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Design and Fabrication of Broadband Graded Ultrasonic Transducers with Rectangular Kerfs

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Abstract

Broadband ultrasound imaging is capable of achieving superior resolution in clinical applications. An effective and easy way of manufacturing broadband transducers is desired for these applications. In this work, a graded material in which the piezoelectric plate is mechanically graded with rectangular grooves is introduced. Finite Element Analysis (FEA) demonstrated that the graded piezoelectric material could achieve a broadband time-domain response resulted from multiple resonant modes. Experimental tests were carried out to validate these theoretical results. Based upon the FEA designs, several single-element transducers were fabricated using either a non-diced ceramic or a diced graded ceramics. A superior bandwidth of 92% was achieved by the graded transducer when compared to a bandwidth of 56% produced by the non-diced ceramic transducer at the expense of a reduced sensitivity.

I. INTRODUCTION

Ultrasonic transducers have been widely used in various fields including nondestructive evaluation and medical diagnosis. The need for improved image resolution has prompted intensive studies in developing broadband transducers. Broadband transducers not only satisfy the requirement of the improved spatial resolution, but also offer the advantage of allowing for harmonic imaging.

A single-element piezoelectric transducer structurally consists of matching and backing layers in addition to the active piezoelectric material. Basically, any change of a component of the transducer will affect its performance. There are numerous reports in the literature that demonstrate the effectiveness in enhancing transducer bandwidth by optimizing the acoustic properties of individual components. Transducer bandwidth can be improved by:

1. optimized matching or backing layers;
2. optimized structure design;
3. improved piezoelectric materials

In conventional transducer design, a basic idea was that a heavy (higher acoustic impedance) backing that matches the acoustic impedance of the piezoelectric material could achieve a wider bandwidth and a light backing (lower acoustic impedance) could achieve higher sensitivity. But these improvements are limited and cannot achieve better bandwidth and sensitivity simultaneously. Since the 1950s optimizing matching layers has been explored as a means of designing broadband transducers [1]. Desilets et al [2] derived a formula of impedance relationship for two matching layers based upon KLM equivalent circuit model. The results were widely adopted for optimizing matching layers in broadband transducer design. Even so, efforts to optimize the matching layer design have been continuing [3–5]. Hossack et al [6] reported an active piezoelectric matching layer that was incorporated into a novel transducer.

Sonar or underwater transducers because of their large size are more amenable for performance enhancement via structural modification. Butler [7] reported that adding an inactive compliant material in the middle of tonpilz transducer could produce triple resonances, causing a broadband response. The work by Coates, 1991, showed a compound-head transducer design intended to offer broadband behavior [8]. Other compound-structure transducers, like triple-layered piezoelectric bimorph and sandwiched piezoelectric transducers, are often seen in many ultrasound applications [9–11]. These works proved that compound-structures of active multiple piezoelectric layers or inactive materials may be useful to produce multiple resonances and broadband performance.

To improve or change the piezoelectric material is another approach of broadband transducer design. Traditional piezoelectric composites and high coupling coefficient materials belong to this category [12,13]. To achieve a particular characteristic of the piezoelectric material, usually special processes or designs are required. One such approach is to use inversion layer LiNbO_3 (LNO) single crystal was obtained after it is annealed at 1100°C [14]. The inversion layer LNO transducers have been shown to gain wider bandwidth than conventional transducers [15]. In graded transducers the structural characteristics of the piezoelectric material is physically changed, which may be one of the more effective and easier manufacturing methods to achieve the broadband. Physically graded piezoelectric ceramics were constructed by mechanically dicing a number of fine triangular grooves (kerfs) into one surface of a piezoelectric plate. Graded transducers were manufactured using the graded piezoelectric plates when their kerfs were filled with appropriate fillers. The graded transducer is believed to have a broadband performance because the graded piezoelectric material has an effectively graded piezoelectric parameter and/or applied electric field which was supposed to result in the broadband performance of the graded transducer [16,17].

