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# Development of a 20 MHz annular-array – a balancing act between optimized design and technological opportunities

André Juhrig
Inst. of Solid State Electronics
Technical University Dresden
Dresden, Germany
Andre.Juhrig1@tu-dresden.de

Ulrike Schmidt
Inst. of Solid State Electronics
Technical University Dresden
Dresden, Germany
Ulrike.Schmidt@tu-dresden.de

Mario Wolf
Inst. of Solid State Electronics
Technical University Dresden
Dresden, Germany
Mario.Wolf@tu-dresden.de

Elfgard Kühnicke
Inst. of Solid State Electronics
Technical University Dresden
Dresden, Germany
Elfgard.Kuehnicke@tu-dresden.de

Paul A. Günther
Fraunhofer Institute for Ceramic Technologies and Systems IKTS
Dresden, Germany
paul.guenther@ikts.fraunhofer.de

Sylvia Gebhardt
Fraunhofer Institute for Ceramic Technologies and Systems IKTS
Dresden, Germany
sylvia.gebhardt@ikts.fraunhofer.de

***Abstract* — Scanning Acoustic Microscopes for nondestructive imaging commonly use strong focusing single element probes with center frequencies up to 230 MHz. Depending on the test scenario and the materials a resolution down to 10 µm is reachable. This high resolution means a small extension of the sensitivity zone in lateral and axial direction and leads to the necessity of multiple C-Scans for the inspection of a volume. Using an annular-array transducer, the focal point can be shifted in axial direction. Thus, multiple scans in different depth can be replaced by a single scan. To achieve a comparable resolution to strong focused single element transducers it is necessary to increase the center frequency of annular-array transducers. So we present a prototype of a probe, that contains a planar annular-array transducer with a center frequency of 20 MHz and an aperture of 5.4 mm, separated into four quartered rings (16 elements). The characterization of the sound field, using a spherical reflector, shows a sensitivity zone with a lateral extension of 300 µm for focusing without a lens.**

***Keywords — annular-array, transducer, microscopy***

## I. Introduction

Scanning Acoustic Microscopes (SAM) are used for imaging in nondestructive testing (NDT) for example in semiconductor and electronics industry to identify delamination between interfaces and buried cavities in casting compound. A further field of application is the examination of hidden structures in opaque objects and material characterization. Due to the miniaturization of microelectronic structures and size of electronic packages as well as devices, a higher resolution of the imaging is obligatory. Generally, this is reached by high center frequencies, wide bandwidth and strong focusing, which results in a small sensitive zone. Conventional SAMs are working with strong focusing single element probes with center frequencies from 30 up to 230 MHz whereby resolution increases for higher frequencies [1, 2]. A number of applications in NDT prove the performance of ultrasound microscopy, when the transducer is adjusted so that the focus is placed on the desired inspection plane [3]. By using a probe with a long focal zone extending over the whole thickness of the test object, it can be inspected with one single scan [4]. But the resolution is reduced.

Using a multichannel, array-structured probe in an acoustic microscope allows the shift of the focal point in different depths without moving the probe itself. This leads to the advantage that the whole sample can be inspected with improved accuracy in only one single scan, which means lower time consumption. It is advantageous to design the array as an annular array because it offers 2D focusing and reaches the same quality of the sound field with a lower number of elements, compared to arrays with line elements. Current commercial available annular-array probes based on composite material reach center frequencies up to 10 MHz. In research, probes containing transducers made of PVDF with up to 40 MHz center frequency [5] are used. But in contrast to ceramic transducers, their emitted sound intensity is too low. So they are not suitable to test solids. This contribution presents design as well as manufacturing and characterization of a probe, containing a 1-3 piezo composite transducer with a working frequency of 20 MHz, structured as an annular-array.

## II. Construction & Methods

### *A. Array layout and optimization*

The annular-array is designed to have an aperture of 5.4 mm with four concentric rings of equal area, that are separated into quarter elements. Considering the current state of technology and the feasibilities of the laboratories, the gap between two adjacent elements is specified to 100 µm and the narrowest ring (at the outside) has a minimum width of 200 µm. The near field length of each single element as well as the near field length of the whole array determine the focusing range of the annular-array.

