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Imaging flexural waves in microscopic wedges

マイクロ楔形構造における曲げ振動波のイメージング

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1. Introduction

Ultrasonic waves of wedges have spurred a lot of research, such as that concerning ultrasonic transducers, vibration damping, nondestructive testing of blades, moisture detection, black-hole analogies and aquatic propulsion. Various kinds of ultrasonic modes are known to exist in wedges. For example, ultrasonic waves are guided along the thin edge of a wedge, and for perfect wedges with sharp edges such waves are nondispersive. On the other hand, waves launched from inside the wedge towards the thin edge are highly dispersive and show a steadily decreasing sound velocity as they travel. Plane waves launched from inside the wedge parallel to the edge of the wedge are therefore expected to follow curved ray paths. Although laser ultrasonics had been used for the generation and detection of the waves in wedges for years, to our knowledge there has been also no attempt to image them at near-gigahertz frequencies or at micron lateral resolution.

In this paper we use an ultrafast optical technique to excite and to image near-gigahertz flexural ultrasonic waves in gold wedges deposited on thin silicon-nitride slabs [1].

2. Sample and method

A microscopic gold wedge was prepared by a radio-frequency sputtering, making use of a programmable translation stage inside the vacuum chamber. The substrate is a commercial amorphous-SiN slab with a thickness of 100 nm, chosen to be as thin as practicable. The spatial thickness distribution of the gold wedges was mapped by a confocal laser-scanning microscope (**Fig. 1**). Local thickness variations are within 10 µm over imaged region.

The ultrasonic waves is imaged by the use of an optical pump-probe technique combined with a common-path interferometer [2,3]. The pump (frequency-doubled, wavelength 415 nm) and probe (wavelength 830 nm) pulses originate from a mode-locked Ti:Sapphire laser with a 80.4 MHz repetition rate. The pump pulses reshaped by a cylindrical lens and a ×50 microscope objective lens produce a quasi-line source with ~60 um length and ~2 µm width on the sample surface. The line source is perpendicular to the edge of the wedge, and the line center is set at a distance of 45 µm from the edge (Fig. 1(a)). Broadband plane Lamb waves including both quasi-symmetric and quasi-antisymmetric modes with near-GHz frequencies are thermoelastically generated. Out-of plane motion is detected by two probe pulses at an interval of 300 ps at fixed pump-probe delay time. The 2 µm diameter probe spot is scanned over a 120 µm × 160 µm region including the edge of wedge.

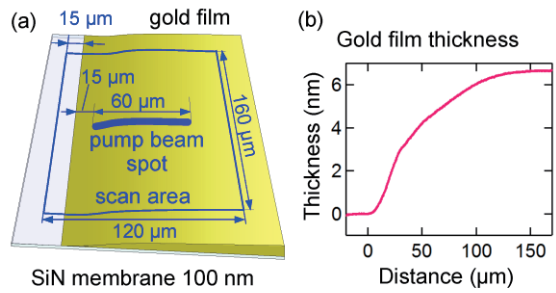

Fig. 1 (a) Schematic of sample structure and imaged region. (b) Thickness of gold film measured by a confocal laser scanning microscope.

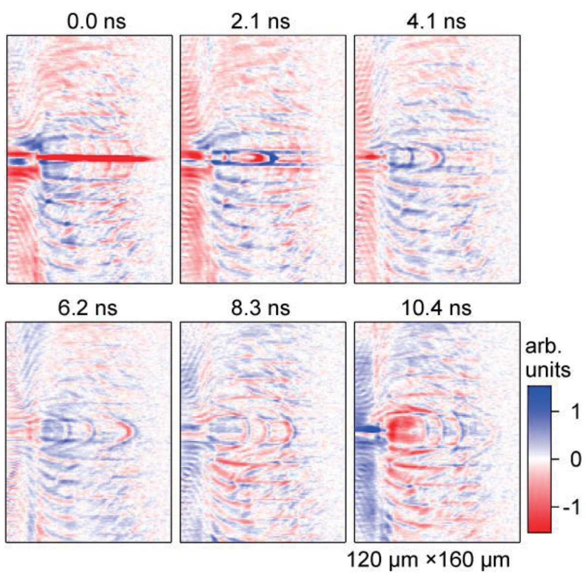

Fig. 2. Time-resolved imaging results the the region shown in Fig. 1(a). The image color represents the out-of-plane surface velocity.

