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Laser generation and detection of interface waves for the acoustic spectroscopy of liquids.

C. Desmet, V. Gusev, W. Lauriks and J. Thoen.
Laboratorium voor Akoestiek en Thermische Fysica, Departement Natuurkunde, Katholieke Universiteit Leuven, Celestijnenlaan 200D, B-3001, Leuven.

ABSTRACT

The pulsed heating of the interface between a solid and a liquid leads to the excitation of acoustic interface waves. These interface waves are detected at a variable distance from the generation region by means of a beam deflection setup. By evaluating the amplitude and phase spectra (using a Fast Fourier transform) of two wave pulses at two different source-receiver distances, the velocity of propagation and the attenuation of the interface waves are measured as a function of frequency (bandwidth of 50 MHz). By fitting these experimentally determined results to theory it is possible to determine the acoustic properties of the liquid as a function of frequency.

INTRODUCTION

In this paper we report on the all optical generation and detection of acoustic waves at the interface between a solid and a liquid and its applications for wide-frequency band acoustic spectroscopy of liquids. Thermoelastically two types of interface waves can be generated on the interface between a solid and a liquid : the leaky Rayleigh wave and the Scholte wave. The Scholte wave is an acoustic guided wave trapped at the solid-liquid interface. The leaky Rayleigh wave corresponds to the Rayleigh wave on the free surface of a solid that becomes damped because of seepage of energy in the liquid, due to to the supersonic velocity the leaky Rayleigh wave relative to the acoustic waves in the liquid.

ACOUSTIC PROPERTIES OF THE LIQUID

A diagram of the measuring cell configuration is presented in Figure 1. The pump radiation (400 mJ Nd:Yag laser pulses with a wavelength of 1064 nm. And a duaration of 10 ns.) is focused through the optically transparent walls of the cell (fused silica) onto the surface of the light absorbing liquid (a water-$CuCl_2$-solution) with a cylindrical lens (beam size ≈ 0.1 × 20 mm). The transient heating of the contacting

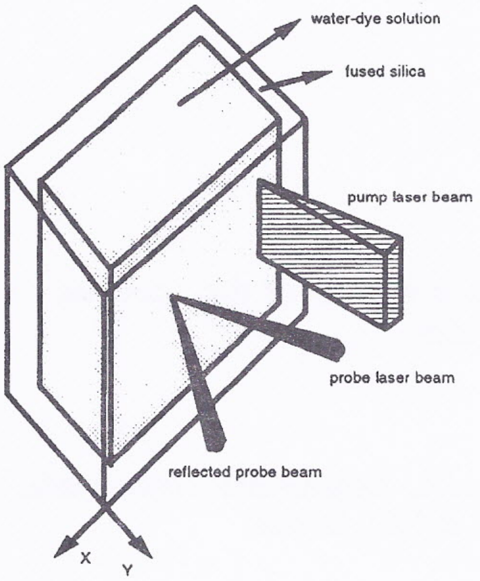

Figure 1. Schematic diagram of the measuring cell configuration.

materials near the interface leads to the buildup of thermo-elastic stresses and the excitation of interface acoustic waves. The leaky-Rayleigh and Scholte wave pulses travel along the interface and are detected at a variable distance from the source by a probe He-Ne laser beam focused to a spot size of 30μm. The changes of the deflection angle are monitored. To have a good reflection for the detection beam, the inner surface of the solid is coated with a thin chromium film (30nm). The deflection of the probe laser beam is caused predominantly by the interface inclination and not by the acoustically induced refractive index changes. The He-Ne laser probe was located just at the edge of the metallic coating, and by consequence the propagation of interface waves was predominanly on an uncoated interface. Under these conditions no influence of the thin coating on the detected signals was observed. A more detailed description of the experimenatl setup can be found elsewhere [1]. An experimentally detected time-profile (showing both the leaky Rayleigh wave and the Scholte wave) is shown in the inset of Figure 2. The experiments were performed on two $CuCl_2$ solutions with different concentrations.

Theoretically the leaky Rayleigh and Scholte wave velocity can be derived from the so-called Scholte determinant :

$$\left[2-\left(\frac{v}{v_{T1}^2}\right)^2\right]^2-4\left[1-\left(\frac{v}{v_{T1}^2}\right)^2\right]^{1/2}\left[1-\left(\frac{v}{v_{L1}^2}\right)^2\right]^{1/2}$$

$$+\frac{\rho_2}{\rho_1}\left(\frac{v}{v_{T1}}\right)^4\left[1-\left(\frac{v}{v_{L1}^2}\right)^2\right]^{1/2}\left[1-\left(\frac{v}{v_{L2}^2}\right)\right]^{-1/2}=0.$$