The following sound field calculations demonstrate the achievable resolution of a 20 MHz array with configuration described above. The simulations are done by means of time harmonic Green's functions in a steepest descent approximation and a superposition of the fields of all point sources. The field of the whole array is calculated as a superposition of the delayed fields of all particular elements. This superposition is arranged in accordance with the focusing mode, whereby the time delays of the single rings are taken into account by a phase shift. Figure 1 shows the longitudinal sections of the sound field of ring 1 and 2 and the focused sound field with focusing at 14 mm. The natural focus of both rings is located at $z$ = 20.6 mm. For ring 1 (fig. 1a) the extension of the -6 dB-area at the focus amount to 0.6 mm, which is a value for the lateral resolution.

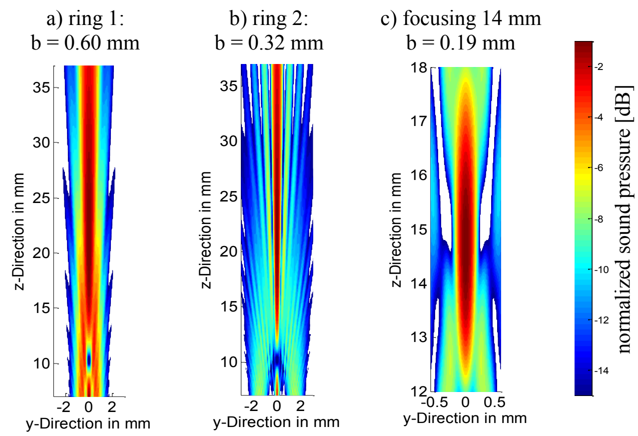


Fig. 1: Calculated sound fields of the 4-ring annular-array in water. Coordinate system is placed on the array, z-coordinate represents the distance to the array, $b$ is the lateral extension of the -6 dB-area.

Since shortening the focus distance of the array causes a decrease of the focus area, the minimal focus distance provides the best resolution. Therefore, the harmonic sound field in water is calculated for a focus distance of 14 mm. As can be seen, focusing greatly improves the lateral resolution and the diameter of the -6 dB-area at $z$ = 14 mm is only 0.19 mm (fig. 1c).

### *B. Fabrication of ultrasonic transducers via Soft Mold Process*

Fabrication of the 20 MHz ultrasonic transducers used in the context of this publication was carried out by Fraunhofer IKTS in Dresden. The samples were produced in the so-called soft mold process, which was developed at IKTS and enables the fabrication of fine-scale 1–3 piezocomposites via slip casting [6]. Soft mold process is based on silicon master molds, which have been structured by microsystems technologies like the DRIE or LIGA technique. From the master molds, flexible intermediate molds made of PDMS are taken, into which a ceramic slurry is poured. After drying, green samples are demolded and sintered. Recently, ultrasonic transducers with operating frequencies of up to 40 MHz have been successfully prepared via this method [7]. Fig. 2 shows a schematic illustration of the soft mold process.

For 20 MHz ultrasonic transducers, master molds with a periodic structure of circular pillar in hexagonal arrangement were prepared. Diameter of the pillars was etched to 40 µm. The kerf width was 10 µm, resulting in a 50 µm pitch (center-to-center distance of ceramic pillars), and the pillars were etched to a height of 180 µm. The overall structured area of the silicon mold was a 6 $cm^2$ equilateral hexagon. From the master molds,

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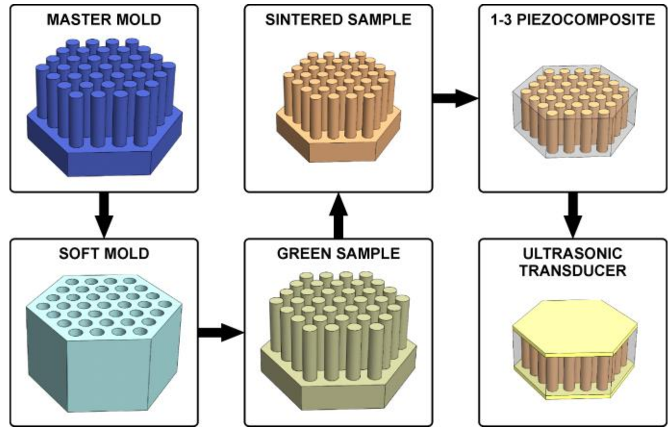


