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The Propagation characteristics of a shear horizontal (SH) wave in a trilayer structure having a viscous fluid layer is analyzed from a numerical analysis. Acoustic phase changes under application of electric fields in a nematic liquid crystal cell are measured using the SH wave. The acoustic phase advances with increasing the applied electric field. This result corresponds with the viscosity change based on a molecular reorientation of the liquid crystal. In dynamic response measurement, the response times in the phase and the optical measurements are different, because the measured area of the acoustic phase is only the vicinity of the glass surface.

Keywords: director; nematic liquid crystal; response time; ultrasonic wave; viscosity

INTRODUCTION

A nematic liquid crystal is an anisotropic liquid based on a cylindrical molecular shape, which have anisotropies of a viscosity, a thermal

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conductivity and a dielectric constant. A measurement of the viscosity is essentially important from the view point of physics as well as engineering. In conventional method, viscosities of liquid crystals have been measured by using rotational viscometer or quartz crystal resonator. At the preset stage, a more convenient measurement system is desired for a real-time measurement system for the small quantity of a test sample. Recently, we have proposed a method for measuring liquid crystal viscosity in the vicinity of a surface using a shear horizontal (SH) wave [1–4]. The SH wave which is one of the ultrasonic shear wave, does not take the form of a leaky wave at a solid/liquid interface [5,6]. Since the acoustic wave device requires low energy loss into a liquid layer for sensing, the SH wave is adequate for sensor applications. The SH wave advantage of the low energy loss at a solid/liquid interface is utilized for mass [7], conductivity [8], density [9] and viscosity [10] sensing. Furthermore, our method also has more advantage that the viscosities of liquid crystals can be measured in a cell structure. In rotational viscometer, liquid crystals are measured in a cylinder which is different from a usage environment. For development of liquid crystal device, it is important to measure the viscosity in an actual cell structure. Until now, we have discussed the viscosity measurement of ferroelectric liquid crystals and nematic liquid crystals using an acoustic phase change of the SH wave [1,2].

In this article, the acoustic phase measurement of the SH wave in a trilayer structure composed of the nematic liquid crystal layer sandwiched between two glass substrates is described on the basis of numerical and experimental investigations. The dynamic response measurement of the acoustic phase of SH wave is also performed under the application and removal of voltage to the nematic liquid crystal layer.

NUMERICAL ANALYSIS

The characteristic of a SH wave propagation in a liquid crystal cell structure was analyzed. Figure 1 shows a coordinate system used for the numerical analysis which consists of two glass plates and a liquid crystal layer. An excitation source of the SH wave was set in the lower glass plate. The excited SH wave propagates the lower glass plate and slightly penetrates into the liquid crystal layer. The propagation direction and vibration displacement direction of the SH wave are along the X_1 and X_2 axes, respectively. In the glass plate as a thin propagation medium, the SH wave propagates in the form of mode. A phase velocity is important to analyze propagation mode characteristics in the

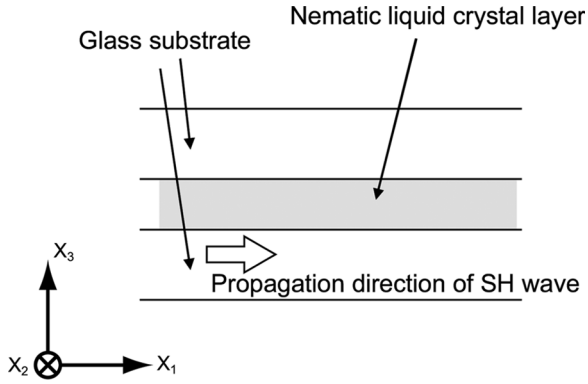

FIGURE 1 Coordinate system of trilayer structure having liquid crystal layer for numerical analysis.

trilayer structure. Because the phase velocity of the SH wave is influenced by the viscosity of the liquid crystal on the glass plate.

