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Measurement Model for Attenuation of Leaky Surface Acoustic Waves by the Line-Focus-Beam Ultrasonic Material Characterization System

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***Abstract*—We experimentally and theoretically studied an exact measurement model for attenuation of leaky surface acoustic waves (LSAWs) using the line-focus-beam ultrasonic-material-characterization (LFB-UMC) system. We measured the LSAW propagation characteristics (viz., phase velocity and attenuation) for two specimens of synthetic silica (SiO_2) glass and borosilicate (Pyrex) glass at 225 MHz. We detected acoustic loss of LSAWs due to the acoustic absorption effect for the Pyrex glass by calibrating the measurement results with reference to those of the SiO_2 glass.**

***Keywords*—line-focus-beam ultrasonic material characterization system; leaky surface acoustic wave; attenuation measurement; synthetic silica glass; borosilicate glass**

I. INTRODUCTION

The line-focus-beam ultrasonic material characterization (LFB-UMC) system can evaluate materials by precisely measuring the propagation characteristics, viz. velocity and attenuation, of leaky surface acoustic waves (LSAWs) excited on the water-loaded specimen surface [1, 2]. Information of the phase velocity V_{LSAW} has been mainly used for material characterization, because of the higher accuracy. Although attenuation is one of the important parameters for material characterization, it has been employed only for several applications, such as evaluation of scattering loss in polycrystalline materials [3] and determination of the elastic constants for thin-film materials using the cut-off characteristics of leaky Sezawa and pseudo-Sezawa wave modes [4]. However, an absolute value of α_{LSAW} has not yet been discussed in detail so far, although the calibration method has been established in essence not only for the LSAW velocity but also for the LSAW attenuation [5]. From the technical view of point for material characterization, it is important to use the α_{LSAW} information in addition to the V_{LSAW} information for applications, such as ultrasonic spectroscopy of materials, e.g., analysis of relaxation processes, as materials are lossy and dispersive. So, it is necessary to measure LSAW propagation characteristics as a function of frequency. For the purpose, we have to establish an exact measurement model for attenuation of LSAWs and calibration of measured attenuation, resulting in improvement of attenuation measurement accuracy.

In this paper, we took two kinds of glasses as specimens: a synthetic silica (SiO_2) glass with negligibly small attenuation and a borosilicate (Pyrex) glass with relatively large loss in the VHF range. We measured and studied an LSAW attenuation of the lossy Pyrex glass, referred to that of SiO_2 glass at 225 MHz.

II. EXPERIMENTS

A. Specimens

Commercial synthetic silica glass (C-7980: SiO_2, Corning Inc.) and borosilicate glass (C-7740: Pyrex, Corning Inc.) were taken as specimens. The elastic constants and the density were measured accurately for the specimens, which were used as the standard specimens for the LFB-UMC system [6–8]. The bulk acoustic properties measured previously [6–8] are shown in Table I. In the VHF range, the acoustic properties, velocity and attenuation, of the SiO_2 specimen were with constant values in the longitudinal and shear velocities (V_l and V_s) and very small attenuations (α_l and α_s) for both wave modes, while those of the Pyrex specimen exhibited velocity dispersion and relatively large attenuations. The typical values of longitudinal and shear waves at 225 MHz are as follows: for the SiO_2 specimen, V_l = 5929.13 m/s with α_l = 0.04 dB/mm and V_s = 3767.62 m/s with α_s = 0.08 dB/mm; and for the Pyrex specimen, V_l =5544.43 m/s with α_l = 1.16 dB/mm and V_s = 3413.45 m/s with α_s = 2.05 dB/mm.

B. LFB-UMC System

We measured LSAW propagation characteristics of the two specimens using the LFB-UMC system at 225 MHz using an LFB device consisting of a cylindrical acoustic lens of sapphire with a curvature radius of 1 mm [1]. The measurement method and system were described in detail in the literature [1, 2]. The LSAW propagation characteristics, viz. phase velocity V_{LSAW} and normalized attenuation factor α_{LSAW}, were measured through the procedure of V(z) curve analysis [1]. Fig. 1 shows the recorded V(z) curves and their processes for the SiO_2 specimen. The interference output $V_I(z)$ is processed by a fast Fourier transform (FFT) analysis. From the spectral distributions, we can determine the oscillation interval Δz and attenuation α_0 in the $V_I(z)$ curve. V_{LSAW} and α_{LSAW} are obtained using the following relations:

