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Investigation of sound pressure waveforms observed using surface plasmon resonance sensors

表面プラズモン共鳴センサを用いて観測した音圧波形の検討

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1. Introduction

Optical devices based on surface plasmon resonance (SPR) have been used in various fields.

In 1967, Teng et al. were the first to optically excite surface plasmons[1]. SPR was used as a gas sensor by Liedberg et al. in 1983[2]. In 1996, Schilling et al. first detected acoustic pulses using SPR[3]. Wang et al. also reported that the SPR sensor could detect ultrasonic waves in the range of 0.68-126 MHz[4]. In 2018, Ichihashi et al. reported that thermoelastic stress could be observed with high sensitivity in the subnanosecond time scale[5].

The SPR sensor has already been applied to photoacoustic microscopy (PAM) and other applications as an ultrasonic detector[6]. However, detailed analysis of the resonance curve and the observed waveform seemed more necessary.

In this paper, we tried to study the resonance characteristics of a SPR sensor and compared ultrasonic waveforms observed by a piezoelectric ultrasonic transducer with those by SPR sensors.

2. SPR sensors

In order to realize SPR, surface plasmon wave and electromagnetic wave must overlap spatially and have the same wavenumber. In the Kretchman-type SPR sensor[7] (Fig. 1), a laser beam enters the metal film through the prism and is reflected, exciting the evanescent waves in the metal film. The wavenumber of the evanescent wave is controlled by the angle θ of the incident wave. When the wavenumbers of the two waves coincide, SPR occurs. The wavenumbers of the evanescent wave k_{ev} and the surface plasmon wave k_{sp} are expressed as equations (1) and (2), respectively[8].

$$k_{ev} = \frac{\omega}{c}\sqrt{\varepsilon_p}\sin\theta \quad (1),$$

$$k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m\varepsilon_d}{\varepsilon_m+\varepsilon_d}} \quad (2),$$

where ε_p, ε_m and ε_d are the dielectric constants of the medium adjacent to the prism, metal and surface medium, ω is the angular frequency of light, and c is the speed of light.

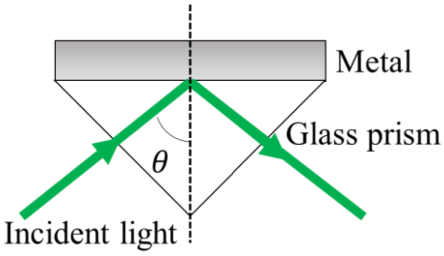

Fig. 1 A Kretschmann type SPR sensor.

In this study, two SPR sensors with Kretschmann configuration (Fig. 2) were used. One was comprised of an Ag metal film on the BK7 glass prism (Refractive index: 1.519), the other is composed of the SF11 glass prism (Refractive index: 1.795), Ag films (thickness: 53 nm) were deposited by an electron-beam deposition apparatus (EB1100, Canon Anelva Corp.). We refer to the former (BK7) and latter (SF11) as sensor A and sensor B, respectively.

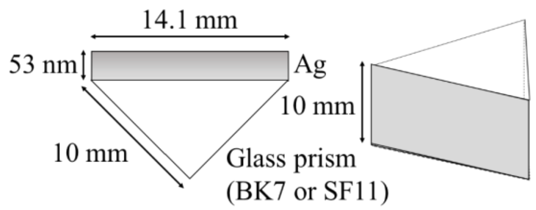

Fig. 2 Kretschmann configuration of our SPR sensors.

3. Experimental methods

3.1 Measurement of reflectance curve

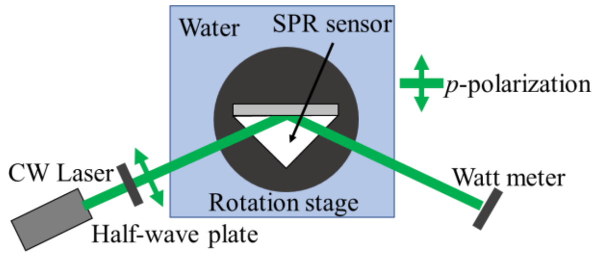

Fig. 3 Measurement system of the reflectance.

First, we measured the reflectance curves of sensors A and B. The experimental system is shown in Fig. 3. The angle of incident light was controlled by an automatic rotation stage. A CW laser beam (Torus mpc-300 Laser Quantum, 532 nm wavelength) was used as the *p*-polarized incident light. The reflected light was measured by using a wattmeter (S120B, THORLAB).