II. Graded Ceramics and Transducer Fabrication

A. Triangular Kerf Test

Graded piezoelectric PbTiO_3 ceramics with triangular V-grooves was fabricated and tested. A hubless metal V shape blade with a 30° angle (Disco Corp, Japan) was used to dice the V-grooves by dicing saw (Thermocarbon, Tcar 864-1). The dicing speeds were 16,000 RPM at 0.7mm per second for the V groove cuts. Fig. 1 shows a SEM image of PbTiO_3 ceramic with the graded V-grooves on its surface, where the angle of the V-groove was 30° . Between the two V-grooves there was a $5\text{ }\mu\text{m}$ flat area, and the pitch equals $32\text{ }\mu\text{m}$. Fig.1 shows that the V-grooves had round angles, and the wedges between two V grooves could be easily broken. The real V shape grooves are difficult to obtain because the ceramics are brittle. On the other hand, the V-grooves will result in a complex vibration of the piezoelectric materials and the shape of the V-grooves may affect the radiation pattern of the acoustic field.

B. Rectangular Kerf and Partial Composite Design

Since the V-groove kerfs of the graded piezoelectric plate have to be diced using special blades, and the slope of the triangles might affect the acoustic field distribution. It then appeared that rectangular kerfs might be an easier way for producing graded piezoelectric plates. Rectangular kerfs were diced on a surface of ceramics with a depth that is less than half of the ceramics' total thickness. After the polymer filler was applied to the kerfs, the resultant active transducer material consisted of one half of 2–2 or 1–3 composite and one half of monolithic ceramic, effectively forming a rectangular graded-material. In this study, circular plates of PbTiO_3 (PT) ceramics (EDO, thickness = $150\text{ }\mu\text{m}$, radius = 3 mm) were used to make graded transducer; kerfs with $70\text{ }\mu\text{m}$ depth were diced on one side of the plate by a mechanical programmable dicing saw (Thermocarbon, Tcar 864-1) with a $20\text{ }\mu\text{m}$ width hubbed metal blade (ASAHI Diamond Industrial Co., Ltd). The dicing speeds were 23,000 RPM at 1.0mm per second. The

pitch was 40 μ m. A SEM image of the graded ceramics cross-section is shown in Fig. 2. These rectangular graded-materials eliminate the technical problem associated with the V grooves.

C. Transducer Fabrication

In this study, we used PbTiO₃ ceramics and the rectangular kerfs were diced on the one surface. A mixture of silver powder and epoxy was used as the kerf filler of the graded ceramics and the first matching layer of the transducer. Parylene and a lossy conductive epoxy were used as the second matching layer and backing layer, respectively. This recipe of the single-element transducer has been widely known because of its reliable performance [18,19]. The designed center frequency for this device was 15~20MHz.

The transducers were fabricated using the rectangular graded-PbTiO₃ ceramics shown in Fig. 2. A $\lambda/4$ silver epoxy matching layer made from a mixture of three parts 2–3 μ m silver particles (Adrich Chem. Co., Milwaukee, WI) and 1.25 parts Insulcast 501 epoxy (American Safety Technologies, Roseland, NJ) was cast onto the negative electrode side (diced side) with the aid of an adhesion promoter (Chemlok AP-131, Lord Corp., Erie, PA). This matching layer was centrifuged at 2000 g for 10 minutes to increase the acoustical impedance and to ensure conductivity over the entire active aperture. The material properties of the passive materials and PT ceramics are shown in TABLE I and II. After curing, the matching layer was lapped down to approximately $\lambda/4$ thickness using a coarse-to-fine grit scheme, with a final lapping particle diameter of 12 μ m. A lossy conductive epoxy (E-SOLDER 3022, Von Roll Isola Inc., New Haven, CT) then was cast on the wafer as the backing material. A lathe was used to shape the matching, piezoelectric, and backing layers into the desired acoustic stack diameter. This fabrication step also served to electrically isolate the conductive matching and backing layers. The positive lead wire was secured to the backing layer with an additional amount of conductive epoxy. A brass housing was placed concentrically with the acoustic stack, and an insulating epoxy was poured into the void between the housing and the device. A layer of chrome/gold then was sputtered across the transducer face, and a quarter-wavelength thick Parylene (Specialty Coating Systems, Indianapolis, IN) film was deposited on the gold electrode surface. Final transducers were housed in modified SMA connectors. In order to compare the performance of the graded transducer and regular ceramic transducer, a regular bulk PbTiO₃ ceramic transducer was built. The thickness of the ungraded flat PbTiO₃ transducer was 140 μ m.

