

## Characterisation and optimization of micromachined ultrasonic transducer arrays using laseroptical investigations

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*Novel laseroptical investigations of mechanical and electrical features of PVDF-based ultrasonic transducer arrays for applications in liquids are described. The thickness vibrations in the range of less than 2 nm with exceptional high frequencies for MEMs (up to 20 MHz) are measured using a surface line scan with a lateral resolution of a few micrometres. The knowledge of the electromechanical behavior leads to an improvement of the transducer array design.*

### 1 Transducer principle, technology and common acoustic characterisation

Micromachined ultrasonic transducer arrays were developed to pan a sound beam electronically in an arbitrary direction. These ultrasonic transducer arrays will be used in fluid flow measurement for example /Daßl-96/.

The ultrasonic transducer array is based on a structured silicon substrate metallized with the desired gold electrode structure (figure 1 and 2) and a top mounted PVDF film. A silicone (or epoxy) layer protects the whole transducer array. One element of the array is formed by a single electrode on top of the silicon chip and the opposite gold electrode of the PVDF film. The PVDF film and consequently the transducer element works as a thickness vibrator by applying an electrical signal between these electrodes /Thie-97/. Each transducer element can be used as a transmitter or as a receiver, too!

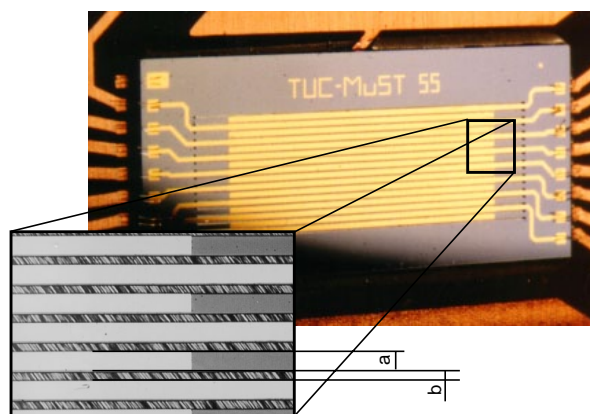


Figure 1: Structured silicon substrate with gold electrodes

The operating principle is known from radar techniques: A time shifted electrical excitation applied to the transducer elements generates an aimed sound beam in the desired direction as a result of constructive sound wave interference (see also figures 8 and 9). The achieved exceptional high frequencies require single transducer element dimensions  $a$  from 20 to 100  $\mu\text{m}$  /Daßl-97/. The element distances  $b$  varies in the same range.

Acoustic far field measurement techniques are mainly used to determine the typical properties of an ultrasonic transducer array up to now. An automated underwater measurement setup including a calibrated hydrophone is used for all acoustic measurements and is able to measure the sound pressure level in an angle range from  $-180^\circ$  to  $+180^\circ$  (directional characteristics) in different distances.

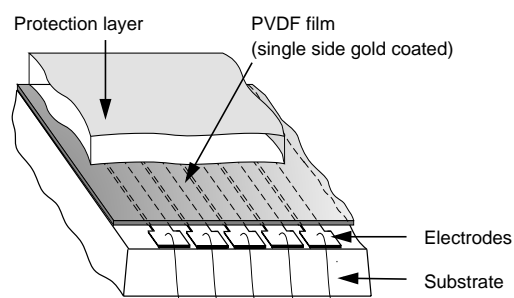


Figure 2: Structure of the transducer array

In contrast to radar applications (burst-mode) the ultrasonic transducer array is driven with short pulses. A typical acoustic pulse response of the transducer is shown in figure 3. A strong broadband characteristics (relative bandwidth up to 0.8) with frequencies up to 20 MHz can be recognized. Furthermore, a good surface to sound pressure level relationship is typical for these ultrasonic transducer arrays (sound pressure level:  $>160$  dB, measuring distance: 10 cm). The realized transducer arrays have a reproducible sound beam panning range of  $\pm 60$  degrees /Thie-98a/. Figure 4 shows a typical directional characteristics aimed into  $45^\circ$ .

The acoustic measurement characterizes transducer behavior in the acoustic far field. Its main disadvantage is the impossibility to investigate the generation of ultrasonic sound (deformation of the piezoelectric film resp. protection layer) and inner transducer effects (coupling between elements, influence of a single element, influence of material properties). This leads to novel optical investigations.

