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MIMUTS

MECHANICALLY INTERCONNECTED MICROMACHINED ULTRASONIC TRANSDUCERS

WHITEPAPER

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INTRODUCTION

Ultrasound transducer are utilized in a large number of applications. These range from medical imaging, nondestructive testing to parking sensors. Micromachined ultrasonic transducers (MUTs) are a new class of ultrasound transducers, which were presented in 1994 [1]. Since that time, a significant amount of research has been conducted to improve the device performance. A recent step in the evolution are mechanically interconnected MUTs (MIMUTs) that profit from the advantages of conventional MUTs and simultaneously overcome their limitations. The utilized fabrication techniques of microtechnologies are beneficial for the devices regarding the following aspects:

- Efficient and reproducible batch fabrication
- Integration of digital and analog circuits, namely ASICs
- Miniaturization.

Consequently, these advantages enable the reproducible fabrication of highly integrated devices with a huge number of acoustic channels. Beside possible improvements in existing applications, new ones can be opened up due to the potentials of these new MEMS devices [2].

PERFORMANCE CONSTRAINTS OF MEMS BASED ULTRASOUND TRANSDUCERS: A GEOMETRICAL DESIGN CHALLENGE

Generally, micromachined ultrasonic transducer are vibrating plates (Figure 1), transmitting and/or receiving ultrasound into or from a surrounding medium. The best-known transduction principles and devices based thereon are capacitive (CMUT) or piezoelectric (PMUT).

Ultrasonic transducers, e.g. MUTs, have a variety of characteristic performance parameters that are relevant for a selected application, e.g.:

- The resonance frequency,
- The transmit and receive sensitivity,
- The fractional bandwidth,
- The acoustic radiation pattern.

The importance of these parameters significantly depends on the selected applications. Furthermore, their choice is always a compromise among themselves, restricted by the geometry and the shape of deflection of the vibrating plates [3, 4]. The shape of deflection affects both the electromechanical transduction efficiency and the mechanical characteristics. The latter includes the resonance frequency and the average deflection. Especially the average deflection determines the transmitted sound pressure and the receive sensitivity. In other words, the vibrating plate forms both the electromechanical actuator and the acoustically radiating surface.

Consequently, changes of the current geometry can enable new degrees of design freedom that can eliminate compromises in performance parameters and increase the overall device performance.

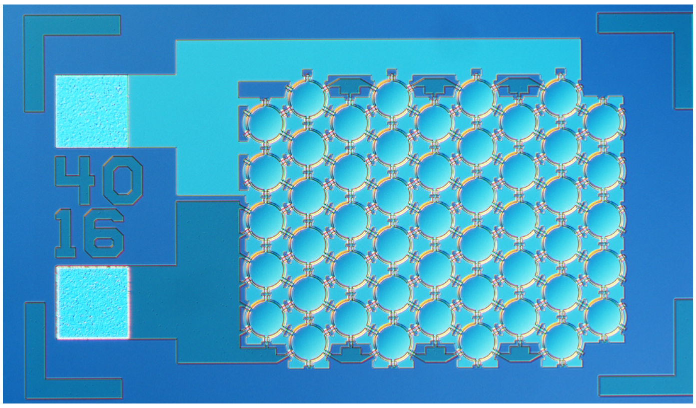

Figure 1: Exemplary single channel CMUT, showing the vibrating plates

PRINCIPLE OF MECHANICALLY INTERCONNECTED MICROMACHINED ULTRASONIC TRANSDUCER

A mechanically interconnected MUT (MIMUT) separates the acoustically transmitting and receiving surface from the electromechanical actuator and thus overcomes the above described limitations of conventional MUTs. A pillar structure in the center of the actuators supports a roof structure on top (Figure 2).

The actuators convert the electrical energy into mechanical energy. The resultant actuator motion is transferred to the roof structure via the pillars and the roof structure emits acoustic waves in transmitting mode. In receiving mode, the pressure of an incoming acoustic wave is weighted by the roof area and forwarded to the actuator via the pillar.

In contrast to conventional MUT structures, allowing only the adjustment of the actuator geometry, more design freedom is gained by the MIMUT geometry. A large fill factor can be maintained, while the resonance frequency, the bandwidth, the operation voltages or the receive sensitivity can be optimized for a specific application.