III. Finite Element Analysis

FEA simulation of the graded ceramics with rectangular kerfs and the transducer fabricated from this material was carried out by PZFlex (Weidlinger Associates INC, Los Altos, CA) with the following specification: the total thickness of PbTiO₃ ceramics was 150 μ m, the depth of rectangular kerf was 70 μ m. The kerf width was 20 μ m and the pillar width between the two kerfs was 20 μ m. Water was assumed to be the loading medium in FEA. Electrical impedances of a single graded ceramics without kerf filler, graded material after the filler was applied to the kerfs, and graded transducer are shown in Fig. 3. Fig. 3(a) is the resonant impedance of single graded PbTiO₃ plate without kerf filler. This figure shows two resonant impedance peaks, which correspond to the piezoelectric thickness of 80 μ m and 150 μ m. When the kerfs were filled with the silver epoxy, another resonant peak appeared between the previous two fundamental resonances [Fig. 3(b)]. The graded transducer composed of a lossy conductive backing and matching layers of silver/epoxy and Parylene showed a 4th resonant peak [Fig. 3(c)]. A traditional piezoelectric resonator has a fundamental resonance and odd-order resonances in the resonant frequency spectrum. The graded material on the other hand produces two fundamental resonances. Fig. 4 shows the FEA modeling results of pulse-echo

performance of the graded transducer. The bandwidth is quite wide reaching a 95% bandwidth at -6dB .

IV. Experiments

The acoustic performance of the transducer was tested in a degassed, deionized water bath in pulse/echo mode by reflecting the signal off an X-cut quartz target placed at the near-far field transition point. For pulse/echo measurements, transducer excitation was achieved with a Panametrics (Waltham, MA) model 5900PR pulser/receiver. The reflector waveforms were received and digitized by 500-MHz LC534 Lecroy (Chestnut Ridge, NY) oscilloscope set to $50\text{-}\Omega$ coupling. Further information on the experimental arrangement using the Panametrics pulser can be found in References [18–21]. The resonant impedance was measured by a HP 4194 Impedance Analyzer.

V. Results and Discussions

Fig. 5(a) shows the electrical impedance of a single graded PbTiO_3 ceramics with rectangular kerfs, Figure 5(b) shows the electrical impedance after the kerfs of the graded ceramic were filled with the silver/epoxy filler and a $\lambda/4$ silver/epoxy matching layer. Figure 5(c) shows the result of the final transducer with a second matching layer and backing. The pulse-echo spectra of the graded transducer and the regular bulk ceramic transducer are shown in Fig. 6 and Fig. 7 respectively. The center frequency is at 15MHz . The -6dB bandwidths of partial composite graded transducer and regular uniform transducer are 92%, and 56%, respectively [Fig. 6 and Fig. 7]. The PZFlex FEA modeling represents a theoretical analysis under ideal conditions and a discrepancy in the parameters of active piezoelectric, matching and backing materials might exist between the assumed and real values, resulting in the difference between the FEA and experimental results. Nevertheless FEA is still a convenient tool for looking at the dependence of the transducer performance on the graded piezoelectric and filler materials without actually fabricating the device and doing the experiments.