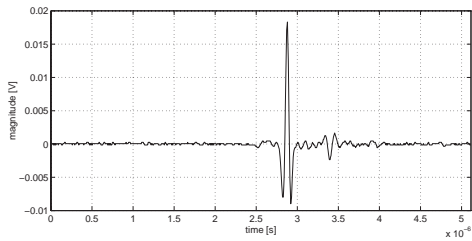


Figure 3: Acoustic pulse response

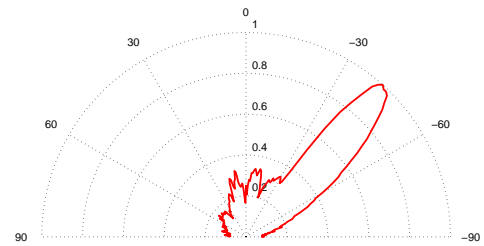


Figure 4: Measured directional characteristics

## 2 Laseroptical investigations of ultrasonic transducer arrays

### 2.1 Measurement setup

The used laser vibrometer is able to measure low deformations ( $< 2 \text{ nm}$ ) at high frequencies. Therefore, it is used to improve the characterization and for the optimization of the transducer array. Up to 800 time signals of deformation per line scan are logged in distances of 2 to  $25 \mu\text{m}$  in touch with a PC-controlled position unit. The laser beam can be focused at the piezo film or the protection layer surface using a focus diameter in the range of 5 to  $15 \mu\text{m}$  (figure 5).



Figure 5: Measurement setup

The measured signals are interpreted in time and frequency domain. An ambiguity plot (like figure 6) is a clear representation of the scanning path (x-axis), measurement time (y-axis) and the deformation level (grey scale). All deformation levels are in Volt (scaling factor  $50 \text{ nm/V}$ ). Figure 6 e. g. represents 600 timeplots of figure 7. The assignment to the transducer electrodes is illustrated for this scan, the eight electrodes driven can be seen very clearly.

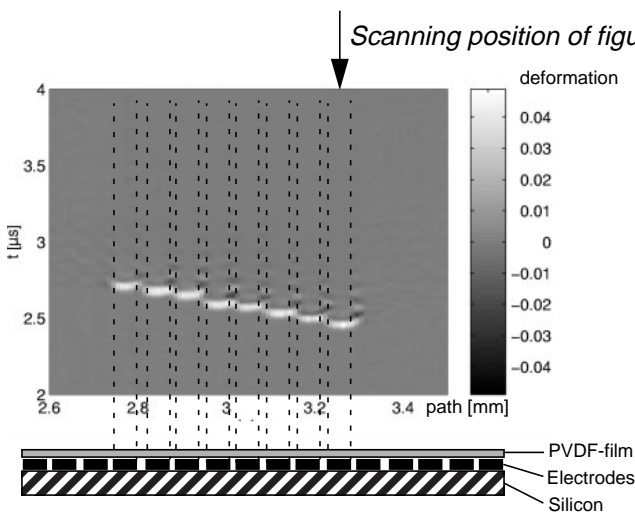


Figure 6: Investigated structure assigned to the ambiguity plot of measured time signals

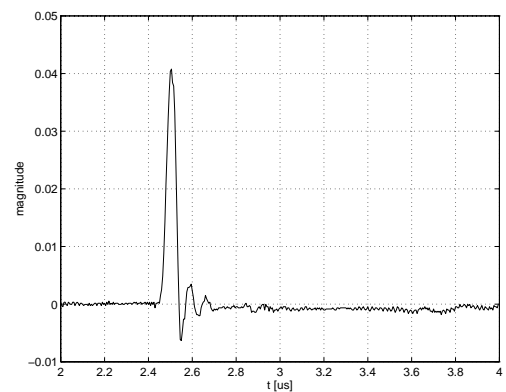


Figure 7: Piezo film deformation vs. time for a single point of the line scan (see figure 6)

## 2.2 Measurement of sound wave superposition and the speed of sound

The following laseroptical investigations of sound wave superposition are needed to determine the influence of the electrode width and distance to the deformation of the PVDF film and/or protection layer and finally to the generation of ultrasonic sound.

