Self-Focused 1-3 Composite $LiNbO_3$ Single Element Transducers for High Frequency HIFU Applications

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Abstract—**In this paper it is shown that $LiNbO_3$ single crystal may be used as a piezoelectric material for high frequency High Intensity Focused Ultrasound (HIFU) applications for its high Curie temperature and low dielectric constant and superior mechanical properties. Simulation results show that $LiNbO_3$ with a 1-3 composite structure is suitable to make large aperture (diameter 22-24 mm) and high frequency (> 10 MHz) single element transducer with desired impedance and required sustainable driving voltage for the expected acoustic intensity in the focal zone. Prototype transducers with the diameter of 23 mm and a surface curvature designed for f#/1 were designed and fabricated. The results are in good agreement with KLM model calculation. The measurement results show that center frequency is 10.5 MHz with the fractional bandwidth larger than 60%. The –6dB lateral and the axial beam widths were measured by a needle hydrophone and they are 160 μm and 98μm respectively, which are also in good agreement with theory (147μm and 83μm).**

Keywords-HIFU therapy; ultrasound transducers; lead free piezoelectric transducer; $LiNbO_3$ crystal

I. INTRODUCTION

Most HIFU single element and phased array transducers operate in the frequency range 0.75-3 MHz for achieving the best penetration and intensity in treating large volume and deep seated tumors in the liver, kidney [1-4], breast [5,6], prostate [7] and brain [8].

The depth of focus is usually at least 6 times the wavelength of the acoustic wave based on the theoretical model and experimental test [9,10]. So as long as the operation frequency for the transducers is determined, it is generally difficult to control the lesion depth. For some applications such as uterine fibroids [11, 12], glaucoma [13], ocular (trabecular meshwork) [14, 15], nervous and transrectal prostate tumor treatment [16,17], where a large penetration is not needed, increasing the frequency of transducer operation may provide a viable alternative.

Higher operational frequency (greater than 10 MHz), i.e. a shorter wavelength, means a smaller depth of focus. Due to the higher tissue attenuation with increasing frequency, a higher acoustic intensity is required to reach the same treating effect than at lower frequency, which means larger aperture and higher driving voltage for transducer. However, it is difficult to build large aperture, high intensity, high frequency transducer with the traditional PZT-4 or 8 materials because their dielectric constant is too high to obtain appropriate matching impedance for a large aperture and de-poling may occur due to the higher driving voltage.

In this paper, we propose to use $LiNbO_3$ 1-3 composite for the fabrication of large aperture, high frequency, HIFU single element transducers for treating the small and shallow tumors. Simulation tools were first used to optimize the aperture size, focal gain, focal zone dimension and acoustic pressure intensity. Prototype devices were subsequently fabricated and evaluated. The experimental results show that $LiNbO_3$ single crystal is a promising material for making high frequency HIFU transducers.

A. *Comparison of performance of PZT-4 or 8 and $LiNbO_3$*

HIFU transducers require piezoelectric materials with high Curie temperature and high electric and mechanical Q value to prevent overheating failure. As a result PZT-4 is the preferred material for the design of low frequency HIFU transducers.

The thickness of PZT-4 ceramics will decrease to 0.16 mm if the operating frequency is increased to 10 MHz. The aperture for good impedance matching if there is no external tuning is around 6 mm due to its large dielectric constant based on the KLM modeling.

$LiNbO_3$ crystal on the other hand has a much higher sound velocity and much lower dielectric constant than PZT-4 [18]. So the thickness is in the range of 0.32 mm for 10 MHz operations and the aperture is 24 mm diameter for a good electrical impedance matching. This means transducer can allow a higher driving voltage and focal gain. $LiNbO_3$ also offers additional advantages for HIFU operation. There is no aging concern due to its highest Curie temperature among piezoelectric materials. De-poling is of no concern due to its very high coercive field (higher than breakdown electric field). There is less heat generation due to its high electric and mechanical Q value.

A commercial software PiezoCAD (Sonic Concepts Inc., Woodinville, WA) was used to calculate the electrical impedances of PZT-4 and $LiNbO_3$ 1-3 composite. The result shows that the optimal aperture size is around 22- 24 mm for $LiNbO_3$ crystal due to the electrical impedance.