Fig. 2. Schematic illustration of the soft mold process with intermediate stages (not drawn to scale).

flexible soft mold templates were taken by casting PDMS into the master mold and demolding after curing. For slip casting, a lead zirconate titanate (PZT) powder (Sonox P505, CeramTec GmbH, Germany) was dispersed into a binder solution. The homogenized slurry was poured into the soft plastic templates under vacuum and left for drying. After demolding, green samples were debindered in air at 450 °C for 2 h and sintered at 1110 °C for 2 h in an $Al_2O_3$ crucible with PbO-controlled atmosphere. During sintering, pillar diameter decreased to 30 µm, resulting in a 40 µm pitch. The sintered arrays were infiltrated with an epoxy resin Epo-Tek 301-2 (Epoxy Technology Inc., USA). After curing, both sides of the piezocomposite were grinded to achieve final thickness of ~ 90 µm for 20 MHz operating frequency. Approximately 100 nm Au was sputtered on both sides of the 1-3 piezocomposite for top and bottom electrodes.

### *C. Construction of the probe*

An ultrasound probe (fig. 3a) contains three main components: a structured transducer to convert the acoustic wave into electric signals, an interconnection layer to connect the transducer elements to the cables and the housing as well as the damping body. Transducer and applied electrodes are manufactured by Fraunhofer IKTS as described above. The electrodes are implemented on the outside (sound emitting side) as a full area covering ground electrode and on the inside as an annular-array (fig. 3b), structured by masking technique in the sputter process.


Fig. 3: a) Schematic drawing of the probe: (from left to right) connecting cables, housing with damping body, interconnection layer, transducer with electrodes structured as annular-array; b) structure of the annular-array.

A printed circuit board (PCB), serving as interconnection layer, offers pads for soldering the coaxial cables as well as pads to connect bond wires coming from the electrodes of the annular-array transducer. The non-insulated bond wires create a stable and good conductive connection on the PCB, but only a loose connection on the electrodes of the transducer, because of the low stiffness of the piezo-composite. Therefore, this connection point additionally has to be fastened with conductive glue. After hardening of the conductive glue the coaxial cables are connected to the PCB and finally the housing is mounted and filled with epoxy resin, acting as damping body.

### D. *Characterization methods*

To characterize the prototype of the 20 MHz annular-array probe the sound field in water is recorded using a 3 mm sphere as point reflector. A 3D sound field scan is performed with an increment of 0.25 mm in each dimension using multiple transmit-receive settings. At each point the received signal is recorded for each transducer element and each transmit-receive setting. These signals are evaluated regarding signal intensity, runtime and frequency spectrum to characterize each ring. Furthermore, the signals are superposed for synthetic and electric focusing to investigate the resolution capability in different depths.

## III. Results and Discussion

### A. *Evaluation of rings*

The recorded signals are analyzed to figure out signal intensity and center frequency of each single element (fig. 4). For this, data from the natural focal point are used.

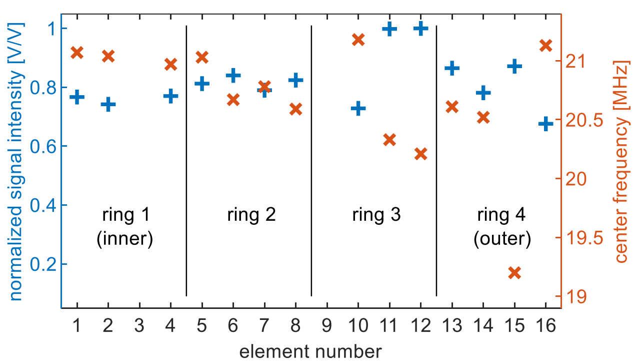


Fig. 4: characterization of the single elements regarding signal intensity and center frequency.