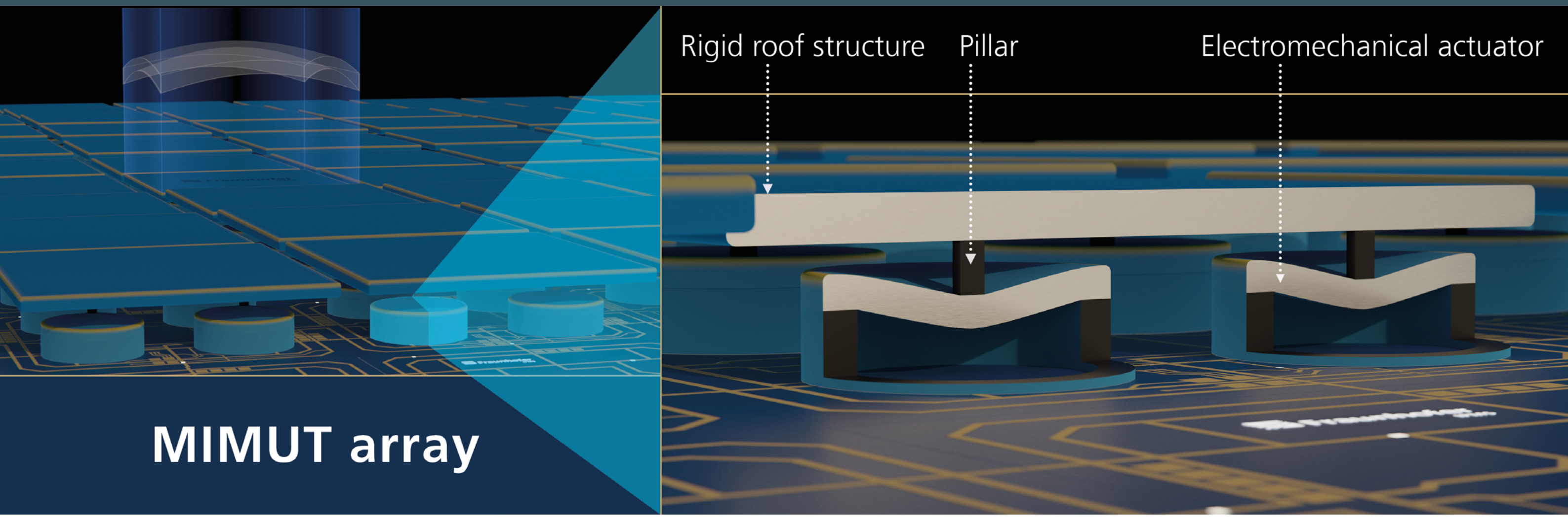

Figure 2: Mechanically interconnected micromachined ultrasonic transducer.

The MIMUT approach was first contrived by Huang [5], who proposed rigid and evenly moving mechanical coupled structures. A similar multilayered CMUT was developed by Savoia et al. [6], consisting several stacked electrostatic actuators. Unger et al. investigated a horn structure on an actuated plate structure numerically [7]. However, the first capacitive MIMUTs (MICMUTs) were fabricated at the Fraunhofer IPMS [8, 9], including their thorough theoretical and experimental analysis.

CHARACTERISTICS OF MICMUTS

CMUT technologies can be utilized in order to fabricate MICMUTs. The main available technologies are a wafer bonding approach and a sacrificial release technology. The Fraunhofer IPMS develops CMUTs based on a sacrificial release technology, enabling flexible and CMOS compatible transducer designs. This technological approach was refined to fabricate MICMUTs.

The performance of an ultrasound transducer is linked to the surrounding medium. In case of airborne ultrasound applications, resonance frequencies between 40 kHz and 1 MHz are especially beneficial due to a lower wave attenuation in this frequency range [10, 11]. Consequently larger distances can be measured in pulse-echo mode compared to high frequency ultrasound waves. And, as a matter of fact, the design freedom of the MICMUT technology enables the fabrication of highly sensitive and efficient ultrasound devices covering the above frequency range below 1 MHz. The fabricated devices comprise an array of several actuators with roof structures [Figure 3 (a)]. Each actuator is equipped with a single roof that is mechanically separated from the adjacent roofs by a small gap [Figure 3 (b)].

