Determination of longitudinal and transversal attenuation coefficients in the frequency domain using zero group velocity Lamb waves

Thomas Berer
BAW R&D
Qorvo Inc.
Apopka, FL/USA
thomas.berer@qorvo.com

Clemens Grünsteidl
Research Center for Non Destructive Testing GmbH
Linz, Austria
clemens.gruensteidl@recendt.at

Ralph Rothemund
BAW R&D
Qorvo Inc.
Apopka, FL/USA
ralph.rothemund@qorvo.com

Susanne Kreuzer
BAW R&D
Qorvo Inc.
Apopka, FL/USA
susanne.kreuzer@qorvo.com

Martin Ryzy
Research Center for Non Destructive Testing GmbH
Linz, Austria
martin.ryzy@recendt.at

Mike Hettich
Research Center for Non Destructive Testing GmbH
Linz, Austria
mike.hettich@recendt.at

Istvan A. Veres
BAW R&D
Qorvo Inc.
Apopka, FL/USA
istvan.veres@qorvo.com

***Abstract*—In this work we are using spatially localized acoustic resonances, so-called zero group velocity (ZGV) Lamb waves, to assess the attenuation parameters from the temporally decaying acoustic waves in thin plates. As these waves are not propagating, the temporal decay of these waves is directly linked to the intrinsic material damping. Guided waves and ZGV Lamb waves are excited and detected fully optically using frequency domain laser excitation and optical vibrometry. The measured responses are fitted with results obtained from finite element simulations. Samples of tungsten with thicknesses in the micrometer range, featuring ZGV frequencies around 2 GHz, were produced. As the damping of the ZGV resonance is influenced by both, the shear and longitudinal attenuation, two ZGV resonances are evaluated in order to assess the overall attenuation.**

Keywords—material attenuation, zero group velocity Lamb waves, laser ultrasound.

I. Introduction

The performance of bulk acoustic wave (BAW) resonators is significantly influenced by the composing materials of the device. Assessing the longitudinal and transversal attenuation of these materials in the GHz region – the typical frequency range of operation - is, however, not trivial. In this work we are using spatially localized acoustic resonances, so-called zero group velocity (ZGV) Lamb waves, to assess the attenuation parameters from the temporally decaying acoustic waves in thin plates. ZGV Lamb waves are non-propagating modes which arise at points in the dispersion relation of plates where the slope of the dispersion curve and, hence, the group velocity become zero. ZGV points have been utilized, e.g., to obtain the thicknesses, Poisson's ratios, or wave velocities of plates and membranes [1-3]. It has been shown that ZGV modes are very well excitable and detectable using laser-ultrasonic techniques [4-6]. Moreover, it has been shown that ZGV waves at frequencies around 2 GHz, which is the region of interest in this work, can be excited and detected using standard microscope objectives to focus the excitation and detection laser beams. As ZGV waves are not propagating, the temporal decay of these waves is directly linked to the intrinsic material damping of the plates under investigation.

II. Method

The temporal decay of ZGV waves is composed of two contributions. The first one is described by a power law, which dominates the temporal decay in the first microseconds. The second contribution shows an exponential decay, which corresponds to material attenuation [7]. Since the mode-shape of a ZGV resonance has longitudinal and transverse components, the exponential decay is dependent on the attenuation of both wave types. For isotropic solids, the attenuation is fully defined by the longitudinal and shear attenuation, α_L and α_T, respectively. To assess both attenuation parameter, α_L and α_T, two independent resonances, which exhibit distinct mode shapes, have to be measured. In our case, we use the first and second ZGV resonances. As attenuation depends on frequency, both ZGV resonances must be evaluated at approximately the same frequency. This is not possible using a single plate, wherefore two samples of different thickness need to be analyzed. The thicknesses of the samples are chosen such that the first and second ZGV resonances lie at the frequency of interest.

In this manuscript, we are interested in the attenuation of tungsten at a frequency of 2 GHz. To assess the shear and longitudinal attenuation, two samples were produced. The first sample exhibited a frequency of 2090 MHz for the first ZGV resonance at a sample thickness of 1 µm. The second sample had a thickness of 1.8 µm, leading to a frequency of 2170 MHz for the second ZGV resonance.

