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Cost-Effective Screen Printed Linear Arrays for Medical Imaging Fabricated Using PZT Thick Films

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***Abstract*—Screen- and pad-printed single-element ultrasonic transducers have been successfully commercialized over the recent years. Typically, PZT (Lead Zirconate Titanate) thick films are pad- or screen-printed on a curved ceramic substrate acting as integrated backing layer and providing mechanical pre-focus. The center frequency ranges between 8 MHz and 80 MHz. The devices are characterized by good sensitivity as well as high relative bandwidth. The main objective of the presented work has been to apply a similar technology to manufacture multi-element transducers enabling novel cost-effective fabrication of imaging arrays for medical applications. The thick film arrays have been integration-tested using a commercial ultrasound scanner (BK Ultrasound bk3000). The integration test revealed that the 32-element thick film transducers are compatible with a commercial scanner, have a frequency range of 7.5 MHz to 12 MHz, and a TX bandwidth of 70%. Moreover, the transducers support linear array beamforming as well as phased array beamforming. Here 32-element transducers are presented, however the technology can easily be extended to fabrication of transducers with 128 or more elements.**

Keywords—PZT thick film, ultrasonic transducer, screen printing, array transducer, linear array, printed transducer

I. INTRODUCTION

The development in ultrasonic imaging is currently driven by a tremendous increase of computational power and miniaturization of portable devices [1]. This is also the enabler for relatively low-cost high quality imaging systems, which also calls for cost-effective solutions for multi-element imaging transducers. Currently a few major trends in medical ultrasound are noticeable. A significant effort goes into the development of cMUTs (Capacitive Micro-machined Ultrasonic Transducer) [2], but this solution is mainly suitable for high volume products due to the need for very high upfront investments. Another trend, especially in higher frequency applications (above 20 MHz) is to down-scale the 2-2 composite technology combined with a heterogeneous integration approach, which in essence leads to increased production costs. There are also reports on solutions where the elements are defined by the electrode pattern (kerf-less design) rather than by dicing, leading to significant simplification of the production process hence reducing production costs [3,4]. However in many cases the kerf-less design compromises significantly the electro-acoustic properties of the transducer (e.g. cross-talk) [5].

This paper presents an alternative solution based on the screen-printed PZT thick film approach, where the whole transducer structure is fabricated using an additive ceramic process. Currently, a similar process is used for commercial production of high frequency single-element transducers [6,7].

The main objective of the presented work is to apply PZT thick film technology to manufacture multi-element transducers enabling a novel method for cost-effective fabrication of imaging arrays for medical applications (patent pending). The main premise of the investigation is that elements of the array can be defined only by the top electrode pattern, since the low lateral coupling of the printed PZT leads to a low cross-talk between the elements. This would be the enabler for cost-effective production of kerf-less transducers.

The paper starts with an introduction to PZT thick film technology. Then the test structures of multi-element transducers are presented, followed by basic electric and electro-acoustic characterization. Final testing results using the commercial BK Ultrasound bk3000 ultrasonic system are shown as well, together with conclusions and an outlook for the future development.

II. PZT THICK FILM TECHNOLOGY

Typically, PZT (Lead Zirconate Titanate) thick films are pad- or screen-printed on a ceramic substrate which can also act as integrated backing layer. Due to the so called clamping effect of the substrate, the films exhibit specific porosity patterns (see Fig. 1), leading to an anisotropic distribution of electric and electro-acoustic properties [6].

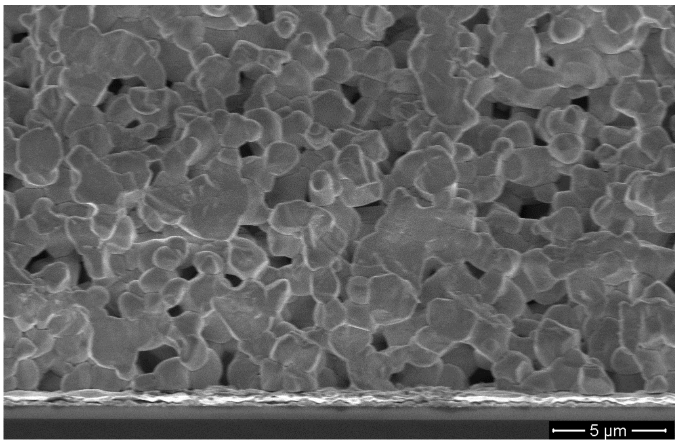

Fig. 1. SEM image of PZT thick film

This effect is manifested in a significant difference between the thickness coupling coefficient and lateral coupling coefficients. Typically $k_t = 0.47$ and $k_p = 0.29$ [7].

