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DOI
10.1002/adem.201800423

Publication date
2018

Document Version
Final published version

Published in
Advanced Engineering Materials

Development of Single-Fiber Piezocomposite Transducers for 3-D Ultrasound Computer Tomography

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Ultrasound Computer Tomography (USCT) medical imaging is a promising approach for early detection of breast cancer. At Karlsruhe Institute of Technology (KIT) a 3-D USCT system is developed. The region-of-interest (ROI) of 10 × 10 × 10 cm^3 volume is surrounded by a aperture of 2014 semi-spherical positioned ultrasound transducers. Results from a first patient study reveals the requirement of a significantly increased ROI to cover bodily variations. Design considerations and simulations show a demand for circular transducers with a diameter of ca. 500 μm, increasing the opening angle of the transducers to ca. 60°. Piezofiber composite technology is predestinated to simply provide circular transducers of the required dimensions. Moreover, piezocomposites based on single PZT (lead zirconate titanate $Pb[Zr_xTi_{1-x}]O_3$) fibers enable a cost-effective and series-production alternative to currently used dice-and-fill composites. A transducer design is presented which utilizes individually arranged single piezoceramic fibers with 460 μm in diameter within piezocomposite discs. As a result, fibers are independently addressable as single transducer elements allowing for the desired transducer arrangement. The electrical performance of each piezoceramic fiber is determined proofing a strong dependence both of the coupling coefficient and the resonance frequency from the transducer thickness. In further processing, the piezocomposite discs are connected to printed circuits, integrated into a cylindrical housing, and backfilled with polyurethane. Ultrasound characteristics such as sound pressure and opening angle are evaluated quantitatively. The results show that the transducer opening angles lie in the expected range, that the desired center frequency is achieved and that the bandwidth could be preserved compared to former dice-and-fill transducers.

1. Introduction

Breast cancer is the most common cancer that occurs in females.[1,2] The spreading probability of the tumor and, thus, the chances of survival are correlated to its size.[3,4] Therefore, early detection plays a vital role in reducing the cancer mortality.

The currently available imaging systems for breast cancer imaging have severe limitation and risks and their value for breast screening in general is therefore controversial debated. Ultrasound based 3D acquisition and reconstruction of speed of sound and attenuation images give a direct access to tissue types and cancer detection as proposed by Greenleaf in the 1980s.[5]

The gold standard system for breast cancer screening mammography offers only 2-D projection imaging of deformed breast by utilizing ionizing x-rays. MRI offers 3-D imaging but is expensive, requires contrast agents, and specialized radiologist for accurate diagnosis.

Subject of this work is a 3-D ultrasound computer tomography (3-D USCT) imaging system developed for early breast cancer detection.[5–7]

This system combines the good properties of existing medical imaging methods

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DOI: 10.1002/adem.201800423

(x-ray based mammography, sonography, MRI) while avoiding the downsides: harmless, non-ionizing low pressure ultrasound, reproducible undeformed 3-D images. Multi-modal imaging should offer the required sensitivity for the detection of early cancer and improved specificity to minimize false positives. Imaging is achieved by Synthetic Aperture Focusing Technique (SAFT) using a multistatic setup of 2041 ultrasound transducers, grouped into 157 Transducer Array Systems (TAS) embedded in a semi-ellipsoidal aperture (**Figure 1**). Each transducer has a center frequency of ca. 2.5 MHz. The 3 dB bandwidth (BW) and opening angle (OA) at 6 dB are 1 MHz and 36°, respectively.[8]

The current USCT 2.0 system covers a ROI of $10 \times 10 \times 10$ cm^3. Each of the 157 TAS consists of 13 rectangular transducer elements with $0.9 \times 0.9\,mm^2$ in size.[9] The transducer elements are fabricated by the dice-and-fill technology, thus, regularly distributed in a square grid, covering just the inner part of the TAS. Four transducer elements are used as emitters and nine as receivers (see Figure 1).