The phase velocity is determined by developing Farnell's and Campbell and Jones' methods [11–13] under a consideration of the viscosity dependence. The equations for an elastic wave propagation are represented in the following form:

$$c_{ijkl}\frac{\partial^2 U_k}{\partial X_i \partial X_l} = \rho\frac{\partial^2 U_j}{\partial t^2} \qquad (j = 1,\ 2,\ 3) \tag{1}$$

where U, c_{ijkl} and ρ are a mechanical displacement, an elastic tensor and a mass density, respectively. In this calculation, the elastic constant c_{44} and the mass density ρ_{g} of the glass substrate are $2.64 \times 10^{10}\,\mathrm{N/m^2}$ and $2760\,\mathrm{kg/m^3}$, respectively. The mass density ρ_{LC} and the thickness of the nematic liquid crystal are $1000\,\mathrm{kg/m^3}$ and $32\,\mu\mathrm{m}$. General solution for U in Eq. (1) is written as follows:

$$U_j = \sum_{m=1}^{6} Z_m C_j^{(m)} \exp\left\{i\left(k_{X1}X_1 + k_{X3}^{(m)}X_3 - \omega t\right)\right\} \tag{2}$$

where k_{x1} and k_{x3} are wave numbers for each directions. The coefficients Z_{m} are determined from boundary conditions. The boundary conditions at the liquid-crystal/solid interface are continuances of the mechanical displacement and the stress, while the air/solid boundary condition is that the stress at interface is zero. Based on the boundary conditions, we could obtain the phase velocity from Eqs. (1) and (2).

Figure 2 shows the calculated velocity dispersion curves of the lowest four modes of the SH wave propagating in the trilayer structure without the liquid crystal as a function of the frequency. The propagation of the SH wave is allowed at certain frequencies, because the SH wave forms propagation modes by multiple reflection in the glass substrate. The 0th mode exists over the entire frequency range, while the higher modes appear critically at the respective cut-off frequency and converge on the 0th mode velocity with increasing frequency.

Figure 3 shows the numerical analysis result of the phase velocity change of the SH wave propagating to the trilayer structure as a function of viscosity. In this calculation, we used the 1st mode SH wave with the frequency of 9.18 MHz, which was denoted as the filled circle shown in Figure 2. The results confirmed that the phase velocity slightly increased with increasing the viscosity. Since the liquid crystal viscosity changes with the molecular direction, the fluctuation of the viscosity can be measured from the measurement of the phase velocity change of the SH wave propagating into the liquid crystal cell.

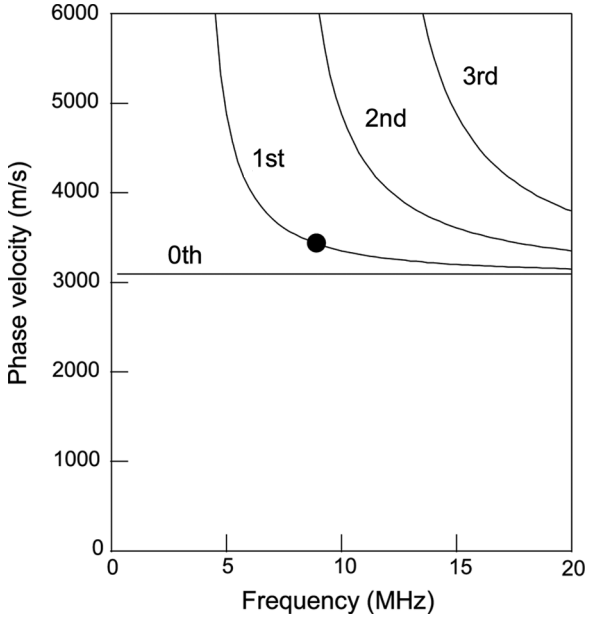

FIGURE 2 Calculated velocity dispersion curves of lowest four modes of SH wave in the liquid crystal cell as function of frequency.

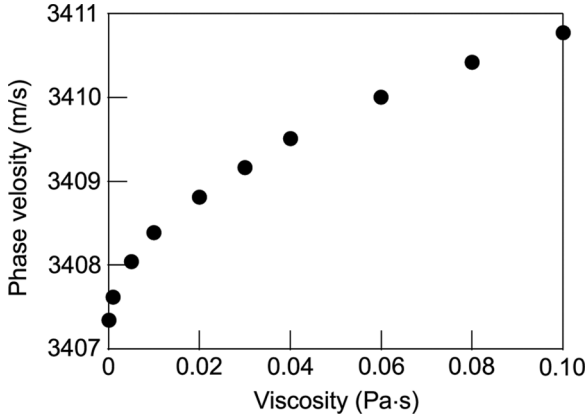

FIGURE 3 Viscosity dependence of phase velocity of the 1st mode SH wave with the frequency of 9.18 MHz.