$$V_{\mathrm{LSAW}} = \frac{V_w}{\sqrt{1-\left(1-\frac{V_w}{2f\Delta z}\right)^2}}, \text{ and} \tag{1}$$

$$\alpha_{\mathrm{LSAW}} = \frac{\alpha_0 \cos\theta_{\mathrm{LSAW}} + 2\alpha_w}{2k_{\mathrm{LSAW}} \sin\theta_{\mathrm{LSAW}}}, \tag{2}$$

where V_w and α_w are the longitudinal-wave velocity and attenuation coefficient of water, respectively [9, 10], and k_{LSAW} is the wavenumber of the LSAWs which equals ω/V_{LSAW}.

To obtain absolute values in velocity and attenuation in this method, we have to calibrate the system including the LFB device at an employed ultrasonic frequency for measurements, according to the system calibration procedure using a standard specimen [5] for which the accurate acoustic properties were measured, that is, elastic constants and density for lossless materials, and for lossy materials dispersive characteristics in velocity and attenuation are needed.

The calibration for V_{LSAW} is conducted by correcting the distance z. The correction coefficient $K(V)$ is obtained by the following equation:

$$K(V) = \frac{\Delta z_{\mathrm{ST}}(\mathrm{cal.})}{\Delta z_{\mathrm{ST}}(\mathrm{meas.})}, \tag{3}$$

where Δz_{ST}(cal.) and Δz_{ST}(meas.) are the calculated and measured values of Δz for the standard specimens.

The calibration for α_{LSAW} is conducted to correct the attenuation α_0 of the $V_I(z)$ curve. The correction coefficients $K(\alpha)$ is obtained by the following equation:

$$K(\alpha) = \frac{\alpha_{0\mathrm{ST}}(\mathrm{cal.})}{\alpha_{0\mathrm{ST}}(\mathrm{meas.})}, \tag{4}$$

where $\alpha_{0\mathrm{ST}}$(cal.) and $\alpha_{0\mathrm{ST}}$(meas.) are the calculated and measured values of α_0 for the standard specimens. In this process, the calibrated V_{LSAW} is used for θ_{LSAW} (= $\sin^{-1} V_w/V_{\mathrm{LSAW}}$) and k_{LSAW}.

To obtain the calibration coefficients of $K(V)$ and $K(\alpha)$, we have to calculate LSAW propagation characteristics numerically, according to the analytical procedure of Campbell and Jones [11] with treating water as an ideal fluid. Then, we can obtain calibrated LSAW propagation characteristics using the following equations:

$$\Delta z(\mathrm{calib.}) = K(V)\, \Delta z(\mathrm{meas.}), \text{ and} \tag{5}$$