B. *Beam profile simulation*

The relative pressure amplitude in the focal zone of spherically focused, circular aperture is related to aperture size even if the f-number is constant [19], which suggested a ratio of focal strength in the range of 0.05 –0.2 to obtain a strong focal gain. The smaller the number, the stronger the focal gain. However, very low f-number is not recommended for a transducer because the near acoustic field would be distorted. As a result most transducers in HIFU applications have an f-number of one.

A useful approach to compare relative acoustic pressure for transducers of different aperture size is to use the FIELD II software [20]. FIELD II can also provide detail information about focal zone dimension. Figure 1 shows the axial intensity distribution for different aperture sizes.

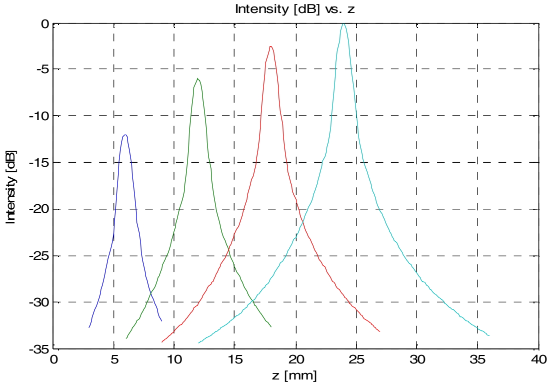

Fig. 1. Comparison of the acoustic intensity along the axial direction around the focal depth for the different aperture sizes: from left to right (diameters of 6 mm, 12 mm, 18 mm, 24 mm; f-number 1 for all cases)

It is necessary to know the acoustic intensity value at the transducer surface to estimate the acoustic intensity at the focal point. Most models cannot predict the acoustic pressure at the boundary between the loading medium and transducer surface. Finite Element Analysis software PZFlex from Weidlinger Associates (Mountain View, CA) was used to estimate the acoustic intensity at the transducer surface as a function of the driving voltage. The results from FIELD II and PZFlex simulation indicate that focal point intensity as high as 5000 W/cm^2, which is in the required level for most tissue necrosis and ablation applications.

II. EXPERIMENTAL RESULTS

A. *Transducer fabrication*

1-3 composites were prepared by the conventional dice-and-fill method. The pitch was 175 µm and kerf width was 25 µm. EPOTEK 301 (Epoxy Technologies, Billerica, MA) was used to fill the kerfs. The composite was lapped to the thickness to 310 µm. Press focusing was used to achieve the surface curvature for self-focusing. A conductive silver-epoxy matching and backing layer was used for acoustic matching and to ensure a good electrical connection over the surface of the composite. Detail of fabrication procedures can be found in Cannata et al., 2003 [21]. Figure 2 shows a picture of the prototype transducer.

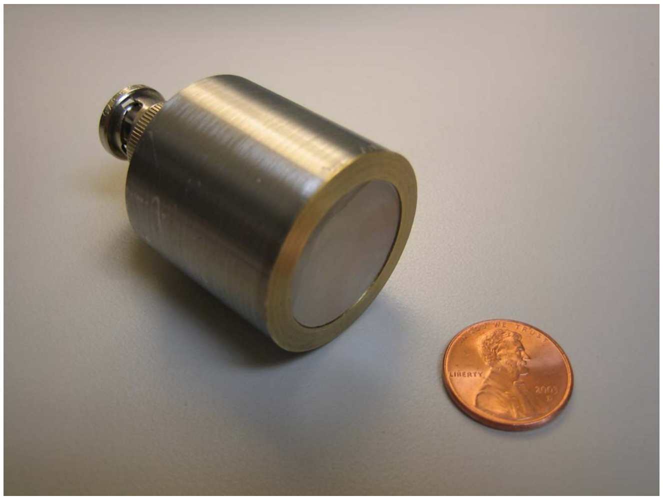

Figure 2 Picture of prototype transducer

B. *Impedance, pulse resonse and beam profile*

The impedance spectrum of the transducer was measured by an Agilent 4294A Impedance Analyzer. Figure 3 shows the results.

