Detection of defects in multilayer solids with laser-induced surface acoustic waves

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Ultrasonic waves are a common tool in industrial quality assurance to detect defects in components. Laser ultrasound (LUS) techniques use short laser pulses absorbed at the sample surface to excite a variety of acoustic modes and a continuous laser to measure the propagation of ultrasound waves, by measuring the surface displacements at defined positions. Since non-contact and non-destructive measurements are possible with a LUS setup, it is frequently used for in-line structural health monitoring (SHM). In addition, the LUS method is used to determine elastic parameters of materials. The advantages of the LUS technique are its speed, good spatial resolution, and the easy control of the bandwidth of the ultrasonic waves. [1] To detect defects such as cracks, delaminations and foremost inclusions in multilayer devices, a LUS setup (see Fig. 1), optimized for detecting surface acoustic waves (SAWs), was installed.

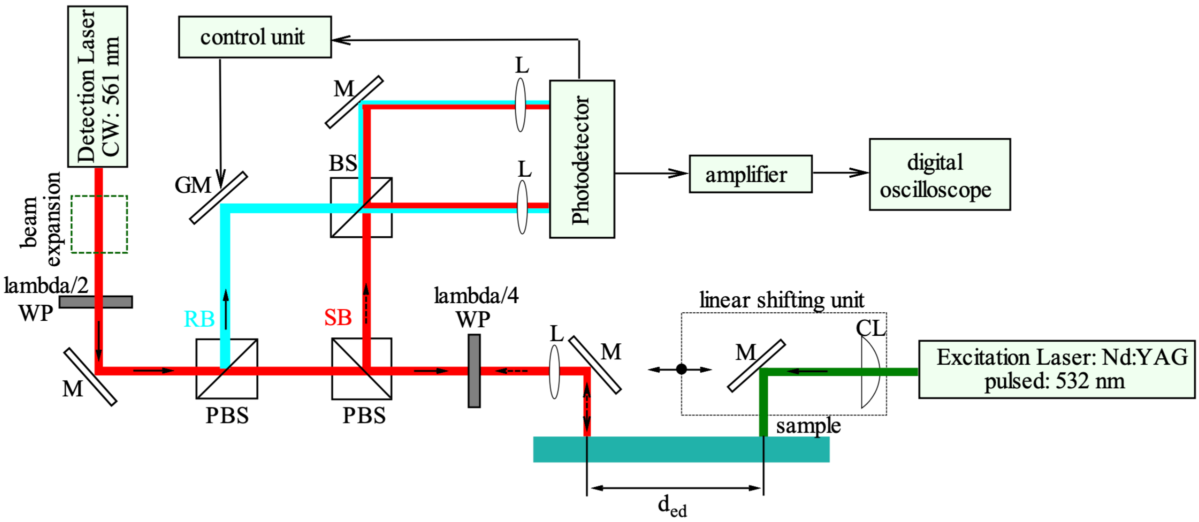

Fig. 1. LUS setup optimized in the detection of surface acoustic waves

In this LUS setup the ultrasonic waves were generated by focusing a pulsed laser beam via a cylindrical lens on a line on the sample surface. The optical and thermal properties of the sample surface determined how the irradiated energy was absorbed and converted into elastic stresses. These initial elastic stresses served as the source of the ultrasonic waves. How the ultrasonic waves propagate in the material depends on the elastic properties of the sample and is affected by any defects. [1] To detect SAWs, a stabilized Mach-Zehnder interferometer was used to record the displacement of the sample surface at specific points. With this LUS measurement system SAWs with frequencies ranging from 100 kHz up to 350 MHz could be detected.

