**3P1-4**

# Experimental study on sensing diameter and sensitivity of SPR ultrasonic sensors

Kota Dezao†, Shuto Nakatsuji, Hayato Ichihashi, and Mami Matsukawa*
(Doshisha Univ.)

## 1. Introduction

Recently, surface plasmon resonance (SPR) has been expected for the application in various fields. Ultrasonic wave detection is one of them. SPR sensors for ultrasonic detection are characterized by their broadband and flat frequency response and are expected as a sensor for the photoacoustic microscopy [1]. However, as described below, conventional SPR sensors have a problem with the measurement field. Therefore, in this study, we fabricated a SPR sensor with a circular sensing area and investigated its sensing diameter and frequency characteristics, comparing the results measured by a calibrated commercial ultrasonic receiver.

## 2. Experimental Principle

Surface plasmon resonance (SPR) is a resonance phenomenon of surface plasmon waves (SPW) formed by free electrons on a metal surface. SPR excitation is mainly performed by an SPR sensor with a Kretschmann configuration [2]. In this configuration, a *p*-polarized laser beam is irradiated from the prism side to a thin metal film. SPR occurs when the wave number of the evanescent wave (EVW) generated on the metal film side matches the wavenumber of the SPW. Each wavenumber is expressed by the following equation.

$$k_{SPW} = k_0\sqrt{\frac{\varepsilon_m n_a^2}{\varepsilon_m + n_a^2}} \qquad (1)$$

$$k_{EVW} = k_0 n_p \sin\theta \qquad (2),$$

where $k_0$ is the wavenumber of the electromagnetic wave in vacuum, $\varepsilon_m$ is the dielectric constant of the metal, $n_a$ is the refractive index of the adjacent medium, $n_p$ is the refractive index of the prism, and $\theta$ is the angle of incidence of the laser on the thin film. As can be seen from equations (1) and (2), when the incident angle of the laser is an angle where the wavenumbers coincide (resonance angle), the reflectance of the light is significantly reduced because of SPR. The change in reflectance with respect to the incident angle of the laser is called the SPR curve. When ultrasonic waves are applied to the metal film on the prism, the refractive index of the medium (water) in contact with the thin metallic film changes according to the equation (1), which changes the resonance conditions and shifts the angle of the reflectance minima in the SPR curve. In other words, when the angle of incidence is constant, the reflected light intensity changes with the ultrasonic pressure. The change in the ultrasonic pressure can be observed as a time variation of the reflected light intensity.

## 3. Experimental Method

### 3.1 Sensor configuration

A Kretschmann-type SPR sensor was fabricated by depositing Ag (31 nm thick) and Au (5 nm thick) films on a glass prism (SF11, refractive index 1.795) by the electron beam deposition (**Fig. 1**). Sensor A was fabricated by depositing the metal film on an entire surface of the glass prism, and sensors B, C, and D (diameters *φ*=1.0, 0.8, and 0.6 mm) were fabricated by depositing the circle metal films.

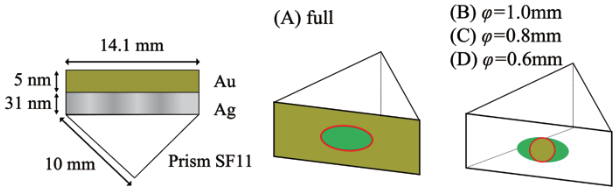

Fig. 1 The fabricated SPR sensor and metal layer.

### 3.2 Experimental conditions.

The incident light and reflected light of a *p*-polarized CW laser (Torus MPC-300 Laser Quantum, wavelength 532 nm, beam diameter 1.26 mm) were measured with a power meter (S120B, THORLAB), and the reflectance at each incident angle was calculated.

The next experimental system is shown in **Fig. 2**. The SPR sensor was irradiated with the *p*-polarized laser at an angle of incidence of 56.05°. In addition, a focused ultrasonic transducer (B5K20I PF40, JAPAN PROBE) was used to deliver one cycle of sinusoidal ultrasonic waves (5 MHz) to the SPR sensor. The reflected light from the SPR sensor was input to a differential photodiode (PDB435A, THORLABS), and the AC component (VAC) of the output was observed by an oscilloscope (DPO7254C, Tektronix) through an amplifier (NF, SA-420F5). For comparison, a needle type ultrasonic transducer (UT) (B2K20I PF40, JAPAN PROBE, effective

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E-mail:†ctwj0306@mail4.doshisha.ac.jp,
*mmatsuka@mail.doshisha.ac.jp

diameter 1.00 mm) was used to observe focused ultrasonic waves in the same way.