Screen- and pad-printed single-element ultrasonic transducers have been successfully commercialized over the recent years. A typical transducer consists of an acoustically matched ceramic substrate, on which a bottom electrode, an active PZT layer and a top electrode are printed in consecutive steps. Thicknesses of the PZT layer ranging between 10 µm and 100 µm are achievable leading to a frequency range of some 80 MHz to 8 MHz, respectively. The PZT thick film involves firing of metal electrode layers and sintering of the PZT layer at temperatures above 800 °C.

III. Multi-Element Transducers

PZT thick film technology has been used to manufacture 32-element transducers with a center frequency of around 11 MHz. A schematic cross-section of the fabricated array transducers is given in Fig. 2. The effective length of the elements is 4.5 mm.

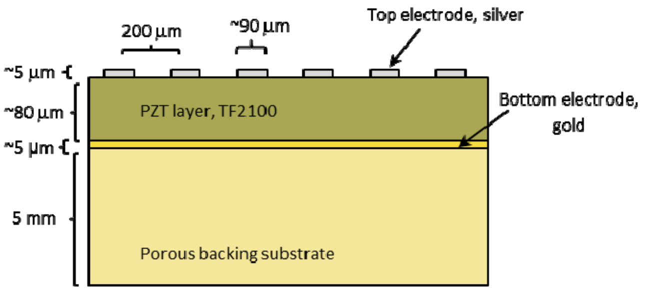

Fig. 2. Schematic cross-section of the fabricated multi-element transducer (not to scale)

The transducers have been fabricated using screen printing technique, where the gold bottom electrode has been deposited first followed by deposition of the TF2100 PZT thick film. The top electrodes defining the elements of the array have been printed as well using silver fine line pattering.

A 5 mm thick ceramic substrate acting as backing material has been used. The backing material thickness as well as the porosity has been matched in order to assure that the acoustic wave traveling towards the substrate is fully attenuated. Several devices at a time have been printed on one larger substrate/wafer. The individual devices have been separated using a diamond saw after the entire printing process. The structures have been poled at elevated temperature and an electric field of 10 kV/mm.

IV. Packaging and Interconnect

Typically, the packaging and interconnect of multi-element transducers is one of the major technical challenges when it comes to design and manufacturing of array devices. The presented solution is based on the flip-chip technique known from the silicon industry where the functional device (chip) is connected to the PCB using solder bumps deposited on the top of the device. Hence the device is finally attached “upside down” with the active side facing the PCB. This technique turns out to be very beneficial for packaging of the acoustic transducers. In the presented solution the top electrode pattern has been designed to match the pattern of conductive pads on a PCB carrier with an opening enabling acoustic coupling to the medium (Fig. 3). As a final step a polymeric quarter-wave matching layer is added.

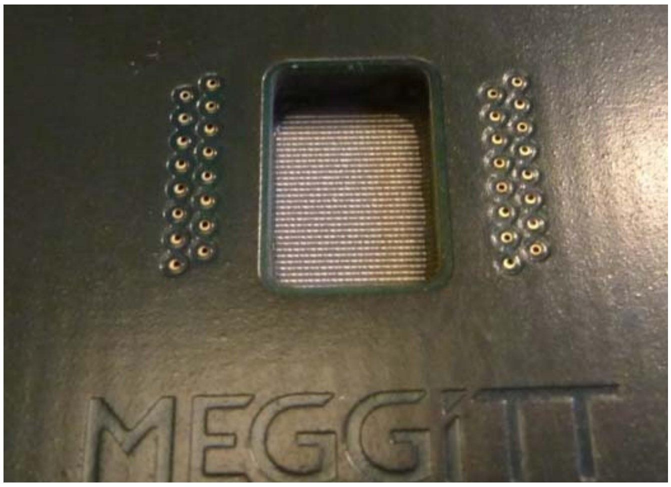

Fig. 3. Top view of a PCB-packaged 32-element transducer

Fig. 4 depicts the flip-chip mounted 32-element transducer, where the backing substrate is easily visible. It also shows another opening designed for another multi-element transducer. This packaging solution has been used for characterization of the transducers and it can also be used for packaging of final devices being integrated into ultrasonic probes.