Results from the clinical trial with the University Hospital Jena indicated that a higher ROI is beneficial to cover a broader range of breast sizes and to adapt to the buoyance broadening effect of floating breasts.[6,7] The fundamental correlation between ultrasound transducer emission and reception sensitivity in the azimuth and elevation angle space is the transducer aperture size. It is well known from literature and antenna theory that a reduction in aperture size increases the opening angle and decreases the directivity.[10] In simulations it was shown that a reduction in size (side length) of the current generation transducer elements from 900 to 460 µm is required to realize an opening angle of ca. 60°. Wave simulations also revealed that a circular instead of the current rectangular aperture will result in additional homogeneity of the sound field.[11]

An increased opening angle, equivalent to omnidirectional transducer emission and reception, will lead to an increased illumination homogeneity for SAFT and more usable emitter-receiver-combinations for transmission tomography imaging among other benefits like improved bandwidth response over greater emission and reception combinations.[12] Moreover, coverage of the K-space, the spatial Fourier-domain, can be increased.[11] Besides, multimodal 3-D USCT method utilizing full-wave inversion imaging benefits from lower frequency components down to 0.5 MHz included in a broader bandwidth.

An irregular distribution of the elements would lead to a greater coverage of the ROI and a more homogeneous illumination. This is inspired by the compressive-sampling concept now used in many apertures of various imaging systems.[13,14]

For next generation 3-D USCT system, transducer opening angle and bandwidth should be improved to contribute to a homogeneous illumination and imaging contrast over the increased ROI. Furthermore, a reliable production technique enabling irregular arrangement of circular transducers with minimal spatial deviation is desired.

2. Experimental Section

2.1. Design

The design parameters for the development of the TAS based on single-fiber piezocomposite transducers were defined by simulations, starting from mono-chromatic assumption-based piston models to later more demanding 3-D finite element simulations.

2.1.1. Material Thicknesses

Considerations on tissue penetration and resolution trade-off indicate transducer frequencies in the low MHz range as suitable for the 3-D USCT. These frequencies define the PZT transducer thickness in the sub-millimeter to millimeter range. To predict suitable PZT thickness and matching layer thickness, one-dimensional (1-D) Krimholtz-Leedom-Matthaei (KLM) simulations have been performed, as it is commonly used for ultrasound transducer layout.[15] As precondition, a single-element PZT transducer with variable thickness and an acoustic impedance of ca. 30 MRayl ($1\ \text{Rayl} = \text{kg}\,\text{s}^{-1} \times \text{m}^2$) has been assumed. For matching layer an aluminum oxide composite TMM4 (Rogers Corp., Rogers, USA) has been selected. It exhibits an acoustic impedance of 6.4 MRayl which is optimal for single-layer matching between PZT and water. The simulations results are

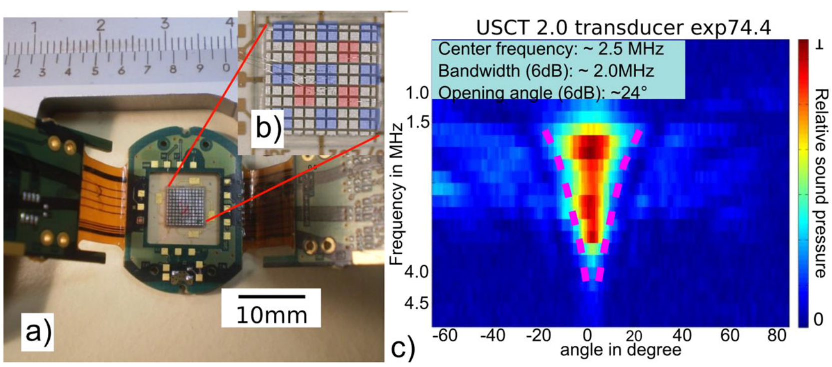

Figure 1. Transducer array system (TAS) for 3-D USCT 2.0 system. a) Inner components of one TAS. b) Close-up view on the piezoelectric elements. Four squares are connected by bonding to form one receiver (blue) or one emitter (red). The complete 2-D PZT array has a side length of 5 mm. c) Frequency versus angle for an exemplary emitter. The frequency-dependent boundary of the opening angle at ca. - 6 dB is indicated by a pink dotted line.

shown in **Figure 2**. From this, a PZT thickness of 750 μm has been chosen. Together with a 370 μm TMM4 matching layer as used in the USCT 2.0 configuration two resonance peaks occur. This is due to a mismatch of the resonance frequency and results therefore in a broadening of the bandwidth (see Figure 2 top).