EXPERIMENTAL SETUP

Figure 4 shows an experimental setup used in this study. Two interdigital transducers (IDTs) with an interdigital periodicity of 400 μm, on two 1-mm-thick piezoelectric ceramic plates (TDK, 101A) with their poling axis in the horizontal direction, were cemented at both ends on the upper surface of a 400-μm-thick glass plate (Corning, 7059). One IDT, which was connected to the first channel of a function generator (Sony Tektronix, AFG320), was used for excitation of the SH wave. The other IDT connected to a RF lock-in amplifier (Stanford Research Systems, SR844) was for receiving. A liquid crystal layer, located on the center region of the acoustic delay line, was sandwiched by two glass plates coated with indium-tin oxide whose surfaces were coated with polyimide (JSR, AL1254) and were rubbed in the direction parallel to the propagation direction of the SH wave for unidirectional alignment of the liquid crystal molecule. The thickness of the liquid crystal layer was 32 μm, which was adjusted using polyethylene-terephthalate films. The liquid crystal material used in this study was 4-cyano-4′ -pentylbiphenyl (5CB). In the above construction, a rectangular voltage with a frequency of 2 kHz using the second channel of the function generator and a power amplifier (NF, 4010) was applied to the liquid crystal layer between two glass plates. The acoustic phase of the SH wave propagating in the cell structure was measured as a function of applied voltage to the liquid crystal layer by using the RF lock-in amplifier. A digital storage oscilloscope (Sony Tektronix, TDS5052) was connected to the

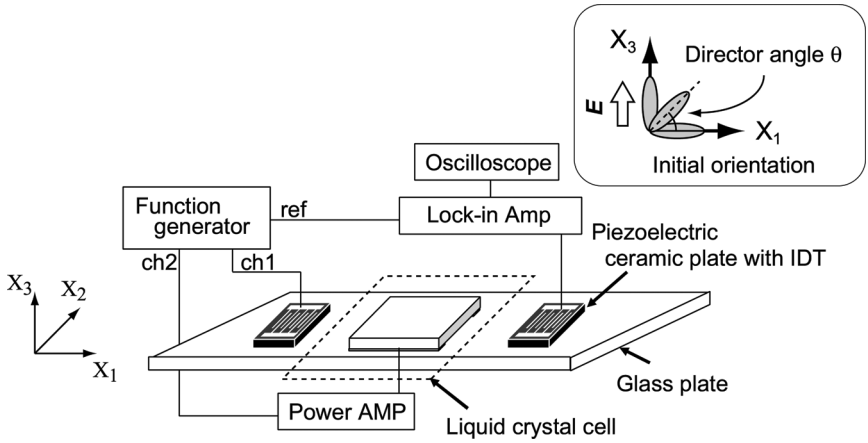

FIGURE 4 Schematic construction of SH wave device and experimental setup.

RF lock-in amplifier for measuring the dynamic response of the phase change.

We also measured the optical response of the molecules reorientation with the applied voltage in order to compare with the phase results. The SH wave device was set in crossed polarizers to measure the transmission characteristics of light. A He-Ne laser was used for a light source and the laser beam was irradiated from the top surface of the liquid crystal sell. The transmitted light was detected by a photodetector.

RESULTS AND DISCUSSION

Figure 5 shows the measured frequency dependences of the insertion loss of the SH wave device with the nematic liquid crystal. Several peaks are observed in the profiles. As already mentioned, the explanation is that the propagations of the SH wave are allowed in certain propagation mode frequencies. These peaks show the mode frequencies with a wavelength of 400 μm. In this study, we used the frequency of 9.18 MHz which corresponds to the highest peak in the insertion loss profile.

