2P2-13

Depth-mapping of refractive index and sound velocity in transparent samples by time-domain Brillouin Scattering

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1. Introduction

Time-domain Brillouin scattering is an all-optical experimental technique that makes use of laser picosecond ultrasonics to investigate transparent materials.[1)] The time-resolved optical reflectance exhibits GHz oscillations resulting from the interference between probe light pulses reflected from the sample interfaces and those scattered from nano-acoustic pulses, as illustrated in **Fig. 1(a)**. These oscillations, known as Brillouin oscillations, occur at the frequency

$$f_B = 2v\sqrt{n^2 - \sin^2\theta_0}/\lambda, \qquad (1)$$

where v is the longitudinal sound velocity, n is the refractive index, θ_0 is the incident angle of the probe light in air, and λ is the probe-light wavelength in air. When the refractive index of the sample is spatially uniform and known, analysing the oscillations using Short-Time Fourier Transforms (STFT) enables the acquisition of depth profiles of v. However, when the refractive index varies with depth, multiple incidence angles of the probe beam are required, thereby complicating the measurement system.[2)]

In this study, we propose a straightforward method to obtain quantitative 3-dimensional (3D) images of v and n by varying the incident angle of the probe light.[3)] By scanning the incidence position of a narrow probe beam on a high numerical aperture (NA) objective lens, Brillouin oscillations can be measured from different oblique incidence angles θ_0.

2. Experiment and results

When the collimated narrow beam propagates parallel to the center axis of the microscope objective, but with an off-axis displacement x and y, the incident angle on the sample is

$$\theta_0 = \tan^{-1}\left(\sqrt{x^2 + y^2}/F\right), \qquad (2)$$

where F is the focal length, as illustrated in **Fig. 1(b)**.

In order to validate the effectiveness of this technique, we select a water-immersion microscope objective (NA=1.0, *F*=3.0 mm, working distance 2

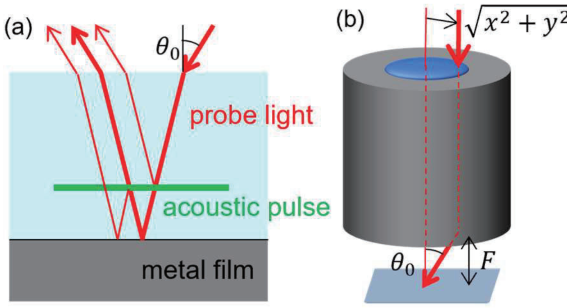

Fig. 1 (a) Schematic showing the interference of probe light components to produce Brillouin oscillations. (b) Schematic showing the relation between the incidence off-axis displacement x and y and the output angle θ_0 of a narrow beam entering a microscope objective with focal length F.

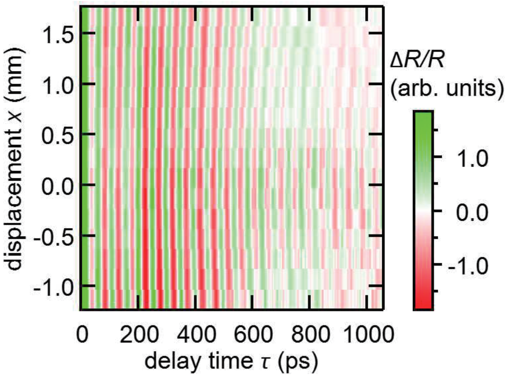

Fig. 2 Probe-beam relative reflectance change as a function of the delay time and the probe beam lateral off-axis displacement on the objective lens.

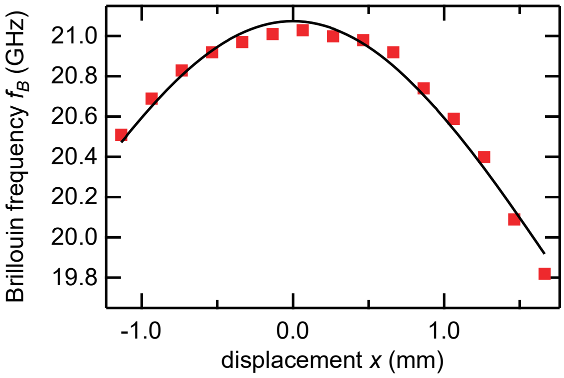

Fig. 3 Frequency of the Brillouin oscillations derived from temporal Fourier transforms of the experimental data (red points) and fitted curve (black solid line).

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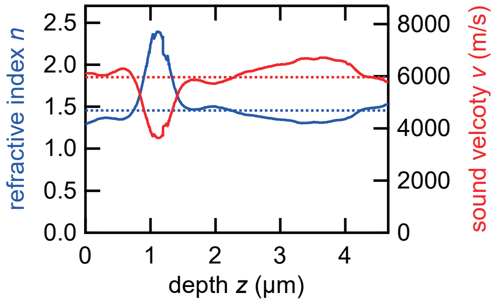

Fig. 4 Derived refractive index (blue solid line) and longitudinal sound velocity (red solid line) in silica sample as a function of depth. The dotted lines represent the expected values.

mm) for focusing and an isotropic fused silica cover glass coated on one side with a titanium film of thickness 640 nm for the sample.

Relative reflectance changes $\Delta R/R$ of the probe light are detected, the results being shown in **Fig. 2**, where Brillouin oscillations at approximately 20 GHz are clearly visible. **Figure 3** shows the frequency of these Brillouin oscillations (red squares) obtained by temporal Fourier transforms over 1000 ps as a function of x. The solid line is obtained by least-squares fitting to the experimental data with Eqs. (1) and (2) using the focal length F and displacement y as variable parameters, and under the assumption that n and v take their literature values n=1.45 and v=5967 m/s. The fitted average values of F=3.05 mm and y= 0.38 mm are of the expected order of magnitude.

By performing STFT on the data for each off-axis displacement x, we obtain f_B for each delay time τ. Through least-squares fitting at each τ and using the fitted values F=3.05 mm and y=0.38 mm from the data of Fig. 3, we calculate the values of v and n. Then τ is converted into depth z by use of the derived value of v, which enables the acquisition of depth profiles as shown in **Fig. 4**. The variations in n and v extracted from our measurements exhibit agreement with the expected values (dotted lines), except for the artifact region around z=1.2 μm, which arises because of the bouncing of acoustic pulses to and fro inside the Ti film.

3. Conclusions

We present a technique in time-domain Brillouin scattering for the depth profiling of both sound velocity and refractive index in a transparent material based on automated optical probe-incidence scanning. This allows incident-angle resolved measurements in a compact system without the need for a cumbersome optical arrangement. This technique is validated with a well-characterized homogeneous glass sample, but it should be applicable to mapping sound velocities, dependent on stiffness, in 3D in a variety of inhomogeneous transparent samples.

A different method in time-domain Brillouin scattering for extracting sound velocity without a knowledge of the refractive index was recently proposed by us,4) which makes use of probe light obliquely incident on a side face—as opposed to the usual top face—of the sample. In the presentation at the symposium, we introduce the comparison of these two methods.

Acknowledgment

This work was supported by the Japan Society for the Promotion of Science KAKENHI Grant Numbers JP25390114, JP16H02123, and JP22K04938.

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