The electrical impedance of the graded transducer varies within the 92% bandwidth. The variation of the electrical impedance can cause signal ringing problems for mismatching with standard 50 Ohm . Improving the impedance matching within the band will yield a better pulse-echo performance. The peak to peak output voltages (V_{pp}) of the echoes for the graded transducer (Fig. 10) and for regular uniform transducer (Fig. 11), V_{graded} and V_{uniform} , are respectively 1.29V and 2.53V . Here the Panametrics pulser was kept at the same setting conditions. The difference of the sensitivities between the graded and uniform transducers could be estimated from the output voltages, $\Delta V_{pp} = 20 \times \log(V_{\text{graded}}/V_{\text{uniform}}) = -5.85(\text{dB})$. That means that while the graded transducer gained a wider bandwidth, its sensitivity was lower by -5.85dB than that of a uniform regular transducer.

VI. Conclusion

In this study, rectangular kerfs were diced on the surface of piezoelectric ceramics to make a graded material. FEA modeling showed that the graded materials give rise to multiple resonances. Two single element transducers were fabricated to validate the theoretical analyses. While the bandwidth of the graded transducer with the rectangular kerfs was 92% whereas regular uniform transducer was 56%, the sensitivity of the graded transducer dropped. The experimental results are consistent with the theoretical results. The graded material can be easily manufactured, and has a lower acoustic impedance. Graded piezoelectric materials with rectangular kerfs, because of their wider bandwidth, are very attractive for various applications in medical imaging and nondestructive evaluation.

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References

1. Collin RE. "Theory and Design of Wide-Band Multisection Quarter-Wave Transformers,". Proc IRE Feb 1955:179–186.
2. Desilets CS, Fraser JD, Kino GS. "The Design of Efficient Broad-Band Piezoelectric Transducers,". IEEE Trans Sonics and Ultrason 1978;SU-25(3):115–125.
3. McKeighen RE. "Optimizing Transducer Design for Medical Imaging,". IEEE Engineering in Medical & Biology Society 11th Annual International Conference 1989:0402–0404.
4. McKeighen RE. "Optimization of Broadband Transducer Designs by Use of Statistical Design of Experiments,". IEEE Trans Ultrason Ferroelect Freq Control 1996;43(1):63–70.
5. Chao MK, You YL, Lai WP. "Transducer Characterization and Optimization,". 2000, IEEE Ultrasonic Symposium 2000:1097–1100.
6. Hossack JA, Auld BA. "Multiple Layer Transducers for Broadband Applications,". Ultrasonics Symposium 1991:605–610.
7. Butler SC. "Triply Resonant Broadband Transducers,". Oceans MTS/IEEE 2002;4:1334–1341.
8. Coates RFW. "The Design of Transducers and Arrays For Underwater Data Transmission,". IEEE J of Oceanic Eng 1991;16(1):123–135.
9. Ha SK. "Analysis of the asymmetric triple-layered piezoelectric biomorph using equivalent circuit models,". J Acoust Soc 2001;110(2):856–864.
10. Rogacheva NN, Chou CC, Chang SH. "Electromechanical Analysis of a Symmetric Piezoelectric/Elastic Laminate Structure: Theory and Experiment,". IEEE Trans Ultrason Ferroelect Freq Control 1998;45(2):185–194.
11. Liu S. "Sandwiched Piezoelectric Ultrasonic Transducers of Longitudinal-Torsional Compound Vibrational Modes,". IEEE Trans Ultrason Ferroelect Freq Control 1997;44(6):1189–1197.
12. Cheng KC, Chan HLW, Choy CL, Yin Q, Luo H, Yin Z. "Single Crystal PMN-0.33PT/Epoxy 1–3 Composites for Ultrasonic Transducer Applications,". IEEE Trans Ultrason Ferroelect Freq Control 2003;50(9):1177–1183.
13. Hackenberger W, Jiang X, Rehrig P, Geng X, Winder A, Forsberg F. "Broad Band Single Crystal Transducer For Contrast Agent Harmonic Imaging," 2003". IEEE Ultrasonic Symposium 2003:778–781.
14. Zhou QF, Cannata J, Huang CZ, Guo HK, Marmarells V, Shung KK. "Fabrication and Modeling of Inversion Layer Ultrasonic Transducers Using LiNbO₃ Single Crystal,". 2003 IEEE International Ultrasonics Symposium 2003:1035–1037.
15. Nakamura K, Fukazawa K, Yamada K, Saito S. "Broadband ultrasonic transducers using a LiNbO₃ plate with a ferroelectric inversion layer Ultrasonics,". IEEE Trans Ultrason Ferroelect Freq Control 2003;50(11):1558–1562.
16. Yamada K, Sakamura JI, Nakamura K. "Broadband Transducer Using Effectively Graded Piezoelectric Plates for Generation of Short-Pulse Ultrasound,". Jpn J Appl Phys 1999;38(Pt 1):3204–3207.
17. Yamada K, Sakamura JI, Nakamura K. "Equivalent Network Representation for Thickness Vibration Modes in Piezoelectric Plates with a Linearly Graded Parameter,". IEEE Trans Ultrason Ferroelect Freq Control 2001;48(2):613–616.
18. Cannata JM, Ritter TA, Chen WH, Silverman RH, Shung KK. "Design of Efficient, Broadband Single-Element Ultrasonic Transducers for Medical Imaging Applications,". IEEE Trans Ultrason Ferroelect Freq Control 2003;50(11):1548–1557.
19. Snook KA, Zhao JZ, Alves CH, Cannata JM, Chen WH, Meyer RJ Jr, Ritter TA, Shung KK. "Design, fabrication, and evaluation of high frequency, single-element transducers incorporating different materials,". IEEE Trans Ultrason Ferroelect Freq Control 2002;49(2):169–176.
20. Shung KK, Zipparo M. Ultrasonic Transducers and Arrays. IEEE Eng Med Biol 1996;15:20–30.

