). A strong second harmonic peak at 9.0 MHz is clearly seen only 17.5 dB down from the fundamental echo (at 4.50 MHz). The sub-harmonic was not visible at this transmit frequency although it could be just barely seen (ungated) if the transmit frequency was increased. It therefore seems that the high center frequency of the transducer when driven with a tone burst was probably responsible for the low sensitivity to the sub-harmonic. This could be potentially alleviated by tuning the transducer with a transformer to better match the impedance. However, some investigation will be required to understand the differences in crystal transducer response to impulse compared to tone burst drive and why these differences are not predicted by our current model.

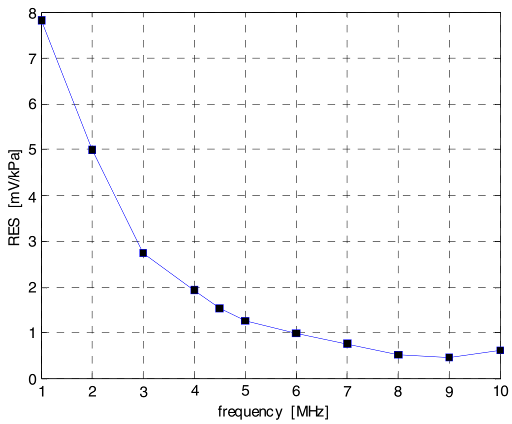

Figure 4: Receive sensitivity for prototype #2.

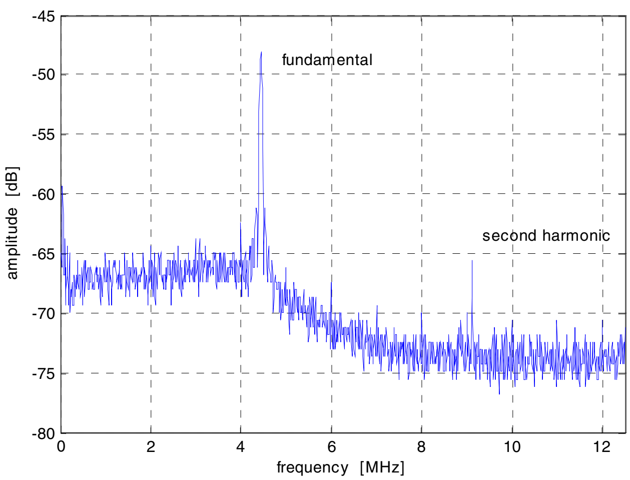

Figure 5: Spectrum from Sonazoid obtained using the crystal transducer at 4.5 MHz (i.e., the second harmonic peak is located at 9.0 MHz).

IV. Conclusions

A single element transducer was constructed from 1-3 PMN-PT crystal-epoxy composite with two matching layers and a backing. The transducer had a remarkably broad band width of 130% when driven with an impulse and 100% for a tone burst. The transducer was easily able to detect the 2nd harmonic generated from Sonazoid contrast agent. The sub-harmonic was much harder to observe, but better electrical impedance matching and a more uniform frequency response should improve the low frequency transmit sensitivity for sub-harmonic detection. We plan to follow up on this work by constructing a broad band linear array that can detect both sub and second harmonics.

V. Acknowledgements

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