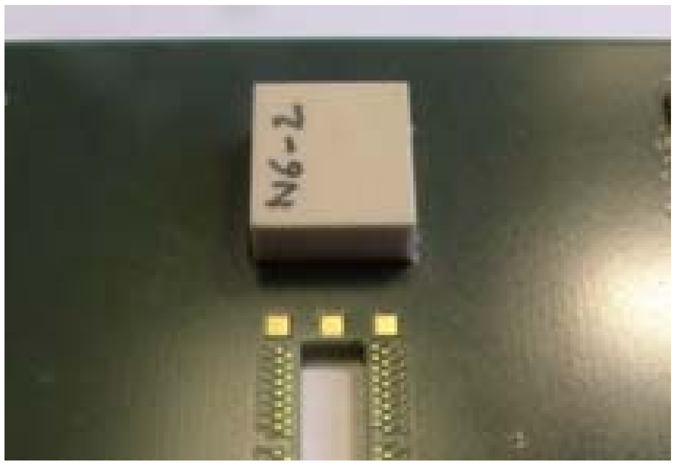

Fig. 4. Flip-chip mounted array chip

V. Basic Properties of the Devices

Basic dielectric properties of the imaging elements have been characterized at 1 kHz at the fully packaged stage. The impact of the parasitic capacitance has been compensated by subtraction of the capacitance values measured for each individual channel of the PCB without the device. The distribution of capacitance over all elements of the tested arrays is given in Fig. 5. It indicates very good reproducibility of the dielectric properties over the range of the elements. The capacitance variation between the elements is less than 14% in average.

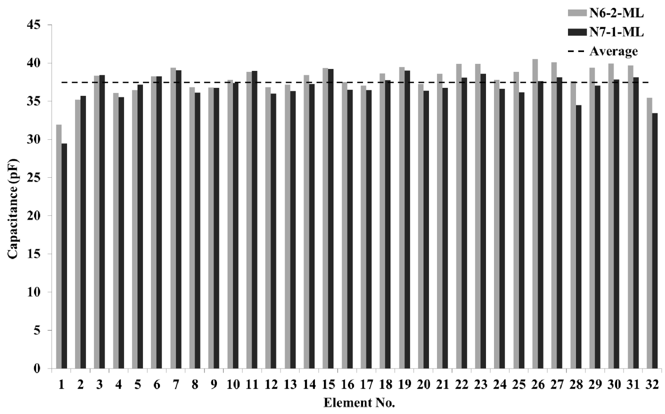

Fig. 5. Capacitance distribution across elements of two different arrays

The test arrays have been characterized at the transducer level using a pulse-echo system consisting of a JSR DPR500 system and a digital oscilloscope (Agilent DSO8064). The samples have been immersed in demineralized water with an acoustic reflector. Several arrays have been tested showing center frequencies ranging from 11 MHz to 13 MHz. A typical pulse-echo response is given in Fig. 6 for the case of a 30 ns 300 V excitation measured with the reflector located at a distance of 5 mm from the transducer.

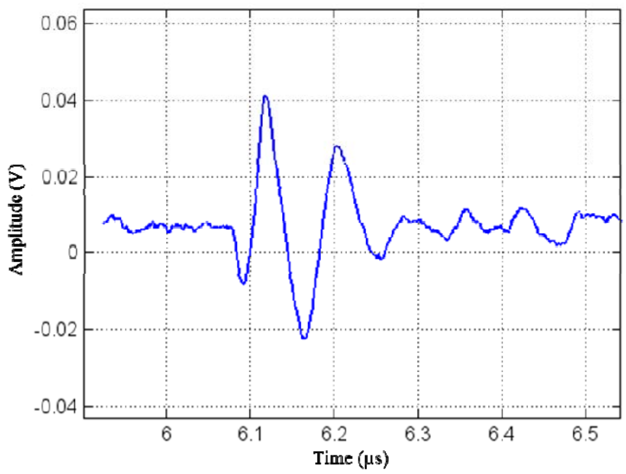

Fig. 6. Typical pulse-echo response, reflector placed 5 mm away from the transducer (without acoustic lens)

Sensitivity measured as the ratio of response voltage amplitude and excitation voltage amplitude expressed in dB has been measured using the same pulse-echo system for all the individual elements of several test structures. In average, a sensitivity of -65.6 dB has been measured. The distribution of the sensitivity across the tested arrays is presented in Fig. 7.

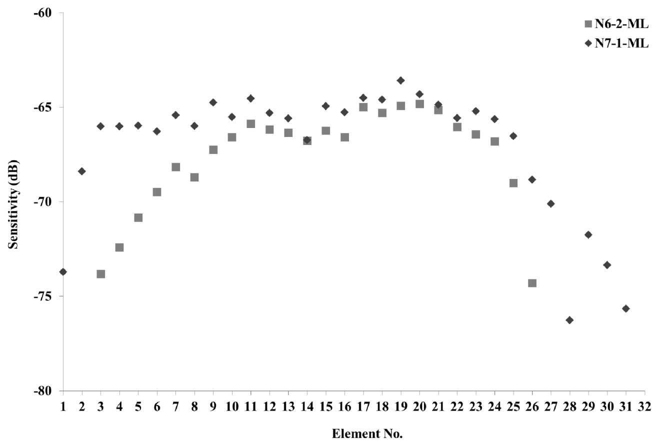

Fig. 7. Distribution of sensitivity across elements of two different arrays

Other electro-acoustic parameters have been measured as well using the pulse-echo system (method for cross-talk measurement described in [8]). The summary is given in TABLE I. In general the transducers are characterized by good reproducibility of the properties.