$$\alpha_0(\mathrm{calib.}) = K(\alpha)\, \alpha_0(\mathrm{meas.}). \tag{6}$$

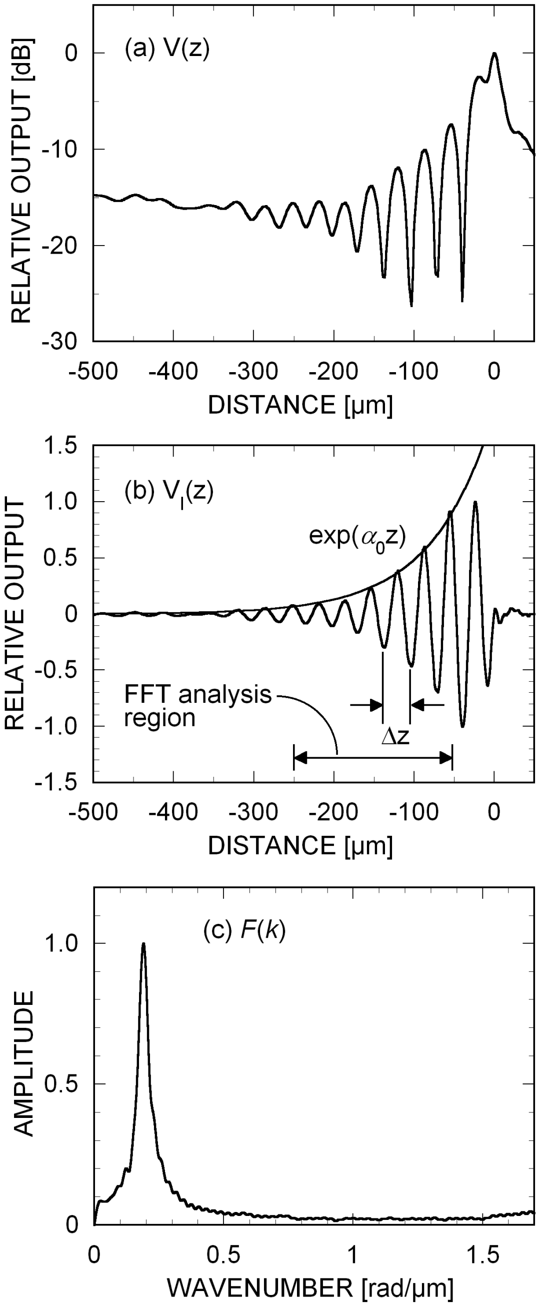

Figure 1. V(z) curve analysis of SiO_2 glass measured at 225 MHz using the LFB-UMC system. (a) V(z) curve. (b) Interference waveform of $V_I(z)$ curve. (c) Spectral distribution analyzed by FFT for the $V_I(z)$ curve shown in (b).

Here, we used both the specimens of SiO_2 and Pyrex glasses characterized as the standard specimens, so obtained final results must be equal to the calculated results. So, in this study of the LSAW loss measurement, we try to obtain LSAW attenuation reflecting the bulk-wave absorption loss in the Pyrex glass by calibrating measured α_0 with the calibration coefficient for the SiO_2 standard specimen, $K(\alpha\text{: } SiO_2)$.

TABLE I. BULK ACOUSTIC PROPERTIES OF SiO_2 AND PYREX GLASSES AT 23 °C [REFS.[6–8]].

	SiO_2		Pyrex	
	Longitudinal	*Shear*	*Longitudinal*	*Shear*
Velocity [m/s]	5929.13	3767.62	$5538.29+0.0328\times f^{0.27}$	$3401.95+1.53\times f^{0.10}$
Attenuation coefficient [m^{-1}]	$1.1\times10^{-16}\times f^{2}$	$1.9\times10^{-16}\times f^{2}$	$2.30\times10^{-9}\times f^{1.29}$	$1.82\times10^{-9}\times f^{1.33}$
Density [kg/m^3]	2199.82		2222.48	

TABLE II. CALCULATED RESULTS OF SAW AND LSAW PROPAGATION CHARACTERISTICS FOR SiO_2 AND PYREX GLASSES AT 225 MHZ USING THE CONVENTIONAL MODEL OF IGNORING THE ABSORPTION LOSS.

Specimen	SAW	LSAW	
	V_{SAW} [m/s]	V_{LSAW} [m/s]	α_{LSAW}
SiO_2	3406.88	3426.22	0.0390
Pyrex	3106.58	3127.76	0.0412

TABLE III. RAW AND CALIBRATED DATA OF MEASURED LSAW PROPAGATION CHARACTERISTICS FOR SiO_2 AND PYREX GLASSES AT 225 MHZ.

Specimen	V_{LSAW} [m/s]		α_{LSAW}	
	Raw data	*Calibrated data*	*Raw data*	*Calibrated data*
SiO_2	3427.56	3426.22	0.0430	0.0390
Pyrex	3128.66	3127.76	0.0478	0.0431

The measurement reproducibility for $\pm2\sigma$ (σ: standard deviation) of our measurement system was estimated to be ±0.006% in velocity and ±0.16% in attenuation from repeated 50 V(z) curve measurements. We chose the same characterization region from –50 µm to –250 µm for FFT analysis of the $V_I(z)$ curves for all the measurements.

C. *Experimental and Numerical Results*

First of all, we made numerical calculations of LSAW propagation characteristics of the two specimens using the conventional model of ignoring the absorption loss in the solid specimens, in order to obtain $K(\alpha: SiO_2)$ for the present system. Table II presents the results, including calculations for SAW propagation characteristics with no loading of free space. We can understand that, due to the water loading, V_{LSAW} for the SiO_2 specimen is 3426.22 m/s with an increase of 19.33 m/s (0.57%) from V_{SAW} of 3406.88 m/s and α_{LSAW} of 0.0390, while V_{LSAW} for the Pyrex specimen is 3127.76 m/s with an increase of 21.17 m/s (0.68%) from V_{SAW} of 3106.58 m/s and α_{LSAW} of 0.0412. This means that the water-loading effect for the SiO_2 specimen is lighter than that for the Pyrex specimen.