## 4. Results and discussion

The measured SPR and the theoretically estimated curves are shown in **Fig. 3**. The results show almost good agreement with the theoretical curve.

The frequency characteristics of the amplitude spectra normalized by the value of UT are shown in **Fig. 4**. The amplitudes of observed waves by sensors B, C, and D were better than that of sensor A in the high-frequency range. Therefore, the broadening of the frequency range was performed by the small circular sensing area. As shown in Fig. 4, each of the observed ultrasonic waveform of the SPR sensor and UT was normalized by the maximum amplitude. The observed waveforms of SPR and UT were in good agreement, but the wavefronts and negative peak values were slightly different for sensors B, C, and D. The SPR sensor shows the results the laser beam reflected by the metal film area. In the case of the sensor A, the sensing area is elliptical. In contrast, in the cases of sensors B, C, and D, SPR was excited only in a small circular thin metal film, and the output power was relatively small compared to that of sensor A. **Table I** shows the peak-to-peak values of the observed waveforms and the ratio of the sensing area to sensor A. The p-p values of the observed waves were not proportion to the measurement area. One reason for this phenomenon is the effects of light refraction due to the ultrasonic waves which propagate in the prism. We should also investigate the effects of sound field, spatial distribution of laser light etc.

## 5 Summary

The sensing diameter and frequency response of a Kretchman type SPR ultrasonic sensor were investigated experimentally. The frequency response at high frequencies was improved by the circular sensing area. However, the observed waveforms by the SPR sensor may be affected by the refraction of light due to sound waves propagating in the prism. Further study is needed for more accurate measurement of ultrasonic waveforms.

## References

[1] F. Yang et. al, Photoacoustics. 24, 100305 (2021).

[2] E. Kretschmann et. al, Z. Naturforsch. 23a, 2135 (1968).

[3] S. Nakatsuji et. al, IEEE Trans. Ultrason. Ferroelectr. Freq. Control, 70 (6), 562 (2023).

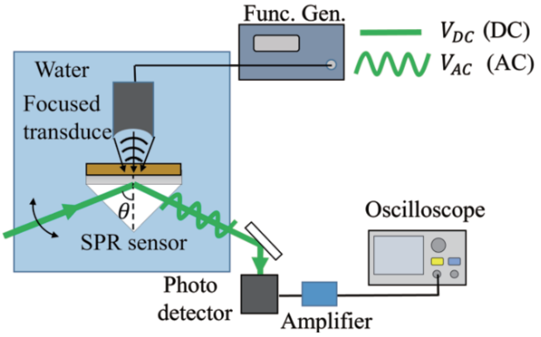

Fig. 2 Experimental system.

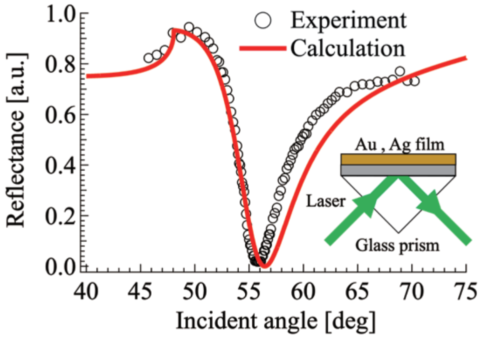

Fig. 3 SPR curves.

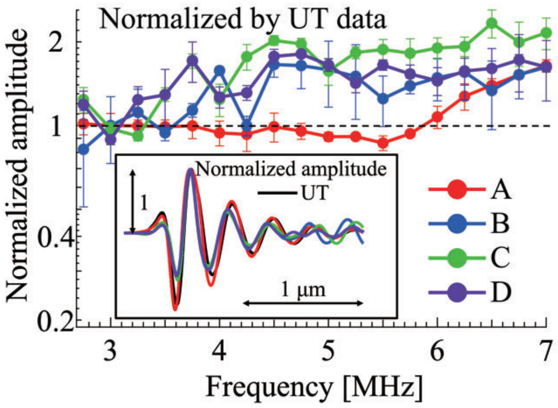

Fig. 4 Ultrasonic waveforms and frequency spectra observed by SPR sensors and UT.

Table I Peak to peak values of observed ultrasonic waves and sensing area ratio.

| | Sensor A | Sensor B | Sensor C | Sensor D |
|---|---|---|---|---|
| $V_{p\text{-}p}$ [V] | 7.81 | 0.58 | 0.64 | 0.52 |
| Sensing area ratio | 1 | 0.38 | 0.24 | 0.14 |