Figure 6 shows the measured applied electric field dependence of the acoustic phase change of the SH wave. The acoustic phase change increased with increasing the applied electric field. This result confirmed that the liquid crystal viscosity changed with the applied

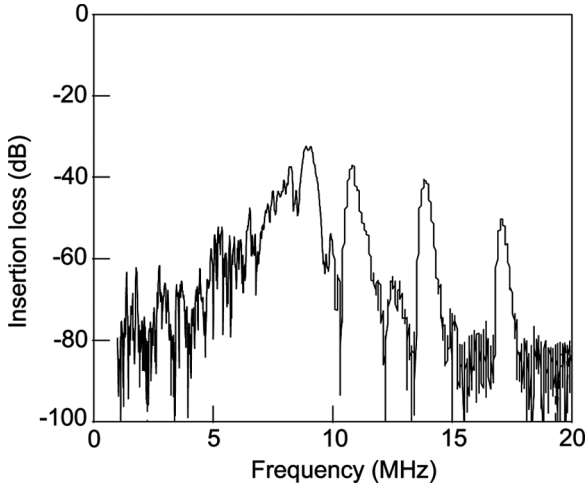

FIGURE 5 Measured frequency dependences of insertion loss of the SH wave device with liquid crystal.

electric field, because the acoustic phase depended on the phase velocity of SH wave related to the viscosity.

Here, we consider the director angle dependence of the nematic liquid crystal viscosity. The viscosity is related to the Leslie

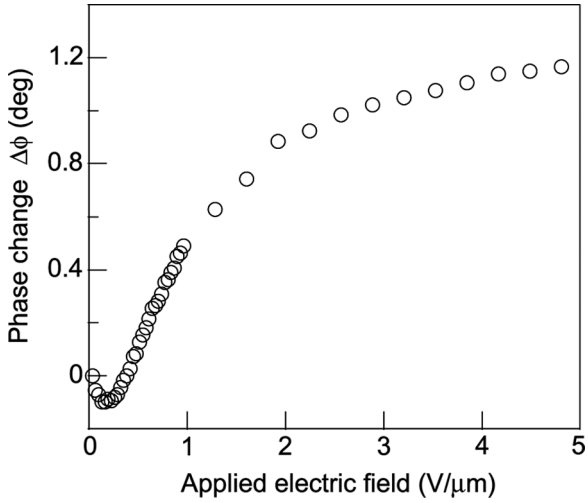

FIGURE 6 Measured applied electric field dependence of acoustic phase change of SH wave propagation in the liquid crystal cell.

coefficients by the following equations:

$$2\nu_1 = \alpha_1 + \alpha_4 + \alpha_5 + \alpha_6 \tag{3}$$

$$2\nu_2 = \alpha_4 \tag{4}$$

$$2\nu_3 = \alpha_4 + \alpha_5 - \alpha_2 \frac{\gamma_2}{\gamma_1} \tag{5}$$

$$\gamma_1 = \alpha_3 - \alpha_2 \tag{6}$$

$$\gamma_2 = \alpha_3 + \alpha_2 \tag{7}$$

In this study, 5CB is used as the nematic liquid crystal. Table 1 shows the Leslie viscosity coefficients of 5CB [14]. The effective viscosity η_e, by which the propagation of the SH wave with the vibration direction along the X_2 axis is affected, is given by

$$\eta_e = \nu_2 \cos^2\theta + \nu_3 \sin^2\theta, \tag{8}$$

where the director angle θ is the angle from the X_1 axis in the $X_1 - X_3$ plane, as shown in Figure 4. The director angle θ dependence of the liquid crystal viscosity expressed by Eq. (8) is shown in Figure 7. It should be pointed out from this figure that the liquid crystal viscosity depends on the director angle θ and monotonously decreases with increasing θ. The explanation is that the contact area between the liquid crystal molecules and the glass plate becomes small with increasing the director angle θ. That is, the decrement of the contact area results in the decrement of viscosity as a friction. Using the director angle dependence of the viscosity, we can explain the acoustic phase change. In Figure 6, the decrement of viscosity with the applied electric field produces the acoustic phase advance, because the viscous resistance for SH wave propagation also decrease.

TABLE 1 Leslie Coefficients of 5CB

Viscosity coefficient (27°C)	(Pa·s)
α_1	− 0.011
α_2	− 0.07
α_3	− 0.0038
α_4	0.071
α_5	0.052
α_6	− 0.028