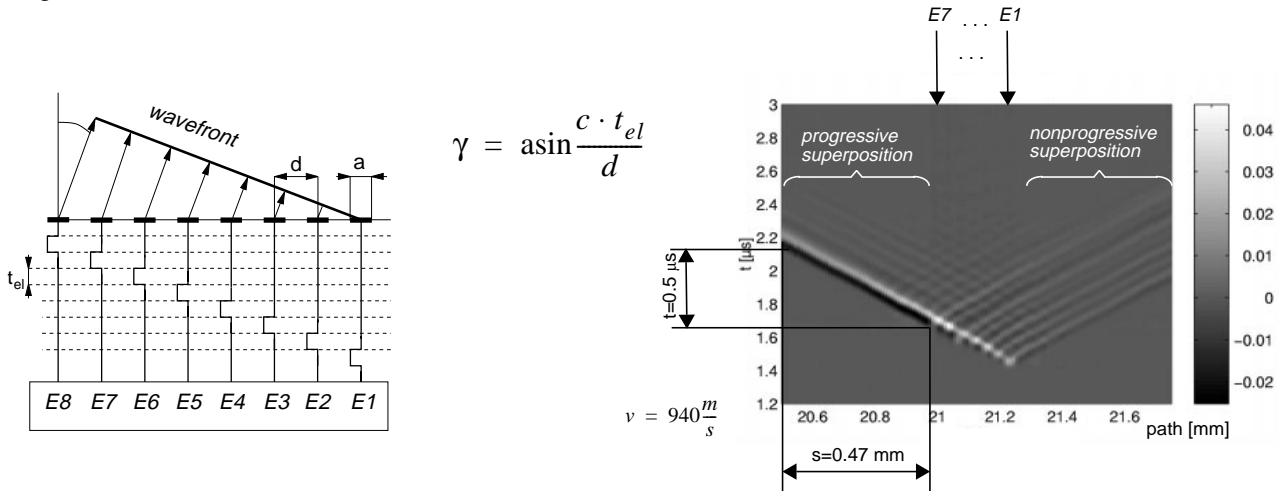


Figure 8: Principle of panning a sound beam using time shifted driven elements

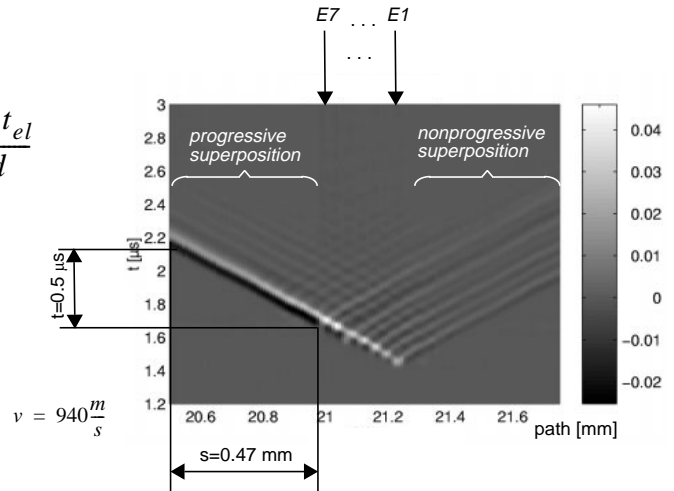


Figure 9: Illustration of speed of sound measurement and sound wave superposition

As mentioned before the pan of a sound beam is a result of progressive sound wave superposition of time shifted driven sound sources (transducer elements). It is possible to change the direction of sound propagation by changing the electrical time shift  $t_{el}$ . Furthermore, the direction of sound propagation  $\gamma$  depends on the speed of sound  $c$  and the distance  $d$  between elements (see figure 8). Sound wave superposition can be observed inside the transducer (in the PVDF film ( $c_{PVDF}=1400$  m/s), the protection layer ( $c_{PL}=900 \dots 2600$  m/s)) and outside the transducer in the fluid ( $c_{H_2O}=1440$  m/s). Only a progressive sound wave superposition in the fluid is desired. Therefore, the speed of sound of the fluid must be used to calculate the time shift  $t_{el}$  for a desired propagation angle. This progressive sound wave superposition inside the fluid can be measured only acoustically (see figure 4), the superposition inside the PVDF film and/or the protection layer can be observed using laseroptical investigations. For demonstration the time delay was adapted to the speed of sound of the silicone protection layer in figure 9.

