Enhanced non-contact ultrasonic testing using an air-coupled optical microphone

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***Abstract*—In this paper three case studies of the application of a compact non-contact, non-destructive setup are presented. The herein employed method is based on the air-coupled detection of acoustic waves in the frequency range up to 2 MHz.**

***Keywords*— optical microphone, sensor, coda wave, laser excitation, ultrasound testing, air-coupled ultrasound, contact-free NDT, semiconductor imaging, PMUT characterization**

I. INTRODUCTION

Modern industrial production processes have a strong demand for fast non-destructive testing as production speeds increase and more often a 100% inspection of parts is demanded. Here an air-coupled ultrasonic NDT inspection method is presented that covers a frequency range from 10 Hz to 2 MHz. This approach enables applications that were previously limited to sensors reliant on couplant media like gel or water, or to laser-vibrometers strongly depending on surface properties of the sample. The herein presented setup is based on a highly optimized, air-coupled opto-acoustic sensor. The methods to characterize components used in combination with this sensor ranges from ultrasonic transmission C-scan images, single-sided ultrasound images to resonance and coda wave evaluation.

II. OPTICAL MICROPHONE

The core technology behind the presented method is an innovative approach to measure soundwaves through an all-optical effect. A soundwave locally modulates the density and therefore the optical refractive index of air. These small variations (~10^{-9} per Pa) are detected by making use of a laser-probed Fabry-Pérot interferometer (see Fig. 1). It converts the refractive index change into an optical signal suitable for photo-detection [1]. The active detection volume is given by the shape of the detection laser beam, with typical width and length of 100 µm and 2 mm, respectively.

This all-optical approach is not influenced by any mechanical resonances, therefore it offers an uncommonly broad bandwidth in combination with a flat frequency response. The sensor head has a small footprint (5 mm diameter) and is optically fiber-coupled.

Fig. 1. Function principle of the optical microphone and image of the sensor head. The modulation of the refractive index of air by interaction with sound waves is measured with a rigid Fabry-Pérot interferometer The mirrors are at the sides of the rectangular opening.

III. CODA WAVES IN CERAMIC COMPONENTS

A. Laser Excitation

By exposing the surface of a sample to a short, high energy laser impulse, the photo-thermal mechanism [2] will excite a thermo-elastic shockwave. This shockwave propagates as a broadband ultrasound transient through the sample.

B. *Acoustic Response Analysis*

Coda refers to the signal resulting from different scatterings and reflections after the arrival of the first wave. The ultrasound propagation is strongly influenced by the mechanical properties and structure of the sample. Defects, such as cracks or delaminations, lead to scattering, diffraction and interference, and consequently alter the ultrasound response emitted to the surrounding air, causing distinct 'acoustic fingerprints'. The Optical Microphone is able to detect these signals in a broad frequency range enabling spectral analysis. In the following, the application of the presented setup is shown for the characterization of quality variations between different production runs for small ceramic components.

The presented setup was used to differentiate between production batches of cylindrical ceramic elements with ~15mm length. The production batches vary in quality, with one batch previously identified as prone for failure. The samples were illuminated by the excitation laser on one end. The acoustic response formed by waves propagating along the cylinder axis was recorded on the other cylinder end with an optical microphone (Eta450 Ultra).

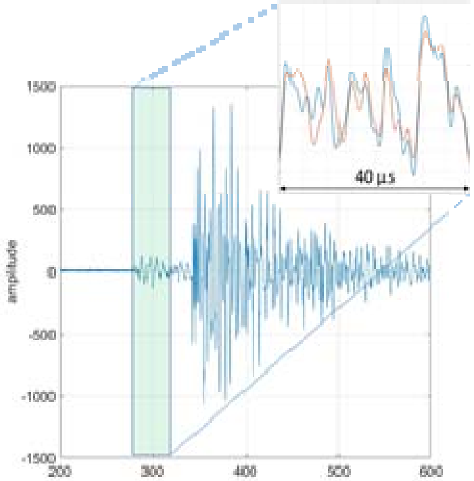

Fig. 2. Exemplary acoustic signal. The signal consists of a sound wave propagating through the ceramic part, relevant for analysis (highlighted), and a high-amplitude delayed component travelling through air from the excitation zone to the microphone.

