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Optical tomographic imaging of picosecond pulses with 200 nm spatial resolution

ピコ秒超音波パルス伝播の 200 nm 空間分解能での光トモグラフィイメージング

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1. Introduction

Imaging of ultrasonic wave propagation in the interior of materials is useful for probing structures therein. In general, photoelastic methods for solid materials and Schlieren methods for liquid and gas materials can be used for ultrasonic field imaging. These methods are often combined with stroboscopic methods or high-speed video camera detection to make a time-resolved movie. But GHz ultrasonic frequencies, corresponding to submicron-wavelength ultrasonic waves, cannot be investigated with these types of detection.

Picosecond laser ultrasonics, which makes use of ultrasonic waves in the frequency range 10-1000 GHz, provides new opportunities to investigate internal structures or physical properties of thin films or micro-/nano- materials[1]. In the conventional setup, ultrashort pump light pulses generate longitudinal ultrasonic ultrasonic pulses in thin metalic films, and delayed probe light pulses detect ultrasonic pulses which are reflected at some internal inhomogeneity and return to the surface. However, until recently, no existing experimental method could image picosecond ultrasonic pulses continuously during internal propagation. To understand their propagation, computer simulations are normally used.

We have developed an optical imaging technique that allows picosecond ultrasonic pulse shapes to be measured during propation in a homogenous and isotropic transparent medium by means of the photoelastic effect, using different probe angles of incidence[2]. Here we have extended this techinique to the use of a shorter optical wavelength 415 nm for the probe beam and improved the measurement system based on automated angle scanning, allowing a ~200 nm resolution of the ultrasonic pulse shape in a glass medium.

2. Principle of imaging method

This method is based on Brillouin scattering of light by ultrasonic waves. When monochromatic light is reflected from an ultrasonic pulse, the amplitude of the reflected light is proportional to the amplitude of the ultrasonic wave component at the particular ultrasonic wavelength, corresponding to the Bragg scattering condition $\Lambda = \lambda/(2n\cos\theta)$, where Λ is wavelength of the ultrasonic wave, λ is the wavelength of the probe light, θ is the probe light incident angle, and n is the refractive index. The reflected probe light from an ultrasonic pulse interferes with the reflected light from an interface in the sample. This interfered light includes information on the amplitude and phase of the ultrasonic wave with the wavelength matched to the incident angle. We measure the optical reflectivity changes at different incident angles and then reconstruct the ultrasonic pulse shapes by use of an inverse method known as singular value decomposition. By repeating the inversion process for a sequence of delay times between the pump and probe pluses, a strain propagation movie can be built up.

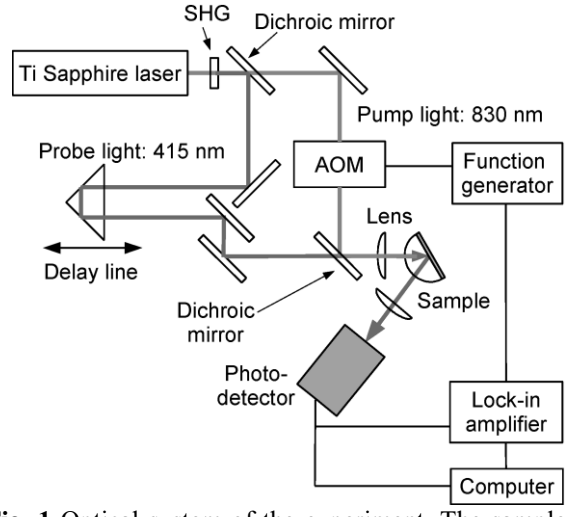

Fig. 1 Optical system of the experiment. The sample is an Al-coated BK7 glass hemisphere. The sample and photodetector are set on θ-2θ rotation stages. SHG: second harmonic generation crystal, AOM: acousto-optical modulator.

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3. Experiment setup and sample

We use a hemispherical sample of BK7 glass (n=1.517) of radius 5 mm coated with an Al film of thickness 400 nm on the flat surface. This shape is chosen to avoid refraction of the probe beam. Picosecond ultrasonic pulses are generated at the Al-glass interface.

Figure 1 shows the experimental setup. We use a mode-locked Ti-Sapphire laser of central wavelength 830 nm, pulse duration ~200 fs, and repetition rate 80 MHz. The laser pulses are divided into pump pulses (of wavelength 830 nm) and probe pulses (415 nm, frequency doubled). The pump light is chopped by an acousto-optic modulator, and the probe light passes through an optical delay line. The two beams are focused on the Al-glass interface. The intensity of the probe light reflected from the sample is detected with a photodetector and amplified with a lock-in amplifier. The sample and the detector are set on θ-2θ automatic rotation stages.

4. Results and discussion

Figure 2 shows relative reflectivity changes as a function of angle (10-80°) and pump-probe delay time (−60-520 ps). The time step is 0.2° and the time step is 20 ps. This measurement took about 12 hours. The reflectivity is normalized by cosθ to compensate for the change in the elliptical pump light spot area with angle.

The reconstructed strain in shown in **Fig. 3**. The strain clearly propagates in the depth direction in the sample. The diagonal straight line from the bottom left to the top right in the image is a result of the ultrasonic pulse generated at 0 ps at the 0-nm position and propagating at constant velocity. The longitudinal sound velocity of BK7 glass, 5900 m/s, can be derived from the gradient of this line. The parallel straight line starting at 230 ps corresponds to the second pulse reflected from the Al film surface. The vertical stripe pattern in the image is thought to be an artifact in the measurement. This artifact can be partly decreased by some data processing (not shown here).

5. Conclusion

We have developed an automatic measurement system for imaging GHz-frequency longitudinal ultrasonic pulse propagation. This technique is restricted to one-dimensional probing in homogeneous, isotropic and transparent solids, and demonstrated only in a hemispherical sample at present. But in future the technique might be extended to three-dimensional GHz ultrasonic wave imaging in plate-shaped samples by combination with probe-beam two-dimensional lateral scanning.

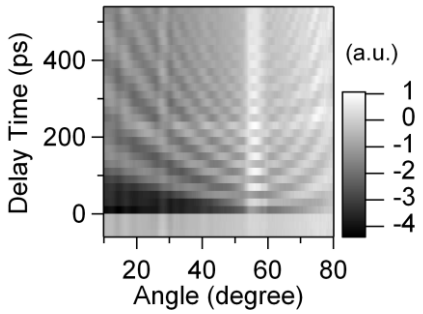

Fig. 2 Measured relative reflectivity changes $\delta R/(R\cos\theta)$ vs. delay time t and probe light angle θ. The probe angle step is 0.2° and the delay time step is 20 ps.

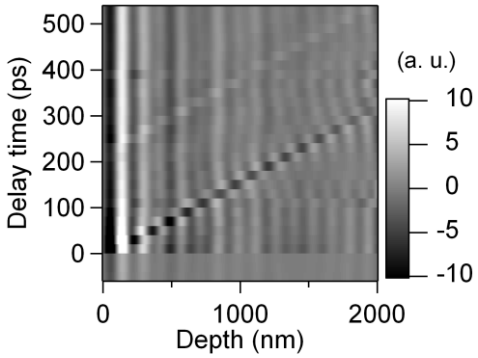

Fig. 3 Reconstructed strain image as a function of depth and time.

References

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