The speed of sound of used materials can be determined (figure 9:  $c_{silicone}=940$  m/s) and the equality for each single transducer element could be verified as side effects of laseroptical line scans.

## 2.3 Electromechanical coupling effects within the transducer

The primary objectives of present laseroptical measurements are the investigations of electrical, mechanical and electromechanical coupling effects within the transducer array. These coupling effects lead e. g. to sound wave propagations in undesirable directions, like the sound peak into the normal direction of  $0^\circ$  (figure 10).

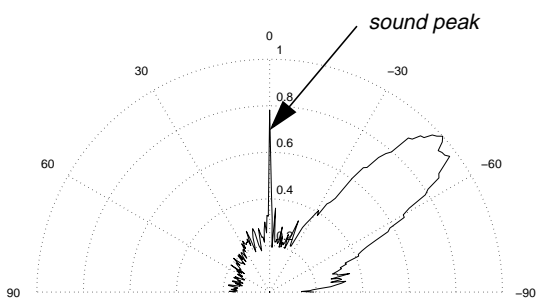


Figure 10: Directional characteristics incl. peak

Based on the theory of sound wave emission the vibrating surface must be much larger than the lowest wave length of the sound signal to achieve such a peak [Thie-98b]. A mechanical coupling inside the silicon substrate and/or inside the PVDF film was assumed to be responsible for the peak. But laseroptical measurements could not observe any vibrations on the silicon substrate.

An observed solid-born sound wave propagation inside the PVDF film is too slow to generate the normal direction peak.

This leads to investigations of electrical coupling effects:

The investigated ultrasonic transducer array consists of 16 transducer elements (figure 1). Only eight electrodes in the middle of the transducer were connected to the power amp channels to test the electrical cross-talk. The outer electrodes were not connected. The connected electrodes were time shifted driven (beginning with the rightward element) as shown in figure 11 (left plot). As expected, all non-excited but power amp connected elements are quiet. This is a result of the ground potential of non-active power amp channels. An electrical coupling can be detected to non-connected elements.

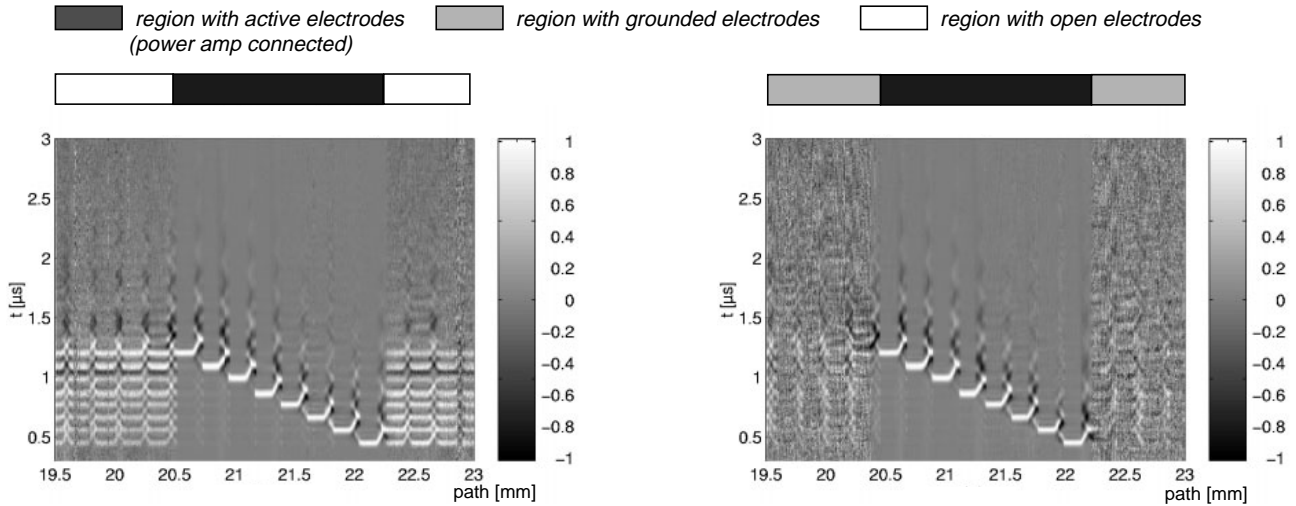


Figure 11: Deformations of a time shifted driven ultrasonic transducer array without and with grounded electrodes (column normalized plot!)