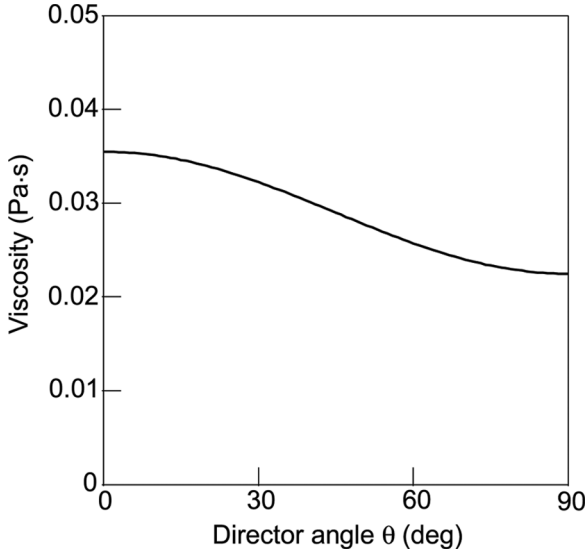

FIGURE 7 Director angle dependence of nematic liquid crystal viscosity.

On the other hand, we can also explain the acoustic phase change from viewpoint of phase velocity change. Figure 8 shows the schematic illustration of the 1st mode SH wave propagations in the glass substrate with different phase velocities. The 1st mode SH wave propagates to the glass substrate. In this figure, the phase velocity v_1 is faster than v_2. In other word, the glass plate propagating SH wave with v_1 is attached the higher viscous liquid. The relation between the viscosity and the phase velocity is also confirmed from Figure 3. This figure also shows that the acoustic phase with v_2 at detecting point advances than that with v_1. Therefore, the phase advance is also understood from the change of the phase velocity linked with viscosity. From these results, we confirmed that the measured acoustic phases accord with the change of viscosity which is based on the molecular reorientation with the applied electric field.

Figure 9 shows the dynamic response of the acoustic phase of SH wave with the application and removal electric field of $3.5\,\mathrm{V}/\mu\mathrm{m}$ to the liquid crystal layer. The rise and decay response waveforms are shown in Figures 9(a) and 9(b), respectively. The phase advance and delay were observed with the application and removal voltage. It should be noted that the decay response is very fast in spite of using nematic liquid crystal of 32-μm thickness. In general, a relaxation of a nematic liquid crystal needs the order of several tens milliseconds

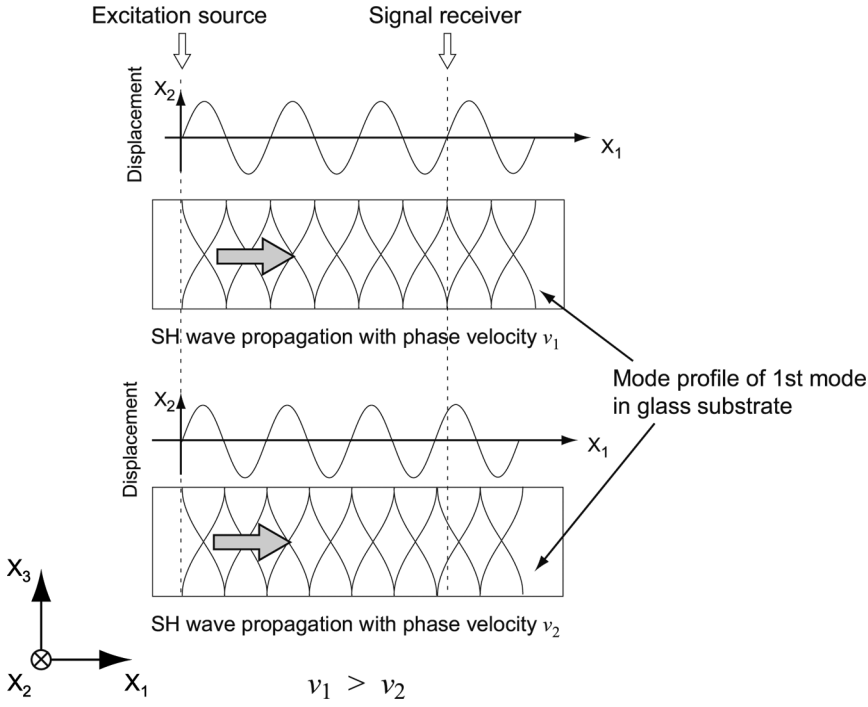

FIGURE 8 Schematic illustration of the 1st mode SH wave propagations in the glass substrate with different phase velocities.

or the order of several hundreds milliseconds. In this case, however, the decay time shows several milliseconds.