3.2 Observation of acoustic waveforms

We observed ultrasonic waveform using sensors A and B. The experimental system is shown in Fig. 4. The SPR sensor was placed at the focusing point of the wave radiated from an ultrasonic transducer (B2K20I PF40, JAPAN PROBE) in a water tank. A variable beam splitter (VBS) was used to keep the reflected light intensity to 0.5 mW and input to a photodiode (PDB435A, THORLABS). The output of the photodiode was observed by an oscilloscope (DPO7254C Tektronix). The ultrasonic waveform was compared with that observed using a PVDF ultrasonic transducer (UT) (NH8264 Toray Engineering, effective diameter: 0.5 mm).

4. Results and discussions

The reflectance curves of sensors A and B in water are shown in Fig. 5. The reflectances of sensors A and B showed minimum at 73.42° and 54.27° (Resonance angles) respectively. This difference is due to the material properties of the glass prisms. The theoretical estimations[9] of the resonance angles were 73.26° and 54.27°, respectively. The measured and estimated values of the resonance angle of sensor B were similar, whereas the values of sensor A were a little different. This seems to be due to oxidation of the silver films. The discrepancies of high reflectivity area may be due to the reflection at the glass sidewall of the water tank.

The waveforms observed by sensors A and B (incident angle: 73.09° (A), 54.00° (B)) and the piezoelectric ultrasonic transducer are shown in Fig. 6. All waveforms were normalized by their maximum values. The wave observed by UT showed late initial increase. This may be due to the superposition of the negative wave diffracted at the edge of the cylindrical PVDF transducer[10], although sound wave was observed in plane, in the case of SPR sensors.

5. Summary

In this study, we compared the waveforms observed by the ultrasonic transducer with these observed by SPR sensors. The waveforms were almost similar. However, small differences were found due to the diffracted waves at the surface of ultrasonic transducer. SPR sensors may be more useful to observe waveforms ultrasonic waves without cables.

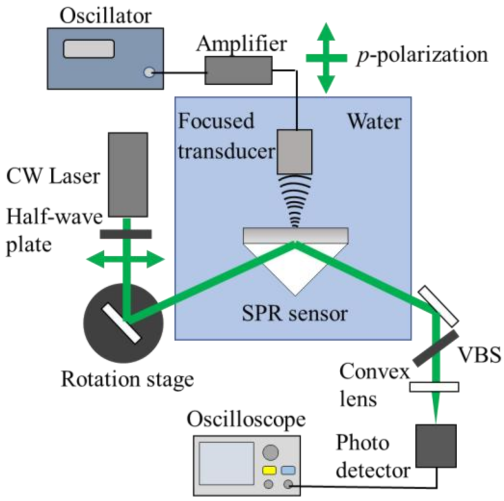

Fig. 4 Experimental system of reflectivity changes due to ultrasound radiation.

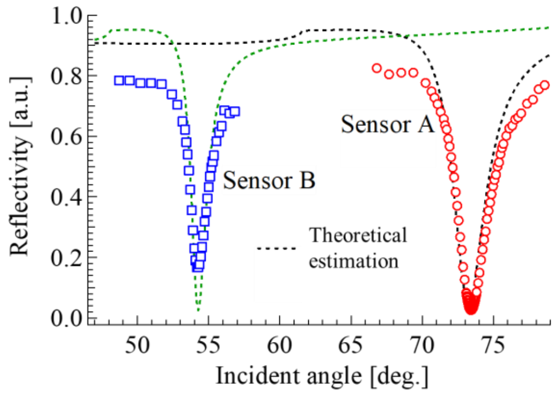

Fig. 5 Reflectance curves (experiments and theoretical estimations).

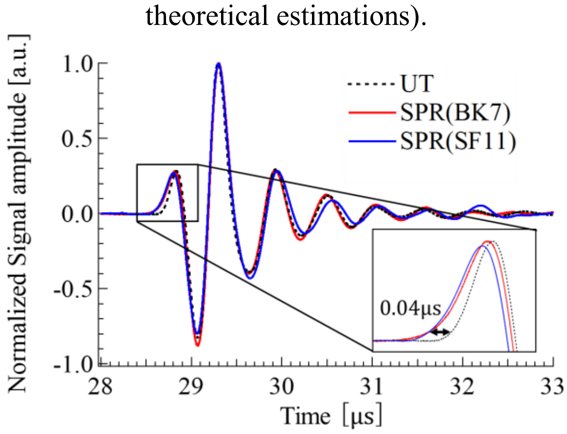

Fig. 6 Comparison of measured ultrasonic waves by SPR sensors and an ultrasonic transducer (UT).

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