2.1.2. Transducer Design

As 1-D KLM simulations are insufficient to analyze lateral and shear wave effects of a particular arrangement, higher spatial dimensional simulations are necessary. Finite element (FE) simulations in 2-D and 3-D were performed to analyze the influence of the materials and their oscillation modes on the transducer performance. For this, PZflex (Weidlinger Associates Ltd, Glasgow, UK) was applied as it supports simulation of piezoactive and non-piezoactive materials. The spatial meshing was selected at least three times the required minimal spatial Nyquist sampling. The temporal sampling rate of the simulation was derived automatically by the simulation tool. From the simulations, the resulting sound pressure far field in several cm water-to-transducer distance and the response values over angular and frequency domain can be extracted, as can be seen in Figure 2 bottom left and right.

The simulation results support the use of PZT fibers with 460 μm diameter and 750 μm thickness. The frequency response covers the expected angular and frequency range, which is ca. $\pm 25°$ and ca. 1…5 MHz, as can be seen in Figure 2e. The resulting pressure field is almost homogenous. There are no other significant oscillation modes visible than the desired longitudinal one as the pressure field seems undisturbed.

2.2. Fabrication

A random transducer element distribution within a 3-D USCT would be of great advantage to allow for the suppression of unwanted interactions between neighboring transducers and for the minimization of side lobes in imaging. Piezoceramic fibers enable for circular transducers and can be regularly or randomly arranged in piezocomposites.[16] Therefore, a pseudo-random TAS inspired by compressive sampling techniques has been developed, as shown in **Figure 3**. [17] The design criteria aimed for a homogeneous covering over the surface of the whole USCT aperture by a close arrangement of 157 TAS.

2.2.1. Single-Fiber Piezocomposite Transducer

To provide the required circular single transducer elements, piezoceramic fibers with 460 μm diameter (see Figure 3) were fabricated using fiber spinning technology.[18] A piezoceramic slurry, based on a commercial PZT powder (Sonox P505, CeramTec GmbH, Germany), was dispersed into a binder solution consisting of polysulfone as binder and *N*-methylpyrrolidone as solvent. The resulting piezoceramic slurry was extruded through a nozzle and deposited into a water bath. During phase inversion between solvent and water, the binder coagulates and solidifies the fiber geometry. Subsequently, the fibers were cut in length, dried, and sintered. More detailed information regarding fiber fabrication can be found elsewhere.[18]

In total, 13 fibers (17 in second iteration) were positioned into a mechanical mask to reproduce the desired transducer arrangement.