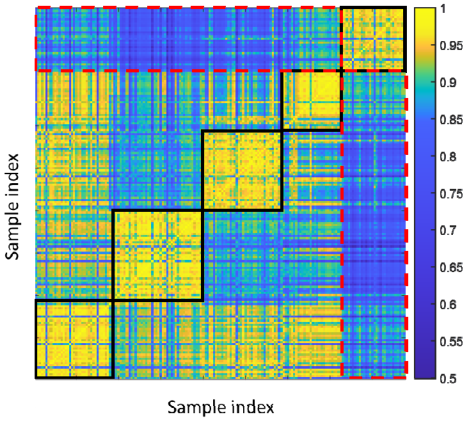

Fig. 3. Pearson correlation between acoustic signals recorded as shown in figure 1 from 175 samples. Black boxes indicate production batches, the red-dashed box highlights the low-correlation between faulty batch 5 and the rest of the samples. Blue lines within a production batch indicate deviations from other specimen of the batch that may indicate defects.

C. *Results of Coda-Wave Analysis*

Segments of the recorded signals (Fig. 2) from 175 different samples were subjected to a correlation analysis, revealing clustering according to the different production batches. Figure 3 displays the Pearson correlation coefficients for each pair of signals, where brighter areas indicate higher correlation. While certain batches feature significant cross-correlation, notably the NOK-labelled batch (cluster 5 in Figure 3) deviates from the remaining samples in terms of its acoustic response.

IV. INSPECTION OF SEMICONDUCTORS

A. *Setup*

For inspection of semiconductor samples to obtain an ultrasound image, a classical C-scan approach is used employing laser excitation from the top and the optical microphone positioned below the sample. The benefit of this method is that, unlike conventional methods delivering high spatial resolution, no coupling medium is required. The distance between the sensor and the sample is typically 2-4mm. To obtain a C-Scan image, both the laser spot on top of the sample and the acoustic sensor below the sample are raster scanned across the sample surface.

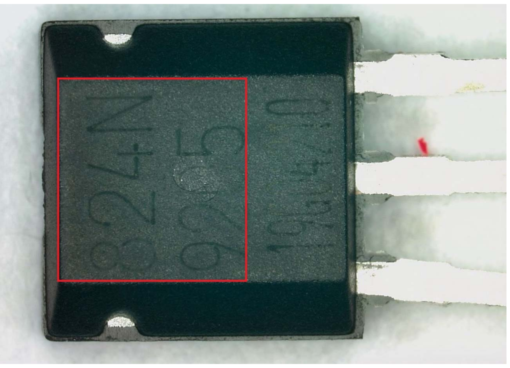

Fig. 4. Semiconductor in TO92 housing used for scanning demonstration. The red rectangle marks the scanning area

B. *Comparison with liquid coupled acoustic microscopy*

The scan using the optical microphone was conducted with a 30 µm stepping. The acoustic signal that is transmitted through the sample couples into air and its amplitude is measured by the optical microphone. Figure 5 shows a comparison with liquid coupled scanning acoustic microscopy. For demonstration a sample in a TO92 housing with a defect that was induced by mechanical stressing was used. Although the high resolution of the liquid coupled scan was not fully matched, all details of the defect are clearly visible. As lasers with pulse repetition rates of up to several MHz are available, the air-coupled method allows fastest scanning with sufficient lateral resolution to characterize common defects in even packaged microelectronic components.

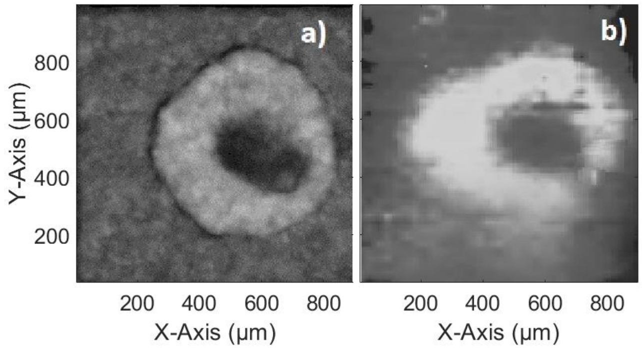

Fig. 5. Comparison of liquid coupled scanning acoustic microscopy (a) with air-coupled optical microphone technique (b) for a fully packaged chip exposed to mechanical stress leading to internal damage

V. SOUND FIELD ASSESSMENT IN AIR

A. *Method*

The small dimensions of the optical microphone together with the unique bandwidth and the flat frequency response make it an ideal tool for the characterization of air-coupled sound sources. The sound sources may range from classical piezo transducers to PMUT [3] and CMUT arrays. In the following, the sound intensity distribution of a thermo-acoustic transmitter is discussed. Unlike the previous sections, no laser excitation is required as a sound transmitter is characterized.

