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Detection of GHz shear acoustic waves in picosecond laser ultrasonics assisted by two-dimensional metallic diffraction gratings

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1. Introduction

When an opaque medium is irradiated with laser light pulses with picosecond temporal widths, acoustic pulses with similar temporal widths are excited therein. The propagating acoustic pulses can be detected using delayed ultrashort light pulses. The light pulses that excite and detect these acoustic waves are called pump and probe light, respectively. By such measurements, physical properties and structure of the medium can be obtained nondestructively without any contact to the medium. This technique is called picosecond laser ultrasonics[1]. When an opaque thin film is formed on a transparent medium, acoustic waves excited by the pump light pulses in the opaque medium propagate to the transparent medium. These acoustic waves scatter the probe light with a frequency shift. The interference between this scattered light and the probe light reflected from the sample surface causes an oscillation in the intensity of the reflected light[1]. This phenomenon is called Brillouin oscillation, and this frequency is hereinafter referred to as the Brillouin frequency.

When picosecond laser ultrasonics is performed on a sample with an opaque isotropic thin film, shear acoustic waves cannot be excited due to the symmetry of the sample. However, shear acoustic waves can be excited in a specific direction by irradiating light pulses to a sample with metallic diffraction gratings on the sample surface [2,3]. To detect these shear acoustic waves, the probe light must be incident obliquely to the sample [2]. Moreover, the condition for the shear wave detection also requires the incident probe light and the reflected or diffracted light must not take the same optical path, resulting in a somewhat complicated optical setup[2]. In contrast, this study demonstrates that shear acoustic waves can be detected with a simpler optical configuration by using two-dimensional metallic diffraction gratings. We also clarify the conditions for the shear acoustic wave detection and the polarization of the probe light.

2. Experiment

The sample is a two-dimensional square lattice of aluminum dots with a period of 380 nm formed on a fused silica substrate of 1mm thickness by the electron beam lithography. Each aluminum dot is a 200 nm square with 50 nm thickness. Measurement is done with a standard picosecond laser ultrasonics setup. A mode-locked Ti-sapphire laser is used as the light source, with 830 nm central wavelength light pulses for the pump and 415 nm central wavelength second harmonic light pulses for the probe. The pump and probe lights are incident to the sample from the side on which the diffraction gratings are formed. The transient reflectivity change of the probe light is recorded as the function of the delay time between the pump and probe light pulse arrival to the sample.

The sample is placed on a stage that rotates about two axes so that the probe light can be incident at arbitrary angle. To clarify the sample position, the laboratory coordinate is defined as XYZ and the sample coordinate as xyz. The Y-axis is taken along the vertical direction of the laboratory, the Z-axis along the propagation direction of the incident probe light (propagating horizontally in the lab), and the X-axis perpendicular to them. The z-axis is taken to be perpendicular to the sample surface and heading towards the sample depth direction. The x- and y-axes are taken to be parallel to the fundamental translation vector of the two-dimensional metallic diffraction gratings. At first, the sample is placed so that XYZ and xyz coordinate systems are coincident. The sample is then rotated by an angle α with respect to the y-axis. The sample is then rotated by an angle β with respect to the x-axis. By this definition, $(\alpha,\beta)=(0°,0°)$ represents the normal incidence of the light to the sample surface.

When the probe light of a wave vector $\left(k_x,k_y,\sqrt{k^2-k_x^2-k_y^2}\right)$ in the sample coordinate is incident on the gratings of period p, the diffraction by the gratings may alter the x and y components of the wave vector by $m_i q\,(i=x \text{ or } y, q=2\pi/p)$ where the integer m_i is the diffraction order. For the two-dimensional metallic diffraction gratings with a period of 380 nm, the diffracted light with diffraction order $\left(m_x,m_y\right)=(-1,-1)$ returns through the optical path anti-parallel to the incident light when $(\alpha,\beta)=(32°,-40°)$.