TABLE I. SUMMARY OF BASIC ELECTRIC AND ELECTROACOUSTIC PROPERTIES OF FABRICATED DEVICES

Property	***Average***	***Std. dev.***
Capacitance (pF)	37.7	1.4
Diel. Loss (%)	2.3	0.2
Sensitivity (dB)	-65.6	2.6
Fractional Bandwidth (%)	55	11
Center Frequency (MHz)	11.4	1.9
Cross-Talk (dB)	-37.6	0.7

VI. ULTRASONIC IMAGING RESULTS

The thick film arrays have been integration-tested using a commercial ultrasound scanner BK Ultrasound bk3000 (see Fig. 8).

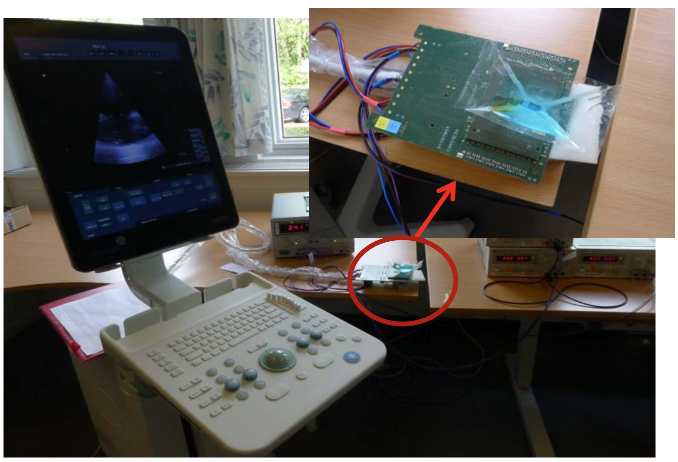

Fig. 8. Test setup including bk3000 ultrasonic system (inset: interconnect PCB with 32-element array transducer)

The integration test has shown that the 32-element PZT thick film transducers are compatible with a commercial scanner, have a frequency range of 7.5 MHz to 12 MHz, and a TX bandwidth of 70%. Moreover, the transducers support linear array beamforming as well as phased array beamforming.

Examples of the imaging results where a 32-element printed transducer with acoustic lens focusing in the elevation direction have been used in phased array mode are given in Fig. 9 and Fig. 10. The images show the capability of the kerf-less transducer arrays to control the phase independently on each element.

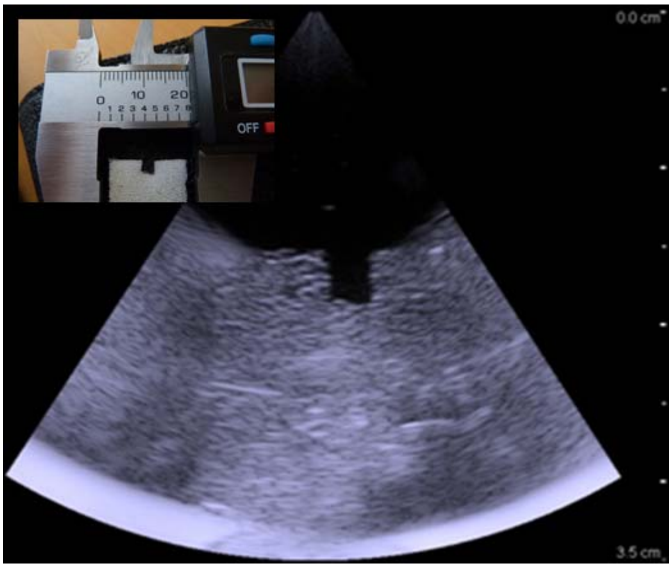

Fig. 9. Ultrasonic image of the phantom (inset: structure of phantom)

Fig. 10. Ultrasonic image of an index finger

VII. Conclusions

The performance of the linear arrays tested at the device level as well as at the system level show that printed PZT technology is suitable for cost-effective manufacturing of high- and mid-frequency linear arrays for medical imaging. The measured properties indicate very good reproducibility and repeatability within as well as between the devices. The presented devices operate at around 11 MHz but the technology enables fabrication of the multi-element devices covering the range of 8 MHz to 80 MHz. Moreover, the presented solution is easily scalable when it comes to the number of elements; hence devices comprising 128 or 256 elements are easily foreseeable.

The presented packaging solution has turned out to be a very useful tool for characterization of the individual array device. It is also believed that it can be applied for packaging of the final devices being a part of ultrasonic probes.

The 32-element PZT thick film transducers have been shown to be compatible with a commercial scanner, and to support linear array beamforming as well as phased array beamforming. Furthermore, the test shows that a 32-element array is sufficient to obtain images with well defined features.

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