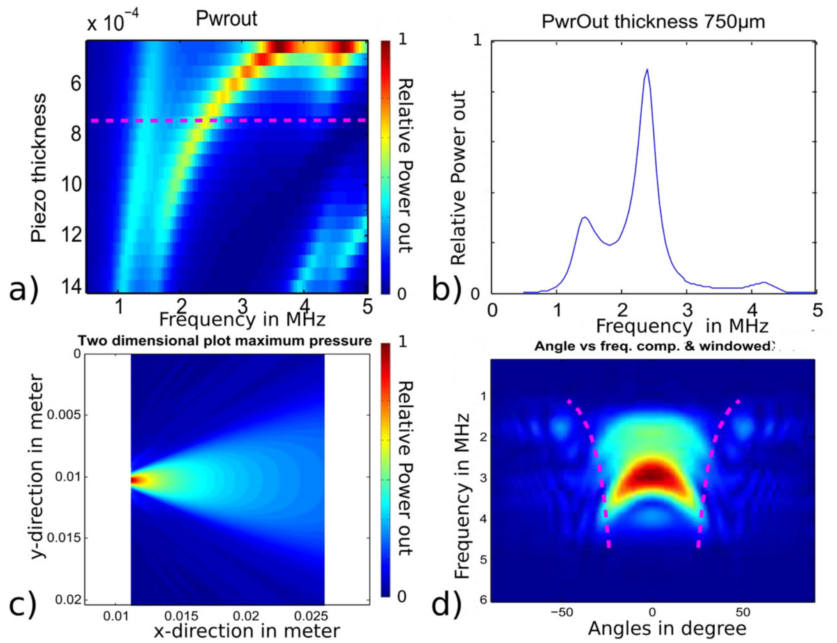

Figure 2. Simulation results. a) KLM simulation showing transducer thickness over frequency range for a PZT disc of variable thickness with 370 μm TMM4 matching layer. The selected PZT thickness of 750 μm is indicated by a pink dotted line. b) KLM frequency response for 370 μm TMM4 matching layer. For comparison to measured results, see **Figure 7**. c) Graph of the maximum pressure versus X and Y ($2 \times 1.5\,cm^2$) in front of the transducer (extracted from a PZFlex simulation for a piezocomposite disc of 750 μm thickness, 460 μm diameter, 370 μm TMM4 matching layer, and PU + tungsten backing (7 MRayl)). d) Calculated frequency response versus opening angle extracted from the far field at a semicircle of 1.2 cm distance. X-axis covers the angle domain from −90 to +90 degree, the Y-axis the frequency domain from 0 to 6 MHz.

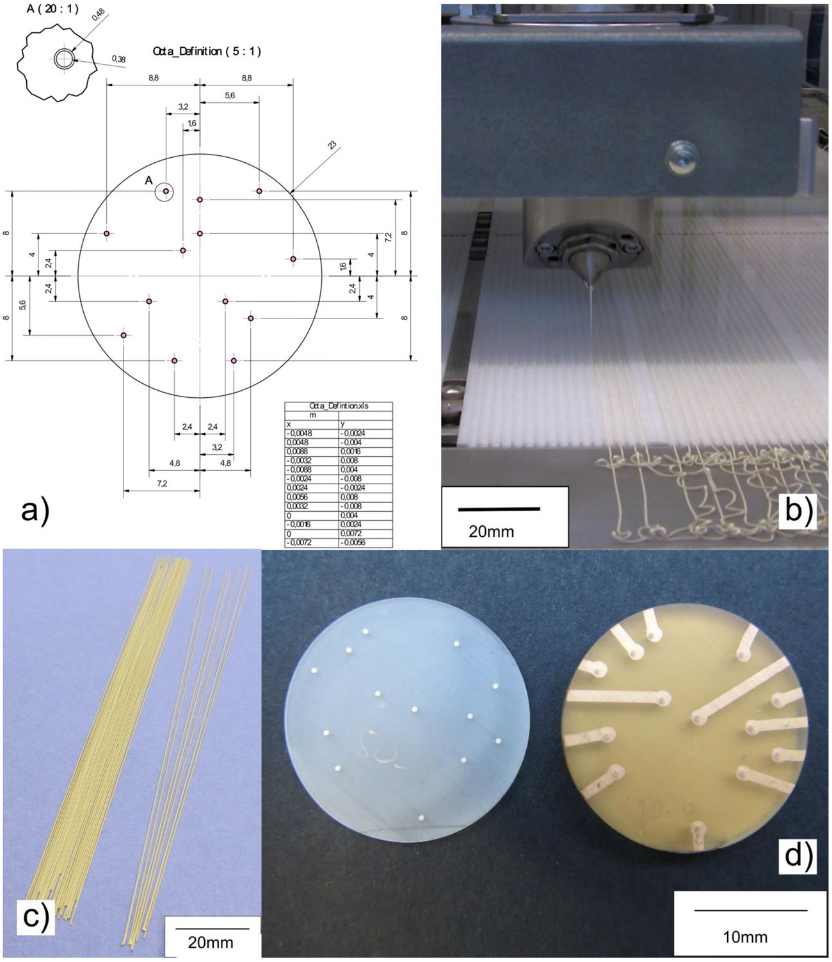

Figure 3. Single-fiber piezocomposite. a) Definition of a 13 element pseudo random single-fiber piezocomposite transducer. b) Fiber spinning process. c) Sintered piezoceramic fibers. d) Piezocomposite disc without and with sputtered electrodes.

The fibers were then embedded into epoxy polymer (EPO-TEK 301-2FL, John P. Kummer GmbH, Germany). After curing, the resulting composite strand was machined to 180 mm length and 23 mm diameter and subsequently sliced into 40 piezocomposite discs each with defined thickness ranging from 400 to 2050 µm in six increments (400, 550, 750, 1050, 1450, and 2050 µm). Thus, a series of discs with identical position and properties of single-fiber transducers was achieved. Subsequently, the composite discs were metallized via sputter coating with ca. 150 nm Au and poled with ca. 2 kV mm^{-1}. By using structured top electrodes for single connection of each fiber and a common ground electrode, the fibers are individually addressable as single transducer elements (see Figure 3).