Therefore, the electrostatic crosstalk should be decreased down to the noise level using grounded electrodes. The right plot of figure 11 shows the same transducer array with grounded outer electrodes. With respect to the column normalized plot only noise can be observed outside the active electrodes. The electrical crosstalk could be avoided.

After using shield electrodes near active electrodes the peak level decreases but never disappears. Because of technological reasons the PVDF film covers the complete silicon chip. Therefore, the scanning area was enlarged to the whole PVDF film width. A vibration outside the electrode region could be observed as shown in figure 12. It can be made out very clearly that there is no time shift for this excitation. Thus, the excitation must be forced by an electrical coupling through the silicon. This was confirmed by a spectral analysis of the acoustic signal of the sound peak, the possibility of a mechanical eigenmode of silicon could be excluded.

The explanation of the ripple in the grounded electrodes region of figure 12 are the ungrounded areas (width  $b=30\ \mu\text{m}$ , see figure 1) between the grounded electrodes ( $a=40\ \mu\text{m}$ ). The shown electrical coupling between and outside the electrode area enlarges the active transducer surface and leads to a poor acoustic behavior (e. g. the sound peak in figure 10).

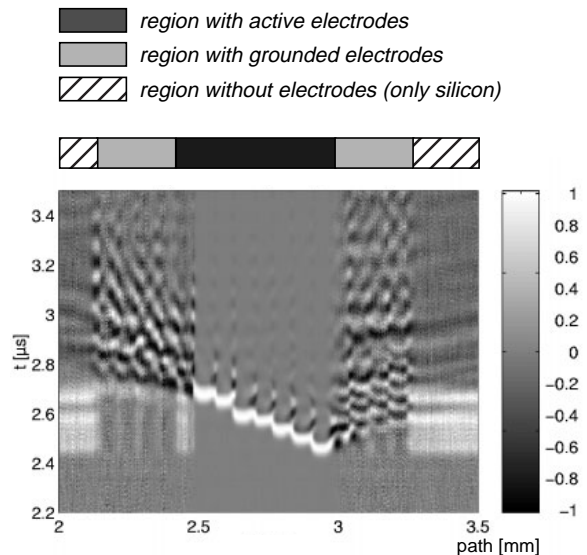


Figure 12: Deformation plot of a time shifted driven array (column normalized plot!)

Next transducer preparations will have large shield electrodes around the electrode region and grounded electrodes between the active electrodes as result of this. Other considerations lead to doped and grounded silicon. First tests have validated the possibility of elimination of the undesired sound peak.

#### 2.4 Protection layer influence to piezo film damping and surface vibration mode:

A protection layer is needed to protect the transducer array from mechanical damage and chemical corrosion. The acoustical impedance of the protection layer must be adapted to the acoustical impedance of the fluid. Because of the very broadband characteristics of PVDF based transducers a  $\lambda/4$ -adaption layer (like known from ceramic transducers) is not applicable, but also not necessary. Since acoustic impedance of PVDF is nearer to fluids compared to the impedance of ceramic transducers, only the acoustic impedance of the protection layer must be chosen for a desired application.

The deformation of a single transducer element without and with an epoxy protection layer is shown in figure 13 resp. 14. Only a low damping can be detected, the ripple near the element edges decreases with protection layer. Furthermore, some wave propagation in the epoxy layer occurs. Both effects have no important influence to the acoustic behavior. Only the acoustic refractive index of the protection layer influences the directional characteristics and finally the maximum panning range. Consequently, the appropriate protection layer can be chosen for the desired fluid.