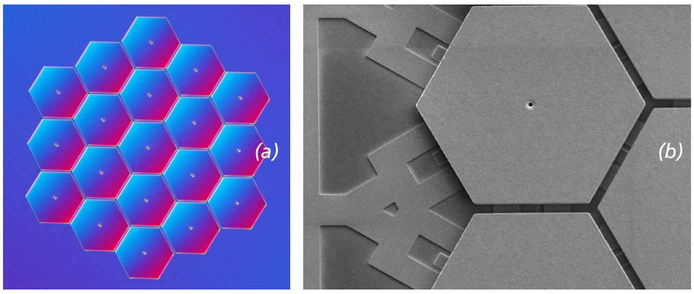

Figure 3: MICMUT fabricated by Fraunhofer IPMS: (a) microscope image and (b) scanning electron microscope image of several roof structures.

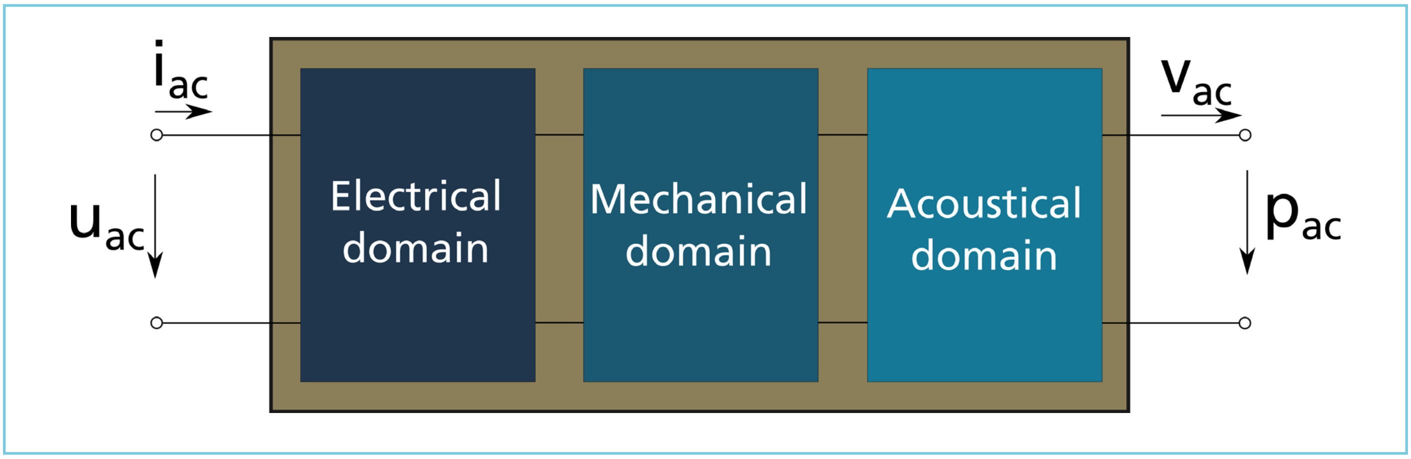

Figure 4: Black box representing the transducer model that describes the conversion from electrical in acoustical domain or vice versa.

The most important performance parameter, which had to be defined, is the resonance frequency. Analytical und numerical models can be utilized to describe and design the behavior of the MICMUT. The Fraunhofer IPMS developed analytical and numerical models, describing the transduction from the electrical parameters voltage u_{ac} and current i_{ac} to the acoustic parameters pressure p_ac and particle velocity v_{ac} or vice versa (Figure 4) [9, 12]. Fast and efficient simulations can be conducted to define design parameters depending on specific requirements, e.g. the resonance frequency.

Many properties of the system can be described, using the electrical impedance

$$Z_{\text{in}} = \frac{u_{\text{ac}}}{i_{\text{ac}}}. \quad (1)$$

The impedance depends on the electro-mechanical behavior of the transducer, thus its measurement provides information on the transducer (e.g. the resonance frequency and bandwidth) [13].

An experimental evaluation of the present MICMUT technology has been performed with three different characterization methods. At first, the resonance frequency was determined from the maximum of the real part of the electrical input admittance. Then the motion of devices was measured by laser Doppler vibrometry. The results provide information about the deflection amplitude, the uniformity of the separated roofs and the fill factor. The third method aimed to determine the acoustic performance, i.e. the transmitted sound pressure and the receive sensitivity. For this purpose an optical microphone and piezoelectric bulk transducer with the same resonance frequency as the MICMUT were utilized.