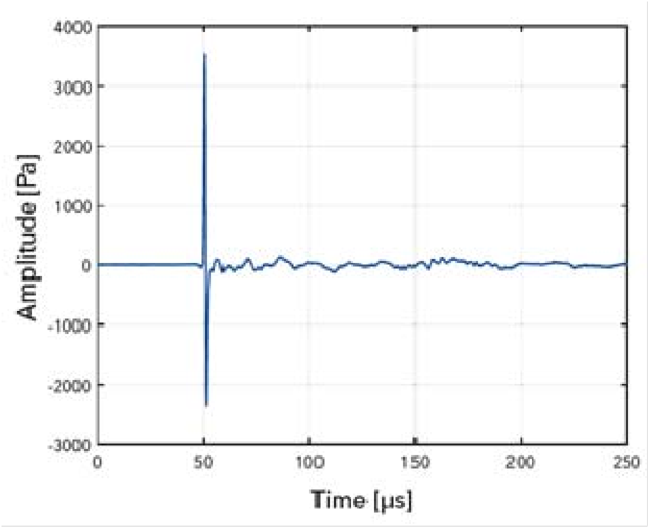

Fig. 6. Time signal of the thermo-acoustic emitter, measured with an optical microphone. No post-pulse oscillation is observed, since the optical micorphone does not contain a mechanically movable element which would cause ringing (such as for a piezoelectric ultrasound transducer or a membrane-based microphone)

The thermo-acoustic ultrasound emitter is based on a glass substrate that is electrically heated and generates a broadband acoustic spike. Figure 6 shows this acoustic response measured with the optical microphone. Due to the broad bandwidth of the microphone no ringing is observed. This ultrasound source transmitter is used in situations, where laser excitation of ultrasound cannot be applied, due to, e.g.optical transparancy of the material. To generate the soundfield scan, the microphone is moved by an xyz-robot system.

B. *Sound Field of Themo-acoustic transmitter*

One feature of the thermoacoustic-transmitter is the narrow focal point, that enables high resolution scanning. Figure 7 shows the sound field in a plane along the main axis of the transmitter. The focal point with a lateral dimension of only 1-2 mm is shown in high resolution. Also the near field effects and the side-lobes of the sound field are clearely visible.

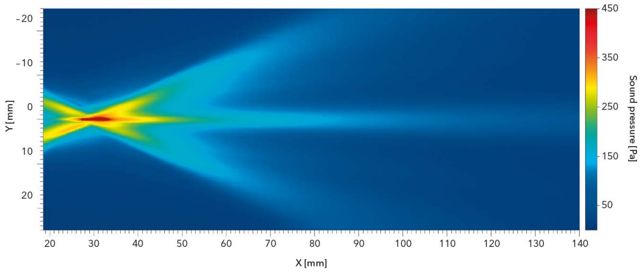

Fig. 7. Sound field of a thermo-acoustic transmitter. The position of the focal point can be displayed with high resolution

VI. CONCLUSIONS

An air-coupled optical microphone was discussed and demonstrated for three applications: Coda-wave analysis to characterize small ceramic parts during a production process in high speed for quality assurance (end of line testing), high resolution air-coupled scanning of a semiconductor component for high speed in-line, non-contact delamination detection, and finally, acoustic sound field characterization of air coupled transducers. For coda waves, a correlative analysis yielded in a good distinction of the production batches of small ceramic parts, clearly identifying a defective batch. This method is highly promising for fast air-coupled testing directly within the production line. For the C-scan imaging of a microelectronic component, a defect present in the sample was made clearly visible by fully air-coupled testing setup, at slightly reduced resolution compared to liquid coupled scanning acoustic microscopy. The results show that fast in-production testing of semiconductor components can be achieved using the optical microphone in combination with laser-ultrasound excitation.

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