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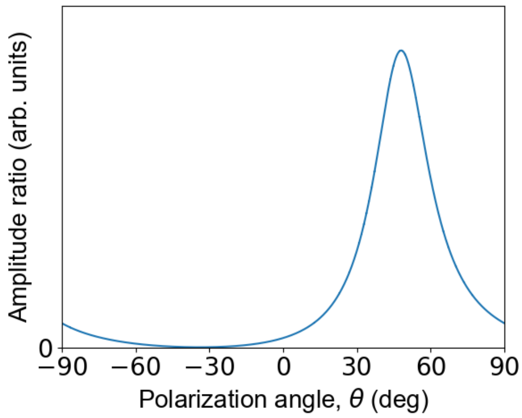

Fig. 1 Ratio of Electric field intensity of probe light scattered by the shear and longitudinal acoustic waves (at 24.7 GHz and 39.2 GHz, See Fig. 2) versus the rotation angle θ of the polarization plane of the incident probe light (see the main text for the full definition)

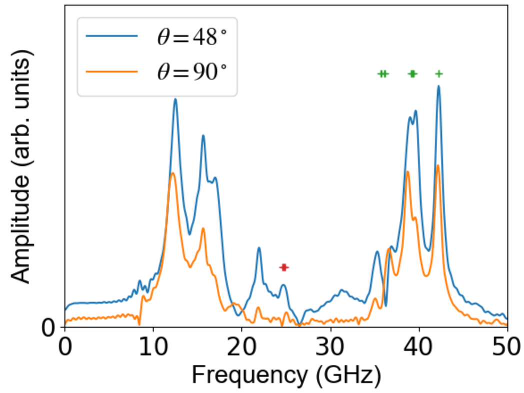

Fig. 2 Norm of Fourier amplitude of the transient reflectivity changes. The spectrum for $\theta = 90°$ is magnified by 4. The + symbols in green and red colors indicate the calculated Brillouin frequencies for the longitudinal and shear acoustic waves, respectively.

The direction of polarization of the probe light is important in the detection of shear acoustic waves [2, 3]. The angle θ is defined as the angle of rotation of the polarization plane of the incident probe light from the X-axis in the counterclockwise direction with respect to the Z-axis. Thus the normalized polarization vector in the XYZ coordinate is given as $(\cos\theta, \sin\theta, 0)$. Figure 1 shows the ratio of the electric field amplitude of the light scattered by the shear and longitudinal acoustic waves, which change the diffraction order of the probe light from $(-1, 0)$ to $(0, 0)$ or from $(0, 0)$ to $(-1, 0)$, versus the angle θ. It is calculated for the electric field radiated from the dipole moment induced by the photoelastic effect at $(\alpha, \beta) = (32°, -40°)$. The photoelastic tensor components for fused silica used in the calculation are $P_{11} = 0.121$, $P_{12} = 0.270$, $P_{44} = -0.075$ [4]. The shear acoustic waves would be strongly detected when the polarization direction is $\theta = 48°$ and not detected when it is $\theta = -33°$ as shown in Fig. 1.

3. Result

The measurement is done at $(\alpha, \beta) = (32°, -40°)$. Since the intensity of the reflected light is not strong enough when the polarization direction is $\theta = -33°$, we use the data taken at $\theta = 48°$ and 90° below.

Figure 2 shows the Fourier spectra of the obtained transient reflectivity change. The theoretical value of the Brillouin frequency can be obtained by considering the conservation of momentum before and after the probe light is scattered by the acoustic waves. The sound velocity and the refractive index used in the calculation are the same as those in Ref. 2. The obtained Brillouin frequencies are plotted in Fig. 2 with + symbols.

The peak around 25 GHz is detected when the polarization direction is $\theta = 48°$, but not when $\theta = 90°$. This is consistent with the simulation result shown in Fig. 1. In addition, the theoretical value of Brillouin frequency of the shear acoustic wave agrees well with the observed peak position around 25 GHz. These facts suggest that the observed peak is due to the shear acoustic waves.

There are several peaks that do not correspond to the theoretical values of the Brillouin frequency in Fig. 2. The origin of these peaks has not been clarified yet.

In conclusion, GHz acoustic waves propagating in a fused silica substrate have been studied by picosecond laser ultrasonics using two-dimensional metallic diffraction gratings. The importance of the polarization direction in the detection of shear acoustic waves has been demonstrated.

References

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