The measured resonance frequencies range from 400 kHz to 900 kHz depending on the actuator diameter [Figure 5 (a)], which are suitable for airborne applications. The analytical model predicts the measured frequencies very well up to an actuator diameter of 45 µm with deviations less than 6 %. The deviations increase for larger diameters up to 70 µm, due to neglected material stress and squeeze film effects.

The vibrational motion of the transducer was measured at its resonance frequency. The roof structures vibrate uniformly and in phase, forming a large active area [Figure 5 (b)].

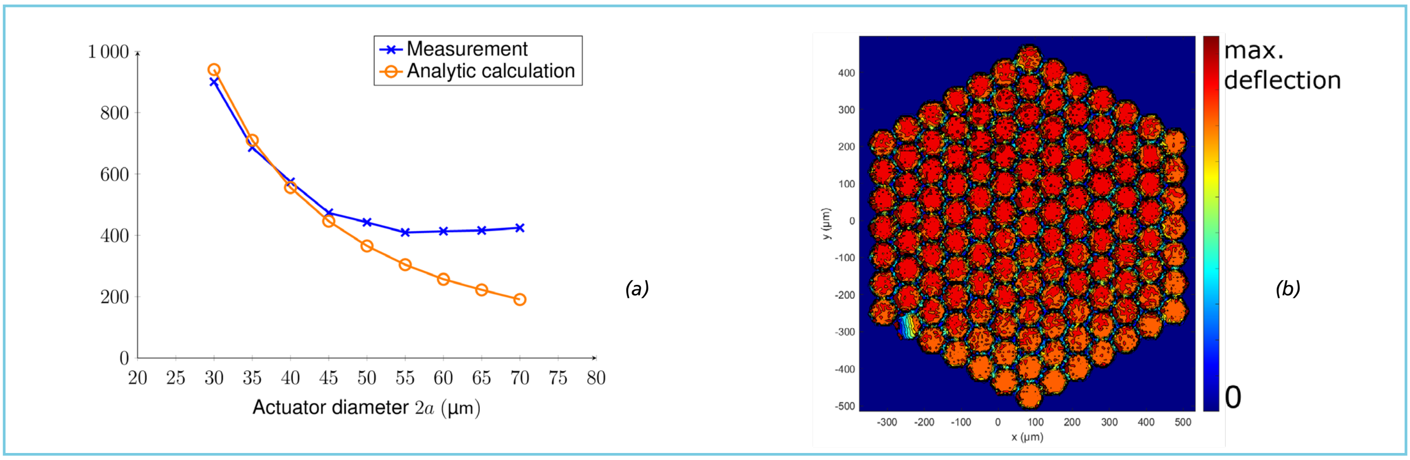

Figure 5: Experimental results on MICMUTs by Fraunhofer IPMS: (a) measured resonance frequency in comparison to analytical calculated frequencies and (b) measured homogenous motion of the roof structures at its resonance frequency.

The acoustic performance of a MICMUT was compared with a commercially available piezoelectric transducer (MULTICOMP, MCUSD11A400B11RS) under the same conditions as the MICMUT. Both transducers have a resonance frequency of 400 kHz and were excited with an AC voltage of 30 V. The same electronics were utilized for transmit and receive measurements. Beside the transduction principle, the active area diameter of the piezoelectric transducer is about 10 times larger than the diameter of the MICMUT.

In the far field, the transmitted sound pressure

$$|p(z)| \sim D^2 \qquad (2)$$

at a distance z from the transducer depends on the transducer diameter D squared [14]. Therefore, the difference in transducer size needs to be considered with a correction factor. The receive sensitivity of the MICMUT depends on the size of the active aperture as well [15]. In receive mode, a capacitive device such as the MICMUT generates an electrical current, which is converted into a voltage with a transimpedance gain of 220 kΩ. A voltage can be directly measured in case of the piezoelectric transducer. The resulting receive voltages are utilized for comparison.

The surface normalized results are shown in Table 1. Considering the surface correction factor, it can be shown that the MICMUT has the significantly better transmit and receive performance. The generated sound pressure is about 8 times higher.