2.2.2. Electrical Connectivity

Electrical connectivity was achieved with a conductive silver glue PC3000 (Heraeus, Hanau, Germany) to attach wires to the individual single-fiber transducers and also to provide contact to the common ground (see **Figure 4**). Curing of the silver glue was carried out at 80 to 100 °C for half an hour on a temperature regulated heating plate or in a temperature regulated oven.

A standard 2 mm pitch plug was soldered to the wires. Finally, the transducers were pot into an aluminum pipe housing and filled with a tungsten polyurethane mixture for backing.

For integration into the novel 3-D USCT 2.5 upgrade, a printed circuit board (PCB) based connection has been developed. A flexprint design was chosen as PCB base for electrical connectivity to the transducers. It allows for easy contact of the single-fiber transducers and overcomes laborious manual bonding process, used for USCT 2.0 TAS. The PCB design involves several holes acting as pinholes for X-Y position accuracy (ca. 0.05 mm) and for later bubble-free filling with backing material. Silver glue dispensing, either manually or automated, was applied for the connection of the sputter-electroded single-fiber piezocomposite discs to the PCB in the final iteration, see **Figure 5**.

2.2.3. Backing

For suppression of spurious oscillation modes and reflections and to improve the bandwidth of the transducer, a polyurethane-based (PU) backing material has been developed. Therefore, 1 g VOSSFlex 2k Polyurethane (PU) (VOSSchemie, Uetersen,

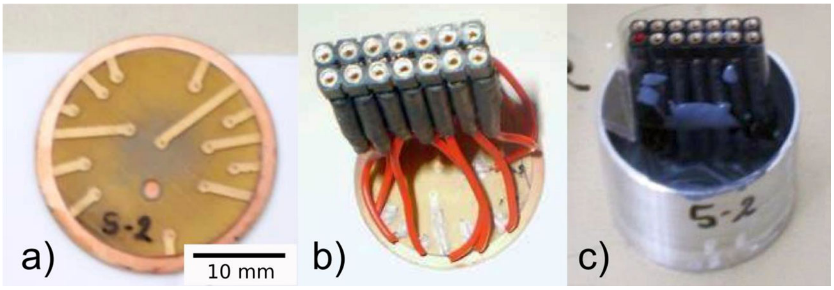

Figure 4. First single-fiber piezocomposite TAS prototype. a) Sputtered Au electrodes on piezocomposite disc for connection of each single-fiber transducer. b) Electrical connection to wires by conductive silver glue, plug soldered manually. c) Finished transducer system in housing.

Germany) was filled with 2.5 g tungsten of 10 μm particle size.[19] The mixing process was supported by 1% BYK-A501 defoamer (BYK Additives and Instruments, Wesel, Germany). The mixture was intensively (ca. 30 min) degassed with pressures down to ca. 50 mbar and subsequently filled into the aluminum housing of the transducer set-up. After curing, this resulted in a strongly attenuating backing with an acoustic impedance of ca. 11 MRayl.

2.2.4. Matching

To improve transmission of ultrasonic waves from the piezocomposite transducer into water, a single-layer matching has been applied. From KLM modeling a matching layer thickness of 370 μm was selected. Thus, a TMM4 plate of 26.75 mm diameter and 370 μm thickness was glued to the piezocomposite front side with Heraeus PC3000 silver glue for the first TAS prototype. In later iterations a low-viscosity underfill polymer glue, Loctite E1216M (Henkel AG & Co., Düsseldorf, Germany), was used.

TMM4 is a very stiff, mechanical mil-and drillable material and exhibits low water absorption. Besides being a strong electrical insulator, thermal conductivity of TMM4 is quite high. This is helpful to acquire correct and unhindered water temperature measurements, as the USCT temperature sensors are situated behind the TMM4 plate.

Additional water-proofing and electrical insulation improvement will be achieved in future with a thin layer of parylene on top of the TMM4 matching layer.