First analysis shows that two of the 16 elements are not working. In case of element 3 a loose contact was detected, so that this element does not work reliable and element 9 has a broken connection. Regarding the signal intensity, the working elements show a minimal deviation. The center frequency is relatively stable for ring one and two at the mean value of 20.9 MHz, but shows a slight decreasing tendency for ring 3 and 4. This can be seen as an effect of the additional fastening by the amount of conductive glue in relation to the narrow shape of the outer rings, that is damping the oscillation. With the ring dimensions from design process and the measured average center frequency, the near field length of the rings can be calculated to 21.8 mm.

For ring 1 to three the determined near field length matches to the determined natural focus position, but at ring four it is shorter (fig. 5). On the one hand the elements in ring four are

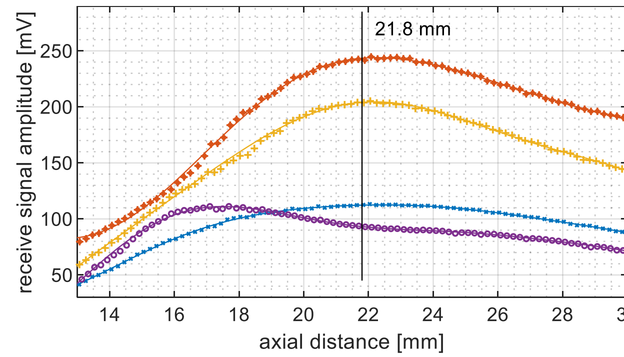


Fig. 5: Sound pressure on acoustic axis for ring 1 (blue x), ring 2 (orange *), ring 3(yellow +) and ring 4 (purple o).

oscillating with a lower average center frequency (fig. 4) and on the other hand these elements are the narrowest and longest ones of the whole array. This means losses due to the internal electrical resistance of each element of ring four lead to the reduction of the oscillating area. Both effects together result in a shorter near field length, as mentioned according to calculation and design data.

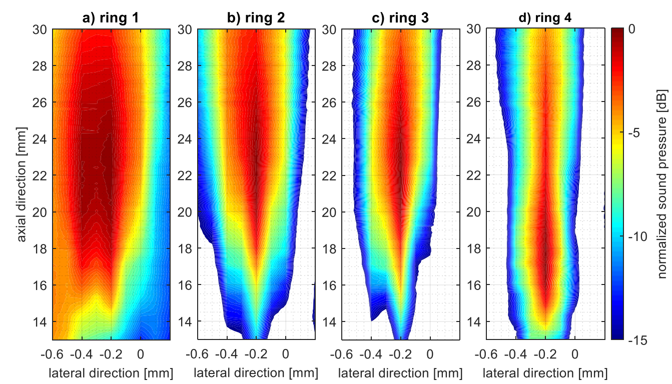


Fig. 6: cross sections of the sound fields of the four rings.

As can be seen in fig. 6a, the defective element 3 has a stronger negative influence on the symmetry of the sound field of the whole ring 1 than defective element 9 on that of ring 3. Ring 1 usually contributes the most intensity to the sound field. Even though this is a disadvantage for focusing with that prototype, the focusing capabilities are tested.

### B. *Synthetic and electronic focusing capabilities*

In prior to the focusing analysis a set of delay times was calculated. For the synthetic focusing, these delay times are applied in the signal post-processing and for electric focusing the delay times are applied as delayed pulse excitation in the transmitter and receiver unit.