To investigate the effect of inclusions in a multilayer structure on the propagation of SAWs, self-made samples consisting of 800 nm silver on a 725 µm thick silicon wafer substrate were prepared by physical vapor deposition. Twelve copper inclusions with different thicknesses d_{Cu} ranging from 50 nm to

400 nm and different widths, ranging from 1 mm to 3 mm were introduced between the silicon and the silver layer. For non-destructive testing of these samples, the pulse energy of the excitation laser can be up to 300 µJ at a repetition rate of 10 Hz. The dispersion behaviour of the SAWs in the samples with the different inclusions was extracted from the measured raw data by a time-frequency analysis and compared with each other and with theoretical dispersion curves calculated with the Global Matrix Method (see Fig 2 left hand side). A good agreement between theory and experiment could be achieved in this first comparison.

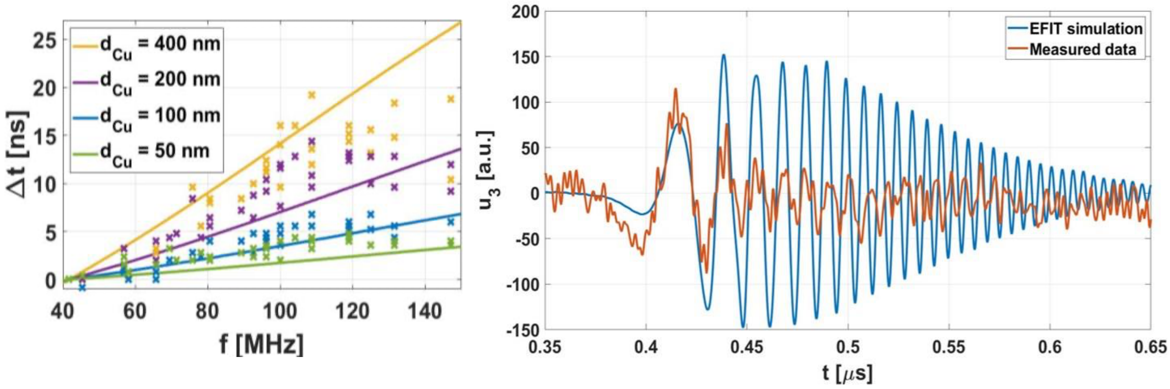

Fig. 2. Left: Comparison between extracted (crosses) and calculated (solid lines) dispersion behaviour of SAWs in multilayer samples with different inclusions.
Right: Comparison of the simulated (blue) and measured (red) propagation of a SAW in a multilayer sample.

Furthermore, the relationship between measured LUS signals and inclusion characteristics (width and thickness) of the self-made samples was investigated by a data-driven Functional Regression approach. For this purpose, Function-on-Scalar as well as Scalar-on-Function models [2] were estimated based on filtered signal data.

Because generally the ultrasonic wave propagation in materials cannot be solved analytically, a program was written that numerically solves the equations of ultrasonic wave propagation in elastic, homogeneous materials. This program is based on the Elastodynamic Finite Integration Technique (EFIT) and solves the elastodynamic equations of motion in their integral form on a discrete staggered grid. A leapfrog algorithm was used for the discrete time steps of the temporal evolution. The advantages of the EFIT method are that different geometries and boundary conditions can be implemented rather easily. [3] Time signals simulated with EFIT on a sample without inclusions were compared and found in good agreement with the measured signals (see Fig 2 right hand side). There are some discrepancies at high frequencies, which are probably due to the different material parameters for silver in simulations and experiment. Since the material parameters of silicon have already been determined, the next step would be to determine the material parameters of silver based on LUS measurements. In conclusion, the detection of SAWs with the LUS setup has proven to be a reliable tool for detecting inclusions in multilayer structures.

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References

[1] C. Scruby, L. Drain. Laser Ultrasonics: Techniques and Applications (2019). doi:10.1201/9780203749098.

[2] S. Brockhaus, D. Rügamer, S. Greven, Boosting Functional Regression Models with FDboost. Journal of Statistical Software, 94:10 (2020), 1–50. https://doi.org/10.18637/jss.v094.i10.

[3] K. Nakahata et al. A Large Scale Simulation of Ultrasonic Wave Propagation in Concrete Using Parallelized EFIT. Journal of Solid Mechanics and Materials Engineering 2 (2008) 1462–1469. doi: 10.1299/jmmp.2.1462.