2.3. Characterization

The diameter and the arrangement of the single-fiber transducer elements were analyzed optically from stereomicroscopic

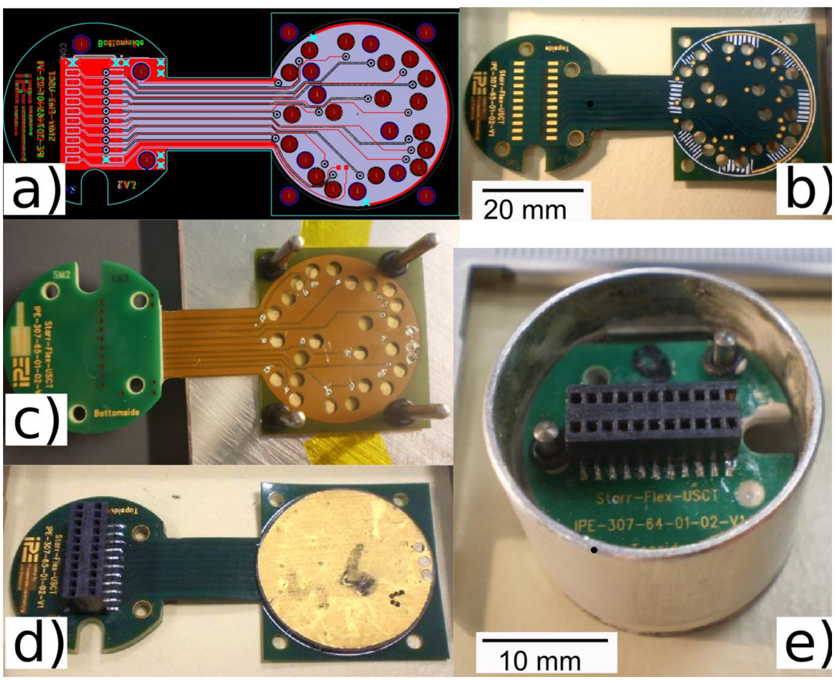

Figure 5. Second single-fiber piezocomposite TAS prototype for 3-D USCT 2.5. a) Layout of flexprint PCB top side. b) Manufactured flexprint PCB top side, holes acting as pinholes for X-Y position accuracy. c) Back side of flexprint PCB on piezocomposite with dispensed silver glue for single-fiber connection. d) Piezocomposite disc connected to the PCB, ground connection visible on the right border achieved by 3 vias. e) TAS with backing and housing, PU based backing is already filled in.

images while the thickness of the piezocomposite discs was measured by means of a micrometer gauge.

The electrical behavior of the transducer elements and the final TAS was determined using a phase-impedance analyzer (Hewlett Packard HP 4149A) after the poling process step. Resonance frequency and coupling coefficient of the thickness vibration mode were derived from the electrical impedance spectrum. Therefore, a sinusoidal voltage signal with a frequency ranging from 0.1 kHz to 15 MHz and a voltage amplitude of 0.5 V was applied.

Ultrasound characteristics were evaluated quantitatively for selected transducer samples using a 3-axis hydrophone measurement system in a water tank.[11,12] The measurement system consists of a $30 \times 30 \times 50\,\text{cm}^3$ measurement container, a 3-movement axis with stepper-motors and mounted hydrophone, sockets for transducers, an arbitrary-waveform generator, a high-voltage amplifier, a data acquisition, and a control PC. Therewith, hundreds of positions on a semi-circular plane, equidistant around the center of the tested transducer, are headed with the hydrophone and on each position a frequency sweep was performed. An excitation voltage of $\pm 100\,V_{pp}$ was used for the frequency sweep with chirps of 0.5 to 5.5 MHz in 250 kHz steps. A calibrated Onda HNC-400 hydrophone (1 to 10 MHz) with a 20 dB pre-amplifier is used. 16× averaging of the same measurement was carried out to achieve a signal-to-noise ratio (SNR) gain by factor four. The measured signal digitization length was 400 µs with as sampling rate of 20 MHz. The measured data was analyzed with MATLAB-based analysis software which provides further compensation and extracts the metrics. The measurement process involves a pre-measurement for accurate spatial detection of the center. Overall measurement time per prototype was several hours.

3. Results and Discussion

3.1. Single-Fiber Piezocomposite Transducer

The selected fiber diameter of 460 µm was produced with good accuracy of ±2% (mean value ± standard deviation). The thickness of the piezocomposite disc varied by ±2% (standard deviation) from the mean value for the different samples thicknesses ranging from 400 to 2050 µm in six increments. Fiber positioning failure was observed to be in the micrometer range. These results indicate that the piezofiber composite technology is perfectly suited to provide the required transducer elements regarding element size, shape, and arrangement.