In the receive mode a higher noise level is observed for the MICMUT. The dominant noise source is the utilized transimpedance amplifier, designed for a broadband reception. Nevertheless, if the MICMUT has the same size as the piezoelectric transducer and an incident wave with 1 Pa is received, the signal-to-noise-ratio of the MICMUT would be 20 dB higher.

In conclusion, the MICMUT has the potential to outperform a piezoelectric transducer under the same conditions. Either smaller MICMUTs with similar properties as a piezoelectric transducer or larger devices with a better performance can be realized. Furthermore, an end to the sensor potential is not in sight. A further increase in performance is expected through optimization of the MICMUTs and the receive electronics, especially for application specific requirements.

Parameter	Piezoelectric transducer	MICMUT
Transducer diameter	10 mm	1 mm
Resonance frequency	430 kHz	420 kHz
Center frequency (DIN EN 12668-2)	430 kHz	415 kHz
Fractional bandwidth (DIN EN 12668-2)	19%	26%
Surface normalized sound pressure (145 mm)	0.006 Pa/mm²	0.051 Pa/mm²
Surface normalized receive sensitivity	0.71 µV/Pa/mm²	2.80 mV/Pa/mm²

Table 1: Transmit and receive parameter of a piezoelectric bulk transducer and a MICMUT at a resonance frequency of 400 kHz.

APPLICATIONS OF MIMUTS

Micromachined ultrasonic transducer, including MIMUTs, are primarily used to transmit and receive acoustic waves in gaseous and immersion environments. The major reason is their good acoustic coupling to these media. The first experimental proof-of-concept was performed with the MICMUT technology for airborne applications by the Fraunhofer IPMS [8, 9].

Some exemplary fields of application are the human-computer-interaction (HCI), environmental sensing and 2D or 3D imaging. The following section describes examples of applications of MUTs and MIMUTs. They shall illustrate the wide range of applications and the benefits of MEMS based ultrasound.

In the field of human-computer-interaction [16], applications are the gesture recognition in mobile devices such as smartwatches or an extension of robot senses. These devices benefit from the miniaturization and integration capabilities of microtechnologies. If the surface normalized performance values of the characterized MICMUT (Table 1) are utilized, a pulse-echo distance limit of about 63 cm can be predicted for a device with an aperture diameter of 5 mm.

Environmental sensing applications are gaseous and liquid flow measurements as one of the major industrial sensor applications worldwide [17]. Furthermore flow measurements are necessary in medical applications, e.g. for respiratory monitoring or blood flow measurements. Especially small sensors reduce the impact on the flow profile and can be utilized for small tubes or channels. A further application is level sensing of liquids, such as lubricants or hydraulic fluids.

Especially if small sensors are needed, e.g. in endoscopic ultrasound diagnostics, the transmitted sound pressure and the receive sensitivity reduce with decreasing sensor size. Therefore a high transmit and receive sensitivity are crucial in order to measure with even small sensors. MIMUTs with the potential for a high transmitted sound pressure and receive sensitivity as demonstrated with a MICMUT in air (Table 1) provide an advantage over conventional piezoelectric transducers of the same size. In comparison to conventional MUTs, a larger freedom of design is gained in order to flexibly define transducer parameters and combinations thereof, such as low frequencies with a high fractional bandwidth.

CONCLUSION & OUTLOOK

A new class of MEMS based ultrasonic transducer was presented: mechanically interconnected micromachined ultrasonic transducer (MIMUT). These devices can be fabricated as compact, highly sensitive ultrasound transducer. A large ultrasound transmitting or receiving surface is maintained while other parameters, such as the resonance frequency or the bandwidth, can be chosen freely within a wide parameter range.

The fields of application range from distance measurements, 2D or 3D imaging to environmental sensing in gaseous or liquid media. For use in gaseous media, the Fraunhofer IPMS optimized and demonstrated the realization of these devices. The potential of MIMUTs was shown by comparing it with a commercial piezoelectric transducer. A better transmit and receive performance was shown under the same operation conditions and device size. Furthermore, the comparison of theoretical and experimental analyses exhibit that the device behavior can be predicted well by simulations. Based on this know-how, the Fraunhofer IPMS provides R&D services for the application-specific development and pilot production of MUT devices.

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