Measuring lateral vibrations within all-silicon loudspeakers

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Abstract
When MEMS are packaged in a silicon enclosure it is impossible to evaluate their dynamic performance with conventional optical methods without opening them up. Beyond the interferometric measurement of out-of-plane vibrations, the **PICO**SCALE *Vibrometer* allows the imaging of in-plane vibrations of encapsulated devices with infrared confocal microscopy.

INTRODUCTION

The majority of loudspeakers in mobile telephones, headphones and hearing aids are miniaturized versions of designs based on magnets and coils that were introduced a century ago. MEMS-based loudspeakers hold many promises in terms of performance, manufacturing and energy consumption but require to step away from traditional designs.
Here, we have tested an innovative loudspeaker developed by the Fraunhofer Institute for Photonic Microsystems (Figure 1). Sound pressure is generated by multiple electrostatic bending actuators that move laterally.
Standard laser interferometry and vibrometry cannot be used for characterizing this particular device. First, the moving parts are packaged in silicon housing, and second, the motion is in-plane (lateral). SmarAct's **PICO**SCALE *Vibrometer* employs an infrared laser (1550 nm wavelength) which makes it possible to 'look' through silicon and in combination with confocal microscopy, selected planes of the MEMS can be imaged as shown in Figure 1. The interferometric measurement function, which allows measurements of out-of-plane (vertical) vibrations, is described elsewhere. Here, we demonstrate alternative (non-interferometric) measurement modes that are available for the characterization of lateral vibrations.

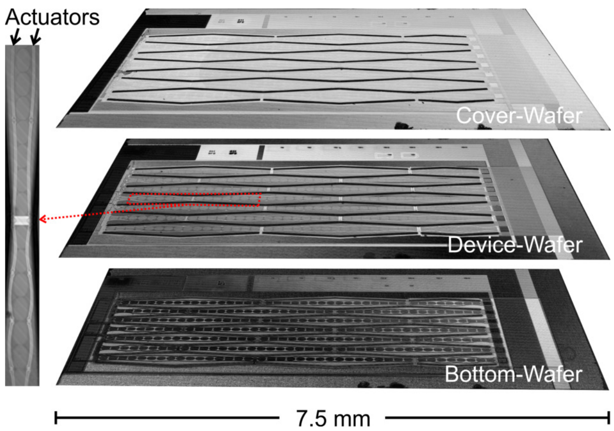

Figure 1. Confocal imaging of different layers of the loudspeaker. *The actuators can be seen in the device-wafer (see also the magnified part at the left). Openings in the cover-wafer (black zigzags) and bottom-wafer (holes) allow transmission of sound.*

RESULTS

Knife-edge point measurement

To detect lateral vibrations, the measurement laser is positioned at an edge of an actuator. When the loudspeaker is driven with an electrical signal, the actuator will move laterally through the laser beam which will modulate the amount of reflected light. Figure 2 shows the measurement principle and a measured amplitude spectrum.
The measured modulation of the reflected light provides a qualitative indicator of lateral motion because the measured amplitude depends also on the size of the focused laser spot and on the contrast of the edge on which the measurement is performed.

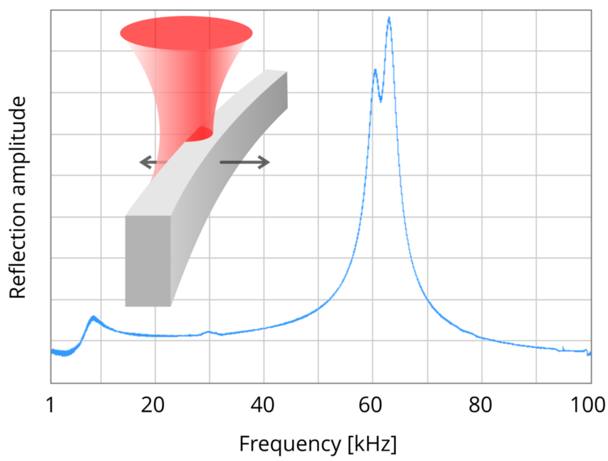

Figure 2. Knife-edge point measurement. *Lateral vibrations were measured locally on the actuator. During the recording, the loudspeaker was excited with a sweep signal from 1 kHz to 100 kHz. Within the audible range the amplitude response is fairly flat, whereas pronounced resonance peaks are visible around 60 kHz. Inset: Measurement principle. When the edge of the actuator moves laterally through the focused laser beam this will affect the amount of light that is reflected.*

Knife-edge imaging

The knife-edge vibration measurement as described above can be extended to an imaging mode by scanning the laser over the sample. Because it is impractical to record a complete amplitude spectrum for each pixel, the **PICO**SCALE *Vibrometer* employs a dual-phase digital lock-in amplifier as an alternative solution. This allows the extraction of the amplitude and phase of the vibration with respect to the excitation signal, so each pixel is defined by just 3 values: reflectivity, amplitude and phase. Figure 3 shows knife-edge imaging while exciting the loudspeaker at 10 kHz. The lateral motion of the left actuator pair increases towards the top of the image, consistent with the clamping at the bottom of the image.