III. Experiments

A. Measurement setup

Acoustic waves in the membranes are optically excited by means of laser ultrasound. For excitation an electro-absorption modulated laser diode (EML) is used, the optical output of which is amplified by means of optical amplification using an Erbium doped fiber amplifier. The amplified light with a wavelength of 1550 nm and a mean power of up to 1W is then focused onto the sample using an objective lens. The output power of the EML is harmonically modulated, leading to harmonic heating and cooling of the sample surface, and consequentially to the excitation of harmonic ultrasonic waves with a frequency as given by the modulation of the EML. The resulting ultrasonic waves are detected using a free-beam optical interferometer in a Michelson configuration. The surface vibrations change the relative phase in one of the interferometers arms. This information is demodulated using a photodiode. The response of the photodiode is measured using a vector network analyzer (VNA). Measurements are performed in the frequency domain by sweeping the modulation frequency of the EML using the driving output of the VNA. The measured response corresponds to the excitation spectrum of the plate. A more detailed description of the used setup can be found in Ref. [4].

B. Finite Element Simulations and Data Analysis

Complementary to the measurements, the membranes are simulated via finite element analysis (FEA), i.e. using PzFlex. The simulations are performed for different combinations of α_L and α_T. All simulations are performed in time domain using a short Gaussian spatial-temporal stress distribution in axial-symmetry to excite waves in the GHz region. The spectrum of the plate is obtained by Fourier transformation of the transient response. In the spectrum of the measured and simulated responses, contributions from waves other than ZGV and cut-off resonances appear. These contributions are caused by transient (propagating) waves. To eliminate these from the spectra, the data is processed in the time domain, which is obtained by an inverse Fourier transform in case of the experimental data. Since simulations are performed in time domain, the corresponding data are already present in this form. To eliminate the transient waves, a time windowing operation is applied to the data. I.e., the first part of the transient displacement field is set to zero, using an appropriate window function, up to a point where the transient waves have left the measurement domains or are small enough to be neglectable. Displacements at much later times can also be set to zero to enhance the noise level. To avoid artefacts from time windowing, the time window must be chosen large enough to avoid broadening of the peaks in frequency domain. Also, the same windowing function should be applied to the measured and simulated data. For this, simulated data are interpolated to the time axis of the measurement data. The measured and simulated curves are then compared in frequency domain by calculating the mean square difference around the center peak.

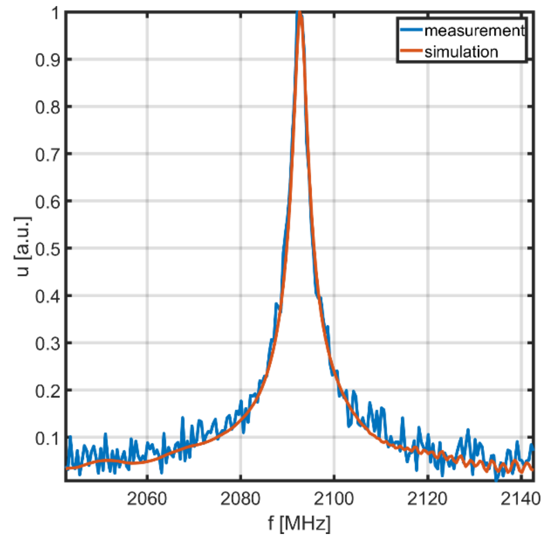

Fig. 1. Measurement and simulation of a 1 µm thick tungsten plate around the frequency of the first ZGV resonance. Blue solid line: measurement. Red solid line: simulation for α_L =9.5 dB/mm and α_T =48 dB/mm.

IV. Results

Figure 1 shows the measured response and a simulated curve for the tungsten sheet sample with a thickness of 1 µm. The center frequency is about 2090 MHz. In the figure, the simulation results for α_L =9.5 dB/mm and α_T =48 dB/mm are plotted, which result in a minimal mean square error to the measurement. However, since the ZGV resonance is influenced by both attenuation values, other combinations of α_L and α_T can be found which fit the measurement equally well. To get an unambiguous result, the second ZGV resonance is analyzed. The measured data are plotted in Fig. 2. As can be observed, the shape of the peak is asymmetric. This asymmetry is caused by a transversal cutoff which is in close vicinity to the ZGV frequency. To get a fit for this response, the sum of two curves is fitted into the measured response. The first curve describes the transversal cutoff. The second curve is a Lorentzian describing the ZGV resonance. The latter curve is then compared to the ZGV resonances obtained from FEA simulations to get a second set of α_L and α_T values.