Here v is the velocity of the interface wave v_L and v_T are the velocities of bulk longitudinal and tranverse acoustic waves and subscripts 1 and 2 denote the parameters of the solid and the liquid respectively. The elastic properties of the fused silica were taken from literature : $\rho_1 = 2.19$ g/cm^3, $v_{L1} = 5.97\times10^5$ cm/s and $v_{T1} = 3.76\times10^5$ cm/s. The phase spectra of two signals with two different source-receiver distances is calculated after windowing the selected wave type. With these phase spectra the velocity of both types of waves has been calculated as a function of frequency. The velocity of the leaky Rayleigh wave v_{LR} exceeds the Rayleigh wave velocity v_R which is in agreement with the expectations (e.g. for the solution with the highest concentration $v_{LR,exp.} = (3.44\pm0.04)\times10^5$ cm/s, $v_{LR,theor.} = 3.45\times10^5$ cm/s and $v_{R,theor.} = 3.41\times10^5$ cm/s). The experimentally determined Scholte wave velocities are given by : $v_{S1}=(1.67\pm0.02)\times10^5$ cm/s and $v_{S2} = (1.72\pm0.02)\times10^5$ cm/s. Their values deviate less than one percent from the bulk longitudinal velocity in the liquid [2]. The increase of the velocity as a function of concentration is caused by the increase of v_{L2} in the liquid. By consequence, for this kind of low density solutions, the value of the Scholte wave velocity can be used as the value of the velocity of the longitudinal velocity in the liquid. Figure 2 shows the experimentally determined (with symbols) and theoretically predicted (straight solid lines) attenuation of the leaky Rayleigh wave for the two solutions described above. The dashed lines are the best least-squares fits to the experimentally determined attenuation. An analytical solution for the attenuation is obtained by introducing a small complex wavenumber $\Delta q = a\ \nu$ ($a>0$ and ν the acoustic frequency) in the Scholte determinant. The experimental values for a are obtained by dividing the amplitude spectra of two signals (calculated with an FFT algorithm) with different source-receiver distance. The values are given by : $a_1 = (1.08\pm0.04)\ \mathrm{cm}^{-1}\ \mathrm{MHz}^{-1}$ and $a_2 = (1.26\pm0.03)\ \mathrm{cm}^{-1}\ \mathrm{MHz}^{-1}$. Knowing the elastic properties of the solid (well known from literature) and the longitudinal bulk wave velocity v_{L2} of the liquid (from measurement of the Scholte wave velocity) and comparing the experimentally obtained values for a with the theoretically calculated ones, it is possible to obtain the density of the solution. Their values are given by $\rho_{21} = 1.34\ \mathrm{g/cm}^3$ and $\rho_{22} = 1.47\ \mathrm{g/cm}^3$ and are, within the experimental accuracy of about one percent, in agreement with the values obtained from a simple weight measurement.

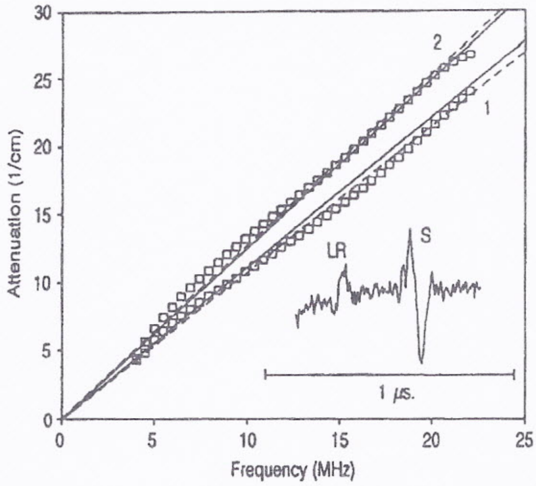

Figure 2. Attenuation of the leaky Rayleigh wave on the interface between fused silica and two water-CuCl$_2$ solutions as a function of frequency.

OPTICAL ABSORPTION OF THE LIQUID

In addition to the determination of the elastic properties of the liquid, it is also possible to determine, with the same measurement, the optical absorption coefficient of the liquid. The full width at half maximum of the observed Scholte wave pulses τ can be measured experimentally and calculated theoretically using the expression given in ref.[1]. In figure 3 the dimensionless ratio $K = \tau / \tau_S$ (where $\tau_S = \tau_0 + x_0/v_S$ with x_0 the width of the optical beam and τ_0 the duration of the optical pulse) is plotted as a function of the dimensionless parameter :

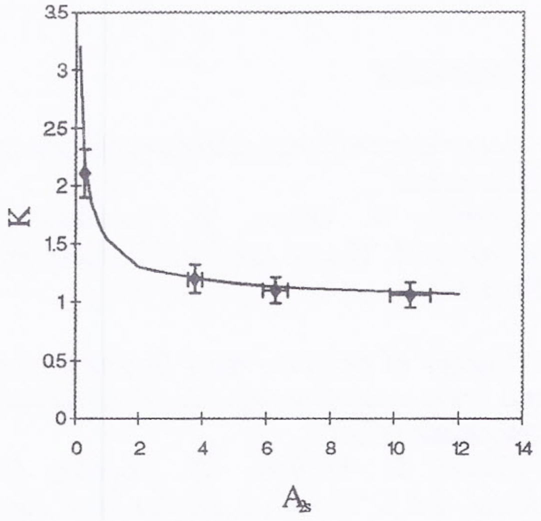

Figure 3. Dependence of the ratio K on the dimensionless parameter A_{2S}.

$$A_{2S} = \frac{\rho_2 \alpha_2 v_{L2}^3 \tau_S}{4 \rho_1 v_{T1}^2},$$

with α_2 the optical absorption coefficient of the liquid, for four water CuCl$_2$ mixtures. Knowing the elastic properties of the solid (literature) and the liquid (measurements) it is possible to estimate the optical absorption coefficient of the liquid. Within experimental accuracy (about ten percent), there is agreement with the absorption coefficients measured in the usual way (measuring the optical intensity in front and behind a container of the solution with a known thickness).

CONCLUSION

We have shown that it is possible to measure the elastical properties and the optical absorption coefficient of a liquid in a fully non-contact way. This was done by measuring the interface inclination caused by the propagation of laser generated leaky Rayleigh and Scholte wave pulses. Results for a (water-$CuCl_2$)-solution with different concentrations (and by consequence different elastic properties and a different optical absorption) have been presented.

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