21. Lockwood GR, Hunt JW, Foster FS. "The design of protection circuitry for high-frequency ultrasound imaging systems,". *IEEE Trans Ultrason Ferroelect Freq Control* 1991;38(1):48–55.

Fig. 1. SEM of graded PbTiO₃ ceramics with V-kerf which shows a bottom round angle and easily broken wedges.

Fig. 2.
SEM of partial 2-2 composite with rectangular kerfs.

Fig. 3. FEA modeling resonant impedances of 2–2 partial composite with air kerf filler (a), 2–2 composite with silver/epoxy ker filler (b), and partial composite transducer (c).

Fig. 4.
FEA modeling pulse-echo of partial composite transducer.

Fig. 5.

Experimental results of graded transducer, (a) single partial composite without kerf filler, (b) partial composite with the silver/epoxy filler and matching layer, (c) graded transducer

Fig. 6.
Pulse-echo measurement of partial composite graded transducer.

Fig. 7.
Pulse-echo measurement of undiced flat ceramics transducer.

TABLE I

PASSIVE MATERIAL, PROPERTIES USED IN THE TRANSDUCER DESIGNS.

Materials	Use	ρ (g/cm ³)	c (m/s)	Z_a (MRayl)	$Loss$ (dB/mm)
E-Solder 3022 (Centrifuged)	Conductive backing	3.20	1850	5.92	110
Insulcast 501 and 2–3 μ m silver particles	Kerf filler and Matching layer	3.86	1900	7.3	13.8
Parylene	Matching layer	1.18	2200	2.6	N/A

TABLE II

PIZOELECTRIC MATERIAL PARAMETERS

Materials	k_t	$\epsilon^s \epsilon_0$	ρ (g/cm ³)	c (m/s)	Q_m	Q_E	Z_a (MRayl)
PbTiO ₃ Ceramics	0.49	200	6.9	5200	120	111	35.9