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Laser-induced surface displacement detection instrument with Doppler shift composed of optical fiber

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Abstract: This article proposes a laser-induced surface displacement detection instrument for measuring the viscosity of liquid. The features of this instrument can obtain the absolute value of time-resolved surface displacement with an adjusted-free and non-calibration. The constitution method of our proposed apparatus and its trial prototype are shown, and experimental results are demonstrated. Finally, our proposed scheme that estimates liquid viscosity is described briefly.

Key words: viscosity measurement, Doppler shift, laser pickup, laser diode, spherical lensed fiber

Introduction

Recently, several laser-applied techniques have been proposed for measuring liquid viscosity [1],[2]. These techniques include non-contact with samples and micro-liter sample volume, both of which provide significant advantages in terms of actual applications. But the advanced skill is required for their operation since the measurement apparatus is complicated. To overcome this problem, we address a new laser-induced surface displacement detection instrument that is composed of an adjusted-free, optical fiber system. Our proposed technique analyzes the time-resolved frequency of the Doppler shift by elastic waves in liquid induced by periodical expansion.

Expansion can be generated by the following phenomenon. Light incident into liquid increases its momentum, which is caused by the difference in the refractive index at the boundary between air and liquid, and gives the surface an upward force as a reaction when a laser beam is not absorbed practically in a liquid, i.e., because a laser beam is rarely converted to a thermal state [2]. This phenomenon is called a laser pickup. First, we describe the constitution method of our proposed apparatus and its trial prototype and then demonstrate experimental results. Finally, we briefly describe our proposed scheme that estimates liquid viscosity.

Measurement system

Figure 1 illustrates the sensing head. The incident laser beam is focused on the boundary surface between the air and the liquid by a spherical lensed fiber (SLF), which returns part of the beam reflected with the surface to the fiber. The distance between the air and the liquid is changed transitionally when the surface is lifted due to above phenomenon. Consequently, the reflected beam, whose frequency is shifted due to the Doppler effects, is returned to the fiber.

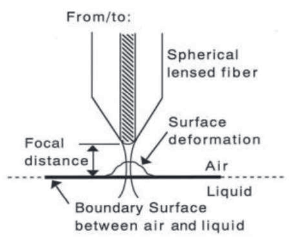

Fig. 1. Schematic of sensing head.

Figure 2 shows a block diagram of our proposed system. We used a laser diode module with a 1.47-μm wavelength and 120-mW fiber output power as the light source of the pumping beam. A 1.55-μm, DFB laser diode module was used as the probe beam. We chose a wavelength for two beams because these modules and their peripheral parts are commercially available for optical communication systems. The probe beam is CW and is branched to two routes by a fiber

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coupler (FC). The side beam is a reference beam that is fed to an acoustic optical modulator (AOM) to generate a frequency shift of 80 MHz for optical heterodyne detection. The other side beam is fed to a wavelength-division multiplexing (WDM) FC that functions as a dichroic mirror and is unified with a pumping beam. The two unified beams are fed to a sensor head through a circulator, and the probe beam is mixed with the frequency-shifted reference beam for heterodyne detection after the reflected (residual) pumping beam is eliminated with an interference filter. Consequently, we believe that the frequency transition due to the Doppler effect, which is associated with a velocity transition of the surface deformation, can be time-resolved measured by a modulation domain analyser.

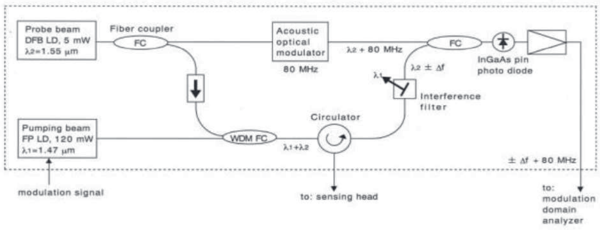

Fig. 2. Block diagram of our proposed measurement system.

Experimental results

Figure 3 shows the relationship between the elapsed time and the surface displacement value for the laser pickup which uses ethanol as a sample liquid. The circles and triangles correspond to the displacement values for lifting the surface by starting the pumping and recovering with a pumping cut-off. The displacement gradually increases (decreases) as time passes and eventually becomes saturated.

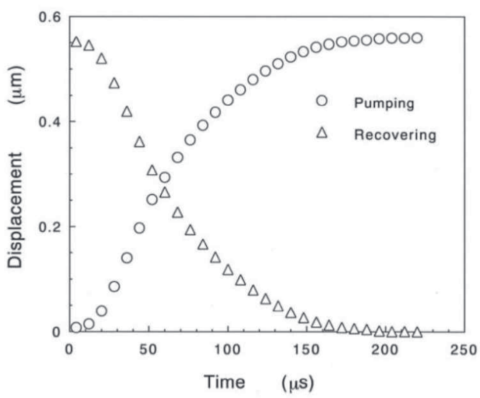

Fig. 3. Relationship between elapsed time and surface displacement value.

Discussions

Dotted lines drawn in Fig. 4 intend a curve fit of exponential decay concerning plots corresponding to Fig. 3 in case of a recovering of surface displacement. As can be seen in this figure, it was confirmed that the displacement with a sample of distilled water is closely match with an exponential curve. This is because the effect of thermal diffusion is dominant compared with that of laser pickup. On the other hand, the displacement with a sample of ethanol is designated a combination of several exponential curves. Incidentally, it is recognized that it is useful for applying an error function in this case, as defined relatively by [2]:

$$S_{(t)} = 1 - 2\Gamma t exp(\Gamma t)^2 erfc(\Gamma t) \quad (1)$$

where t, S and Γ is time, displacement and relaxation constant, respectively. Furthermore, Γ is associated with a viscosity and surface tension of liquid.

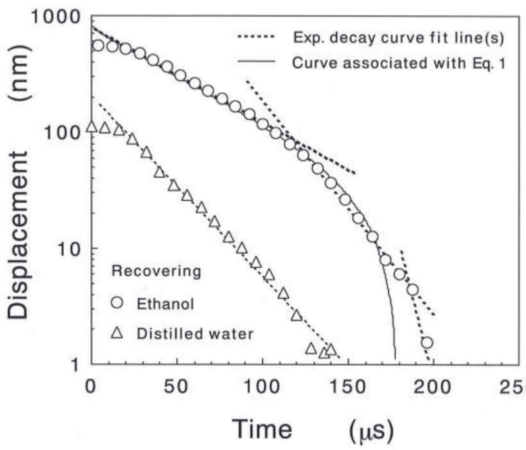

Fig. 4. Logarithmic scale of Fig. 3 for fitting formula curve.

The solid curve drawn in Fig. 4 intends a curve fit with Eq. 1. It seems to almost match with Eq. 1 when Γ was approximately 0.010 (1/μs). In conclusion, as the first step, we are now applying two combinations of three-element Maxwell model for a static viscous-elasticity system using experimental values to estimate viscosity.

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