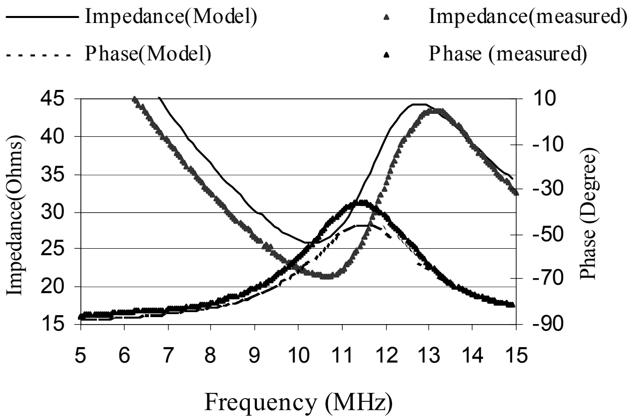

Figure 3 Comparison of impedance spectrum between model simulation PiezoCAD and measurement results

The one-way transmit sound field was measured with a needle hydrophone (HGL-0085, Onda Corp., Sunnyvale, CA). An ultrasonic analyzer (5900PR, Panametrics Inc., Waltham, MA) was used to excite the transducer and a digital oscilloscope (LC534, LeCroy Corp., Chestnut Ridge, NY) was used to record the waveform acquired by the hydrophone. The transducer was driven by 1µJ. After alignment, the maximum peak-to-peak voltage point along the beam axis was found. The time-domain waveform at the maximum peak-to-peak voltage point was recorded and its spectrum was calculated as in the Figure 4. The –6dB axial beamwidth was 93 µm which matches well with the theoretical value of 83 µm. Lateral and axial beam profiles at the focal depth were shown in Figure 5(a) and (b) respectively. The –6dB lateral beamwidth was 160 µm and is also in good agreement with the theoretical value of 147 µm. Equations for theoretical calculation can be found in Foster et al., 2000 [22].

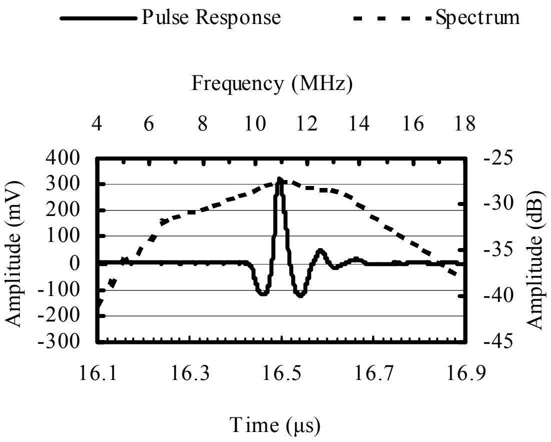

Figure 4 Pulse response measured by Hydrophone

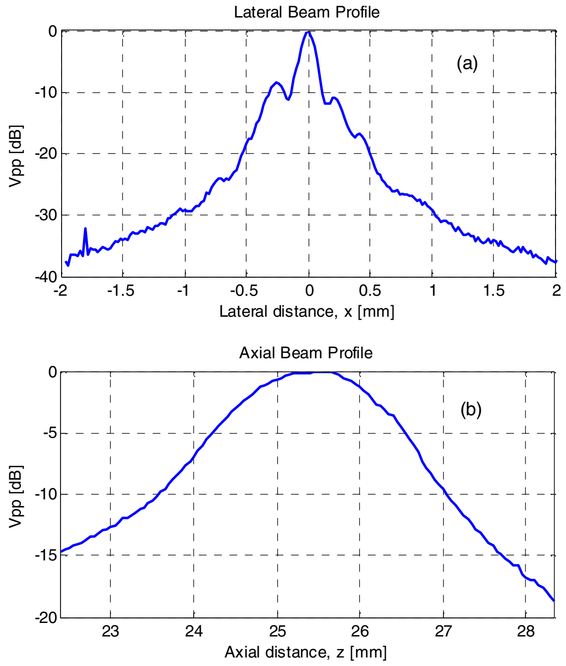

Figure 5. Beam profiles of the $LiNbO_3$ transducer: (a) lateral, (b) axial

Figure 6 shows a Schlieren image of the beam produced by the transducer obtained by OptiSon® from Onda Corp. The transducer was driven by continuous wave at 10.5 MHz.

Figure 6. Focal point beam profile mapped by Schlieren system

III. DISCUSSIONS AND FUTURE WORK

Results obtain in this work demonstrated that lithium niobate single crystal is a promising material for designing and fabricating large aperture high frequency HIFU transducers. With a matching layer, the wide bandwidth allows for easy frequency switching albeit sacrificing the capability of power delivery. This design may be useful for applications where power requirement is moderate but flexibility in depth of penetration and depth of focus is more crucial. For high power applications where frequency modulation is not needed, a better design would be to remove the matching layer. This is currently being pursued.

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