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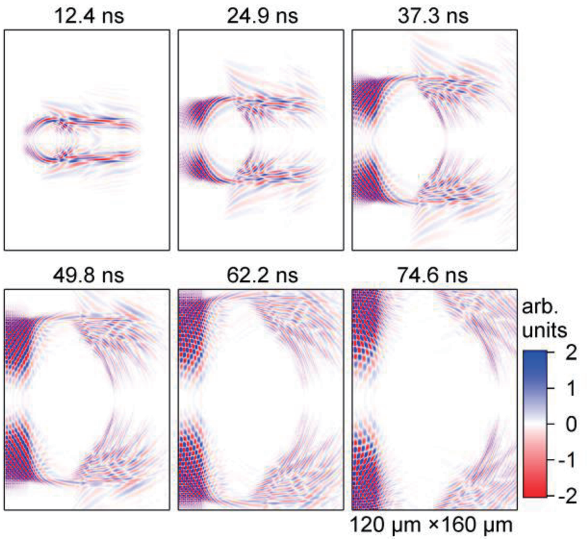

Fig. 3. Time-resolved images corresponding to the simulations. The plotted area is indicated in Fig. 1(a). The image color represents the out-of-plane surface velocity.

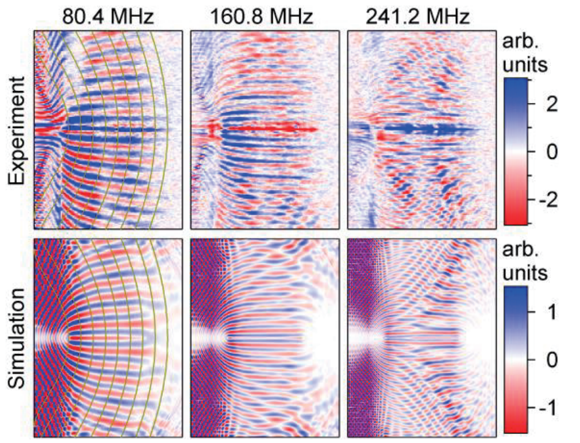

Fig. 4. Constant frequency images corresponding to the simulations. The image color represents the out-of-plane surface velocity. The lines in the 80.4 MHz images are the acoustic ray trajectories obtained from the semi-analytical theory.

3. Results

Fig. 2 shows some representative experimental ultrasonic images, which represent the out-of-plane velocity of the surface at different delay times. These images are made up of a superposition of ripples from ultrasonic waves generated by a pump-pulse train of period 12.4 ns. Ripples propagating up and down on the images from this line source are clearly visible. These waves include both quasi-symmetric and quasi-antisymmetric Lamb-wave modes, and the strongest wave mode is the zeroth-order quasi-antisymmetric mode, i.e., the flexural wave, which is identified by its approximate propagation velocity of ~1200 m/s for our frequency range. As expected, the wave fronts bend toward the edge of the wedge. The gold film area and the SiN area have opposite image contrast. We presume this difference to be caused by multiple optical reflections inside the transparent SiN slab.

Fig. 3 shows ultrasonic images at different times obtained from time-domain finite-element numerical simulation software (PZ-Flex, Weidlinger Associates, Inc.). In contrast to the experimental images which are generated by a pump-pulse train, the simulated images exhibit ripples generated by a single pump pulse. The amplitude of the simulated ripples in the SiN area is bigger than in the gold wedge area because of the smaller thickness and the mass of the former.

To better understand the behavior of the different ultrasonic modes, we calculated temporal Fourier transforms of the set of the experimental and simulated images. **Fig. 4** shows the thus-obtained constant-frequency ultrasonic images. We also semi-analytically calculated ultrasonic ray trajectories, which are plotted on the 80.4 MHz images [1]. These ray trajectories are found to be perpendicular to all wave fronts in both the experimental and simulated images, thus demonstrating the applicability of the ray theory for this frequency.

4. Conclusion

We have imaged propagating near-gigahertz flexural waves in the time-domain in microscopic gold wedges deposited on thin SiN slabs by an ultrafast optical technique. The optical pump pulses are focused to a line source set perpendicular to the edge of the wedge. We observe wave-front bending, especially at low frequencies. This behavior is explained with the help of an analytical model based on the theory of flexural wave propagation in a bi-layer film and on geometrical acoustics, and is reproduced with numerical simulations. This work should stimulate further studies on the propagation of waves in wedges.

References

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