The raw data of measured LSAW propagation characteristics are presented in Table III. The calibration coefficients of $K(V: SiO_2)$, $K(\alpha: SiO_2)$, and $K(V: \text{Pyrex})$ were obtained as 0.999, 0.890, and 0.999, respectively. We observed that calibrated α_{LSAW} for the Pyrex specimen was 0.0431 that is by 0.0019 (4.5%) larger than the calculated α_{LSAW} of 0.0412.

TABLE IV. CALCULATED LSAW PROPAGATION CHARACTERISTICS CONSIDERING ABSORPTION LOSS IN SiO_2 AND PYREX GLASSES AT 225 MHZ.

Specimen	V_{LSAW} [m/s]	α_{LSAW}
SiO_2	3426.23	0.0390
Pyrex	3128.10	0.0419

III. DISCUSSION

To discuss and understand the water-loading effect and the LSAW loss measurement, we further made theoretical and numerical considerations. In the measurement, α_{LSAW} is in general defined as follows,

$$\alpha_{LSAW} = \alpha_{WL} + \alpha_{b} + \alpha_{s}. \tag{7}$$

The quantities α_{WL}, α_b, and α_s are due to the water-loading effect, the acoustic bulk absorption effect, and the structural scattering effect, respectively. In this measurement situation, α_s can be neglected, because the specimens are homogeneous and optically polished.

α_b for the SiO_2 specimen is negligible in the VHF range because the bulk-wave attenuation are very small, while that for the Pyrex specimen must be considered. Therefore, α_{LSAW} is represented as (8) and (9) for the SiO_2 and Pyrex specimens, respectively.

$$\alpha_{LSAW}(SiO_2) = \alpha_{WL}(SiO_2), \text{ and} \tag{8}$$

$$\alpha_{LSAW}(\text{Pyrex}) = \alpha_{WL}(\text{Pyrex}) + \alpha_{b}(\text{Pyrex}). \tag{9}$$

Now, we extended our computation program to calculate the LSAW propagation characteristics for the two specimens taking into consideration the bulk-wave absorption effect by defining complex stiffness constants c_{ij}^* based on the measured results in Table IV. The LSAW velocities for the two specimens did not have any significant changes, but the attenuation increased very slightly by 0.00003 (0.1%) for the SiO_2 specimen and significantly by 0.0007 (1.8%) for the Pyrex specimen.

The α_{LSAW} value of 0.0431 for the Pyrex specimen obtained in the measurement must include the loss due to the bulk-wave absorption effect. We could obtain the calibration coefficient $K(\alpha: SiO_2)$ of 0.890 for the case of considering the absorption effect, but it did not have any influence on the determination of α_{LSAW}. So, we obtained the additional attenuation difference of 0.0011 (2.7%) between the measured value of 0.0431 and the theoretical value of 0.0419 considering the bulk-wave absorption effect which was larger than the theoretical attenuation difference of 0.0007 (1.8%) due to the bulk-wave absorption effect. This suggests that the extra attenuation could be associated with the treatment of the water-loading effect. In the theoretical calculations, water was treated as an ideal fluid, and the shear-wave component was not considered for the boundary conditions. That is, the effect of shear-wave of water should be included in the measured attenuation, but not included in the calculated one in (4). In addition, viscosities of longitudinal and shear waves of water were not considered in the calculation, although they could not be neglected in the VHF range.

IV. SUMMARY

In this paper, we experimentally and numerically studied the LSAW attenuation measurement model as the first step to use the information of α_{LSAW} for materials analyses by the LFB-UMC system. α_{LSAW} of the Pyrex specimen was determined referred to that of the SiO_2 specimen. However, its value was significantly larger than the numerically estimated one. The results suggested that the shear wave behavior in water should be considered for absolute α_{LSAW} measurements. Further investigation will be needed for completing the measurement principle for the LFB-UMC system.

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