Dependencies of thickness coupling coefficient k_t and resonance frequency $f_{R,t}$ from transducer thickness t are shown in **Figure 6**.

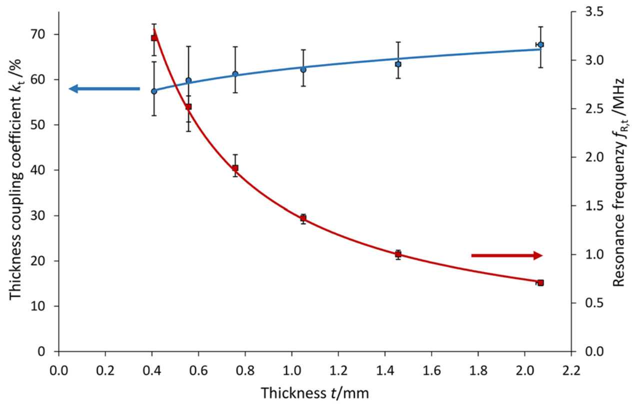

Figure 6. Thickness coupling factor and resonance frequency versus transducer thickness.

With detailed knowledge of the non-linear correlation, transducer thickness can be adjusted to the required resonance frequency. The coupling coefficient k_t slightly decreases to less than $< 60\%$ with decreasing transducer thickness, particularly below 0.75 mm. This reduction can be attributed to the increasing interaction with the planar mode of the piezoceramic fibers resulting also in a larger variation of the values. Since the diameter of the fibers is restricted to the required 460 µm, transducer thickness below 0.75 mm should be avoided due to decreased coupling efficiency.

3.2. Transducer Array System (TAS)

The electrical impedance of the TAS consisting of the piezocomposite disc with electrical connection, backing, and matching was analyzed between 500 kHz and 6 MHz. Therefore, every single-fiber transducer of the 13 elements of the first prototype was characterized. **Table 1** summarizes the data measured on prototypes with different piezocomposite thickness. The coupling coefficient $k_{t,\text{integrated}}$ of the TAS was measured after full assembly of the TAS and includes, therefore, the influences of backing, matching, and electrical connectivity. Based on a sufficient coupling, a yield was introduced which defines the amount of single-fiber transducers working over a set of three tested TAS. For the prototypes with 400, 550, and 750 µm piezocomposite thickness, a yield of 95% could be achieved with 37 of the 39 elements working.

As a result, TAS with piezocomposite disc thicknesses of 400, 550, and 750 µm were considered for further water tank measurements. Prototypes based on disc thicknesses of

Table 1. Results of the electrical impedance measurement on the TAS based on piezocomposites with three different thicknesses.

Thickness of piezocompo-site disc [µm]	Center frequency@max. power [MHz]	Bandwidth@max. power (3 dB/6 dB) [MHz]	Coupling coefficient $k_{t,\text{integrated}}$	Yield [%]
400	3.01 ± 0.24	1.69/2.34	0.51 ± 0.17	92.3
550	2.54 ± 0.07	1.57/1.99	0.52 ± 0.16	92.3
750	2.06 ± 0.11	1.23/1.34	0.47 ± 0.12	100

The $k_{t,\text{integrated}}$ value was measured on the fully assembled TAS consisting of piezocomposite disc, electrical connection, backing, and matching. Therefore, different values compared to the k_t of the PZT fibers may occur. Center frequency and coupling coefficient were analyzed over the 13 elements per prototype, therefore, a mean and a standard deviation value for each group could be extracted. The yield indicates the number of elements which exhibits a sufficient $k_{t,\text{intergrated}}$ value summarized over three TAS per piezocomposite thickness.