Comparing the two solutions leads to a unique set of values that best fit the response of the two ZGV resonances. In our case, the mode shape of the second ZGV of the tungsten plate is dominated by the shear component and the overall attenuation of this mode shows little influence on α_L. Thus, evaluation of the second ZGV resonance leads directly to a value of α_T of 50 ± 5 dB/mm. Inserting this value into the results for the first ZGV point leads to a value of 10 ± 1 dB/mm for α_L.

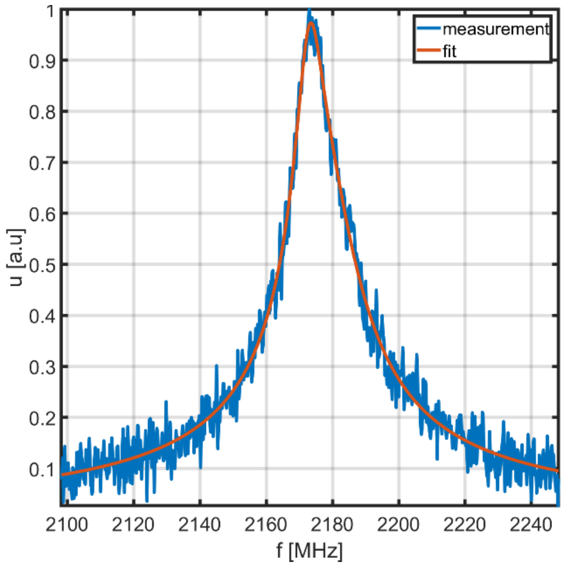

Fig. 2. Blue sold line: Measurement of the second ZGV resonance. The peak is assymetric due to a transveral cut-off in close vicinity to the ZGV. The red line shows a fit of the combined resonance, considering the ZGV and the cut-off.

V. Conclusions

In summary, we have evaluated the longitudinal and shear attenuation of tungsten sheet samples at 2 GHz by making use of the spatial localization of zero group velocity Lamb waves. The ZGV Lamb waves were excited and detected fully optically by means of laser ultrasound. By calculating the mean square error between measured responses and responses obtained by finite element simulations for one ZGV resonance, one set of solutions could be found which lead to minimal errors. A second set of solutions was obtained from the second ZGV resonance. By combining both set of solutions, we concluded that the longitudinal attenuation and shear attenuation for the investigated tungsten plates are 10 ± 1 dB/mm and 50 ± 5 dB/mm, respectively.

Acknowledgements

Financial support was provided by the Austrian research funding association (FFG) under the scope of the COMET program within the research project "Photonic Sensing for Smarter Processes (PSSP)" (contract # 871974).

References

[1] C. Grünsteidl, T.W. Murray, T. Berer, and I.A. Veres, "Inverse characterization of plates using zero group velocity Lamb modes," Ultrasonics, vol. 65, pp 1-4, 2016.

[2] D. Clorennec, C. Prada, and D. Royer, "Laser ultrasonic inspection of plates using zero-group velocity Lamb modes," IEEE Trans Ultrason Ferroelectr Freq Control., vol. 57, pp. 1125–1132, 2010.

[3] D. Clorennec, C. Prada, and D. Royer, "Local and noncontact measurements of bulk acoustic wave velocities in thin isotropic plates and shells using zero group velocity Lamb modes," J. Appl. Phys., vol. 103, 034908, 2007.

[4] C. Grünsteidl, T. Berer, M. Hettich, and I. Veres, "Determination of thickness and bulk sound velocities of isotropic plates using zero-group-velocity Lamb waves," Appl. Phys. Lett., vol. 112, 251905, (2018).

[5] C. Prada, O. Balogun, and T. W. Murray, "Laser-based ultrasonic generation and detection of zero-group velocity Lamb waves in thin plates," Appl. Phys. Lett., vol. 87, pp. 1–3, (2005.

[6] O. Balogun, T. W. Murray, and C. Prada, "Simulation and measurement of the optical excitation of the S1 zero group velocity Lamb wave resonance in plates," J. Appl. Phys., vol. 102, pp1–10, 2007

[7] C. Prada, D. Clorennec, and D. Royer, "Power law decay of zero group velocity Lamb modes," Wave Motion, vol. 45, pp. 723-728, 2008.