For more detail investigation, we also measured the molecular reorientation by conventional optical method. Figure 10 shows the

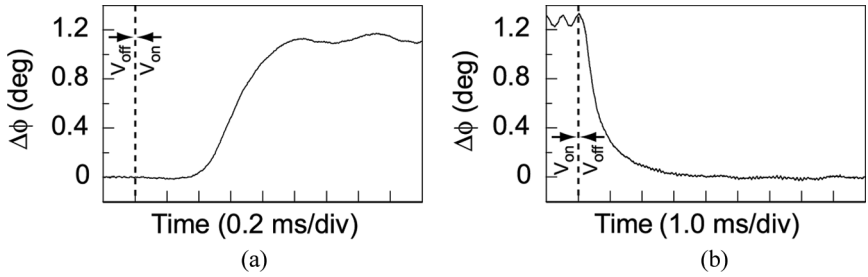

FIGURE 9 Waveforms of phase change in the application (a) and removal (b) applied electric field of 3.5 V/μm to the liquid crystal cell.

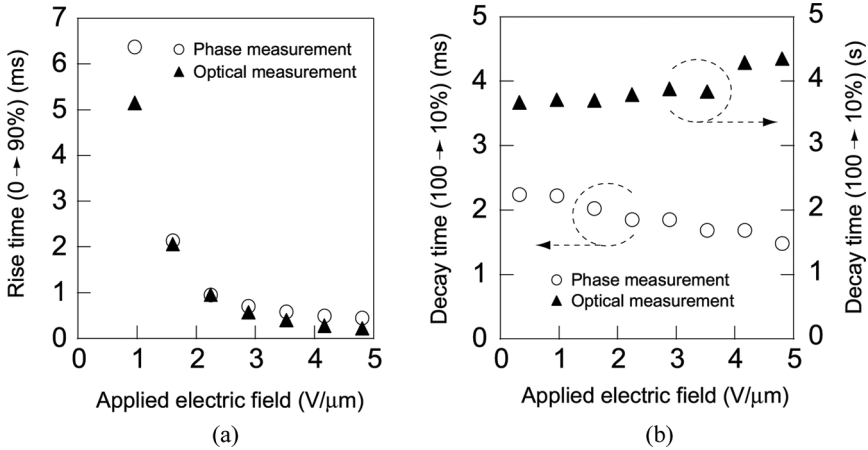

FIGURE 10 Applied electric field dependences of rise time (a) and decay time (b) of phase and optical measurements.

response times of the molecular reorientations in the phase and optical measurements. In this figure, the response times in optical method also show to compare with those of phase measurement. The response time is defined as the time required for the change from 0% to 90% of the total change, while the decay time is defined as that from 100% to 10%. The rise times in both measurements decreased with increasing the applied electric field and both rise times show almost same values. On the other hand, the decay times in both measurements are independent of the electric field. The decay time in the phase measurement, which is around 1.5–2.5 ms, is less than 10^{-3} of that in the optical measurement, which is around 3–4 s. These are explained as follows. It is obvious from our previous work that the displacement of the SH wave exists not in the entire region of the liquid crystal layer but in the region very near the interface between the liquid crystal layer and the glass substrate [3,4]. In other words, the measured phase using the SH wave is influenced by the viscosity in the vicinity of the interface. However, the He-Ne laser beam measured the entire region of the liquid crystal layer. Since the molecular reorientation starts from the interface when the applied electric field is removed, the decay time in the phase measurement is much less than that in the transmitted light intensity measurement. In contrast, the rise time in both methods showed same times, because the liquid crystal molecules reorient from entire region by applying the electric field. This reason is that the origin of the reorientation is dielectric torque

which works to all of the molecules at the same time in the cell. From these results, we could explain the difference of response time between the phase and the optical measurements.

CONCLUSION

The viscosity dependence of the phase velocity in the trilayer structure having liquid crystal cell was evaluated from the numerical analysis of the SH wave propagation to show relation between the viscosity and the phase velocity. The acoustic phase was measured by using SH wave propagating in the liquid crystal cell structure. The acoustic phase advanced with increasing the applied electric field to the liquid crystal layer. This result corresponded with the viscosity change based on molecular reorientation of the liquid crystal. The dynamic response of acoustic phase change and transmitted light intensity were also measured. The decay time in the acoustic phase measurement was much less than that in the optical method, because the SH wave was only affected by the viscosity in the vicinity of the interface.

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