In both methods the shift of the focus position is clearly visible (fig. 7). Theoretically, there should be no difference between the results of synthetic and electronic focusing, but in case of synthetic focusing only the far focal points match to the intended focus point and for electric focusing the close focal points show a good match. At synthetic focusing each ring is emitting and receiving separately. Due to the frequency shifts between the rings a coherent superposition of the signals is not possible. The effect decreases with increasing depth. An

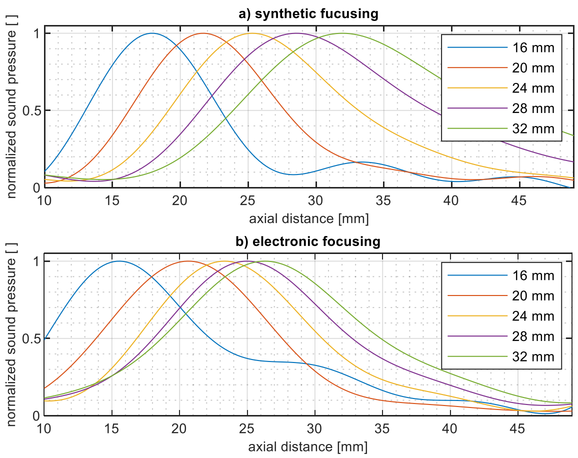


Fig. 7: fitted sound pressure along the acoustic axis for different focal positions by synthetic and electronic focusing.

additional issue is the quantization of delay times, especially at electronic focusing. In this analysis the time delay between two adjacent rings is only in range of 3-20 ns while the time step resolution of the transmitter is 0.25 ns. This leads to a timing failure of 1-8 % which especially influences focusing on long distances and explains the deviation from calculated focal points in fig. 7b.

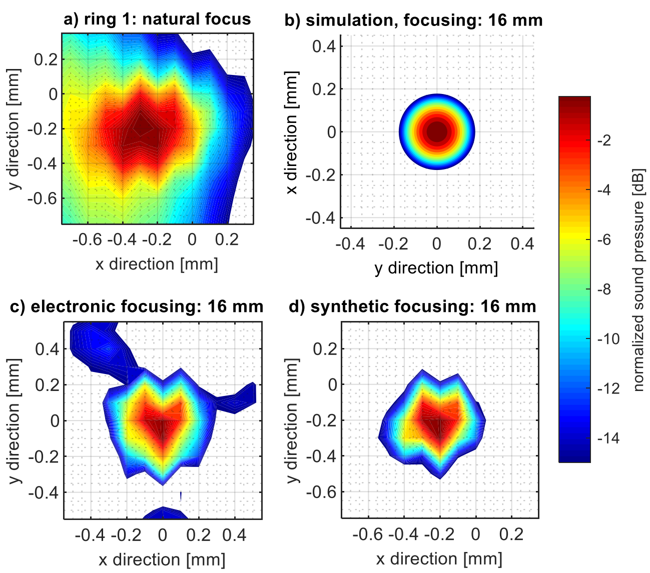


Figure 8: Lateral cross sections of sound fields of ring 1 (a) at near field length, in simulation for focusing at 16 mm (b) and for electric (c) and synthetic (d) focusing at 16 mm prove the increase of lateral resolution by downsizing the sensitive zone by focusing.

The lateral cross sections of the sound fields (fig. 8) demonstrate the focusing capabilities of the prototype. For ring 1 the width of the sensitive zone (-6 dB) is 0.7 mm (fig. 8a). For strong focusing, the sound field simulation demonstrates, that a width of 0.23 mm is achievable with the designed annular array, if all elements have a homogeneous intensity and all elements are working. Both techniques, electronic and synthetic focusing, are showing a width of sensitive zone of approximately 0.3 mm. Due to the determined variations in signal intensity and center frequency (fig. 4) and few single elements that are not working, it is plausible that the width of the sensitive zone is marginal higher compared to the simulation.

## IV. Conclusion

A prototype of a 20 MHz annular array, separate into four quartered rings, was designed regarding the results of sound field simulation, that prove the performance of this probes. The technology to manufacture the 1-3 piezo-composite transducer could be improved by Fraunhofer IKTS to achieve center frequencies above 20 MHz. The final construction technology to fabricate the probe was customized by TU Dresden. This cooperation yields to the probe characterized in this paper. Each ring of the array has a near field length of about 22 mm. The test of focusing capabilities shows a width of the sensitive zone (-6 dB) of 0.3 mm, which is acceptable as a first step of further improvements to build a high frequency annular-array probe usable for microscopy applications.

## Acknowledgment

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