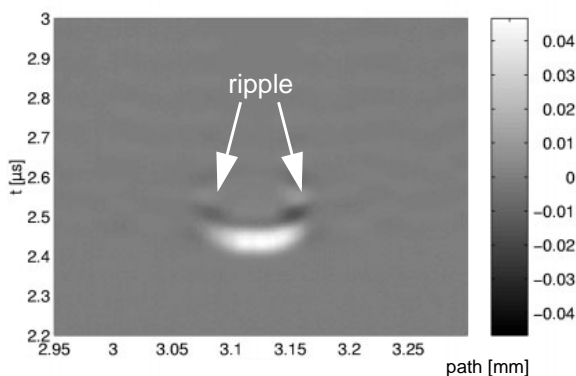


Figure 13: Deformation of a single element without a protection layer

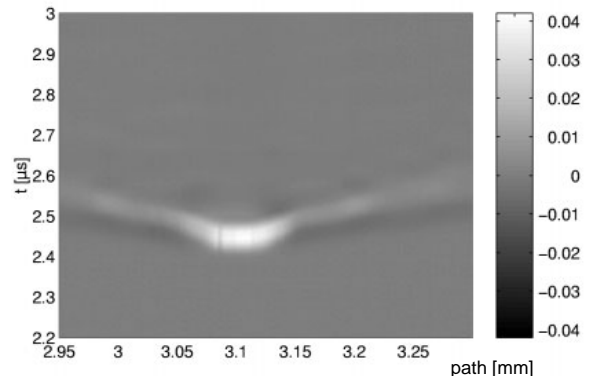


Figure 14: Deformation of a single element with an epoxy protection layer

### 3 Conclusions

The presented micromachined transducers use PVDF as active material. Therefore, these transducers have a strong broadband characteristics, are able to transmit and receive short pulses and have a good impedance relation to fluids. Because of the micromachined realisation on silicon a high equality for each single transducer element can be achieved which is important for a precise wave superposition.

Novel investigations using a laservibrometer have been presented. The laseroptical investigations of piezofilm and protection layer deformation, speed of sound, sound wave superposition, electrostatic and electromechanical coupling effects inside the transducer array allow a detailed characterization of the working principles and an appropriate optimization. This results in a revised array design to avoid coupling effects, enhanced acoustic parameters and a simplification of the transducer structure.

In future the transceiver electronics will be integrated into the transducer. The collaborative research centers in Chemnitz are developing ASIC modules for sender and receiver electronics. The integration of transducer and electronics leads to lower parasitic capacities and better signal conditioning and processing capabilities.

This work is part of the collaborative research centers „*Micromachined Sensor and Actuator Arrays*“ (SFB 379) supported by the *Deutsche Forschungsgemeinschaft*. The authors would like to thank the Center of Microtechnologies Chemnitz for the silicon wafer preparation.

#### 4 References

- /Daßl-96/ H. Daßler, W. Manthey:  
„Sensorarray für akustische Durchflußmessung“;  
8. ITG/GMA Fachtagung "Sensoren und Meßsysteme"; Bad Nauheim (1996):  
VDI-Berichte 1255
- /Thie-97/ L. Thieme, W. Manthey, T. Neundorf:  
"Micromechanicle ultrasonic sensor array with piezopolymer as active sensor material";  
Micro Materials - Micro Mat 97; Berlin; 16.-18.4.1997; ISBN 3-932434-05-6
- /Daßl-97/ H. Daßler, W. Manthey, L. Thieme:  
„Mikromechanisch gefertigte akustische Wandlerarrays“;  
XI. Meßtechnisches Syposium des AHMT e.V.; Rostock; 29.9-1.10.1997
- /Thie-98a/ L. Thieme, W. Manthey, H. Daßler;  
"Micromachined ultrasonic transducer array for applications in liquids";  
MICRO SYSTEM Technologies 98; Potsdam; December 1-3 1998;  
VDE-Verlag GmbH Berlin Offenbach: ISBN 3-8007-2421-9;
- /Thie-98b/ L. Thieme, H. Daßler, H. Enge, W. Manthey:  
„Simulationen und Messungen zum Abstrahlverhalten breitbandiger Ultraschallwandler“;  
ITG/GMA Fachtagung "Sensoren und Meßtechnik"; Bad Nauheim; 9.-11.3.1998; VDE-Verlag  
GmbH Berlin Offenbach: ISBN 3-8007-2330-1; ISSN 0932-6022