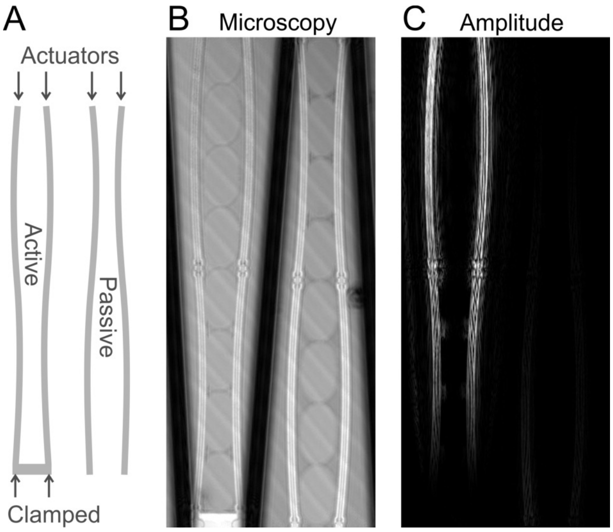

Figure 3. Knife-edge imaging. *A) Arrangement of the imaged actuators. Only the left pair was driven with an electrical signal of 10 kHz. B) Reflection microscopy image of the actuators (460 x 1100 µm, 230 x 550 pixels). C) Simultaneously recorded amplitude image, obtained by feeding the reflection intensity into the lock-in amplifier. The left actuator pair shows a clear signal due to its lateral motion.*

Stroboscopic imaging

To perform a quantitative measurement of lateral motion, a second imaging mode is available in which 20 sequential microscopy images are recorded that span exactly one oscillation cycle. Conceptually this is comparable to video recording with stroboscopic illumination. In a confocal imaging technique, where the image is scanned pixel by pixel, the implementation is more complicated. In brief, the scanning laser halts at each pixel to record 20 sequential reflection intensity values that are synchronized with the excitation signal (and span one cycle). Afterward, 20 sequential images are automatically reconstructed.

If the lateral motion is large enough, it can be directly observed by looking at the successive images. However, in MEMS, the lateral motion will often be on the order of the optical resolution of the microscope, or below. For such cases, the **PICO**SCALE *Vibrometer* VIEW software contains a tracking algorithm to quantify the motion. Figure 4 shows that an amplitude of 20 nm is readily resolved.

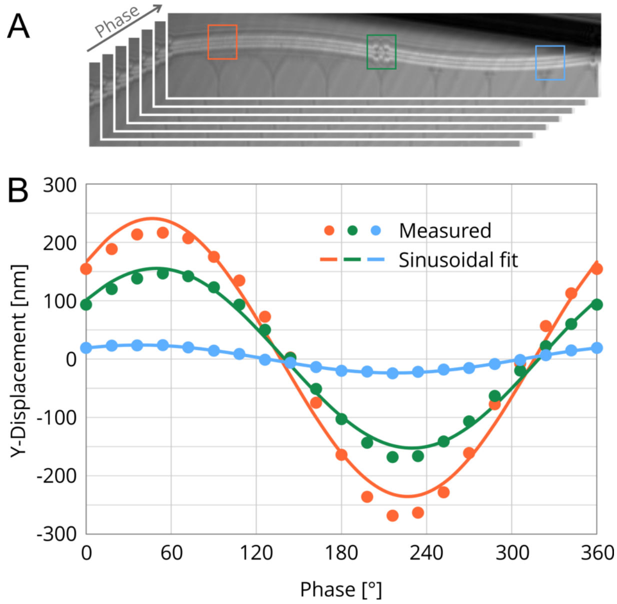

Figure 4. Stroboscopic imaging. *A) A sequence of microscopy images is recorded that span exactly one oscillation cycle. The size of the images is 110 x 1100 µm. B) Via a motion-tracking routine, features in the image can be tracked for lateral motion. The colored boxes indicate the locations along the actuator that were analyzed. The lateral motion is highest at the left part of the actuator which is consistent with the fact that the actuator is clamped at its right (see also Figure 3). Sinusoidal fits (solid lines) confirm the expected harmonic motion.*

CONCLUSION

Confocal imaging with infrared light enables the imaging of MEMS through encapsulating layers of silicon. Besides interferometry for the measurement of out-of-plane vibrations, additional techniques are integrated in the **PICO**SCALE *Vibrometer* for the characterization of in-plane vibrations. Knife-edge measurements provide a fast method for showing the presence of in-plane vibrations. However, this method is qualitative and can be sensitive to cross-talk from out-of-plane vibrations (these also cause fluctuation of reflection intensity). Quantitative imaging of in-plane motion is possible with stroboscopic imaging. This method is slower because the laser stops at every pixel, but vibrations as small as a few nm can be resolved.

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