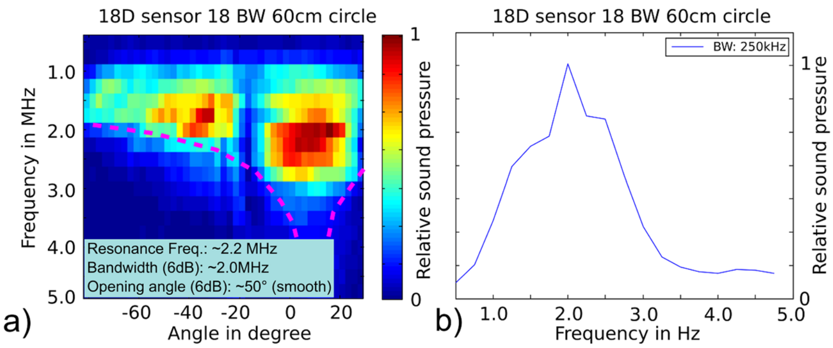

Figure 7. a) Acoustical characterization of a TAS with 750 µm piezocomposite disc. Left: Sound pressure over angle and frequency. Frequency-dependent opening angle (smoothened) at ca.- 6 dB boundary indicated with pink dotted lines. b) Frequency response for the direct facing angle, representing the frequency response of the transducer system.

1050, 1450, and 2050 µm were not analyzed further due to their worse coupling coefficient and low sound pressure.

The transducer opening angles for the TAS with piezocomposite disc thicknesses of 400, 550, and 750 µm have been measured to ca. 50° and were thus in the expected range predicted from simulation, see Figure 2. The values increased significantly compared to the former square transducers fabricated by the dice-and-fill technology, which only showed opening angles of 36°. The single-fiber TAS reached expected absolute sound pressure levels, ca. 25% of the USCT 2.0 transducers due to the reduced emission aperture surface and additional attenuation due to improved backing. A satisfying single-to-noise-ratio (SNR) with the default USCT signal processing chain could be achieved. The value of the bandwidth remained ca. 50%, the center frequency of the TAS was in the expected range (2 to 3 MHz) and was selected to be slightly lower (2 MHz) than for the former USCT 2.0 system (2.5 MHz).

The acoustical performance of the final TAS with 750 µm piezocomposite thickness is displayed in Figure 7. It proves a significantly increased opening angle over the bandwidth of the transducer as predicted by simulations and in acceptable accordance with them.

Finally, a number of 200 TAS will be integrated into a semi-ellipsoidal aperture as upgrade for a 3-D USCT 2.5 demonstrator, utilized in a clinical trial.

4. Conclusions

A single-fiber piezocomposite transducer array system for a 3-D ultrasound computer tomography (USCT) device has been developed. Simulation-based on a KLM model and a finite element model were used to select material parameters and sample dimensions for the manufacture of ultrasonic probes. Piezoceramic fibers with 460 µm diameter were fabricated via fiber spinning technology. They were positioned into a polymer matrix according to a pseudo-random design inspired by compressive sampling techniques to form piezocomposite transducers. Each fiber could be addressed individually for emitting and receiving ultrasonic waves. Electrical characterization with phase-impedance analyzer demonstrated an encouraging yield of 95% for the full assembly already in the early process version.

Prototypes were build-up to select optimum center frequency and bandwidth and to evaluate the performance of the single-fiber transducers. Piezocomposite discs with 750 µm thickness were chosen for the final build-up of the full set. A flexprint design was employed as PCB base for reliable electrical connectivity to the single-fiber transducers. Backing and matching layers have been carefully selected and applied to build full probes. Compared to former dice-and-fill-based transducers, the bandwidth could be retained and the opening angle improved. The frequency response could be extended to lower frequencies (<1 MHz) which will benefit USCT imaging techniques like paraxial wave inversion approaches.

The piezocomposite approach allows for the production of transducer arrays with defined position and properties of circular transducers based on single piezoceramic fibers. The process is superior in cost-efficiency and ready for the production of a large number of transducers from one piezocomposite block. A semi-automated process for electrical connection minimizes manual error-prone and work-intensive steps. The assembly of a full set of 200 transducer systems is ongoing and expected to be finalized in mid of 2018. This transducer system will be used as upgrade for a 3-D USCT 2.5 demonstrator, utilized in a clinical trial.

Acknowledgement

This research was supported by the Deutsche Forschungsgemeinschaft (DFG) in context of the Collaborative Research Centre/Transregio 39 PT-PIESA, subproject K04.

Keywords

medical imaging, piezocomposite fibres, ultrasound computer tomography, ultrasound imaging, ultrasound transducers

Received: April 23, 2018
Revised: August 23, 2018
Published online: September 25, 2018

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