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Local measurement of ultrasonic pulse wave by SPR type sensors

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1. Introduction

Surface plasmon resonance (SPR) is widely used in various fields. Recently, SPR sensors have been expected as good ultrasonic receivers for the photoacoustic microscopy (PAM) because of their broadband and ultra-flat frequency responses [1]. However, the detailed characteristics of the SPR sensors, especially for the pulse wave measurements, have not been discussed in detail.

In this study, we experimentally investigated the effect of the sensing diameter and frequency to the characteristics of SPR sensors.

2. Experimental Principle

The surface plasmon wave (SPW) generates due to the collective vibration of free electrons on a metal surface. The resonance phenomenon of surface plasmon waves is called surface plasmon resonance (SPR). The Kretschmann configuration is well known for SPR excitation (Fig. 1) [2]. When a *p*-polarized laser beam is irradiated from the prism to a thin metal film where the beam is reflected, the evanescent wave (EVW) is generated on the thin metal film side. SPR occurs when the wavenumbers of SPW and EVW coincide.

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

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

where k_0 is the wavenumber of the electromagnetic wave in vacuum, ε_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 θ is the incident angle of the laser. The SPR can be excited by controlling the incident angle θ of the laser. When the SPR occurs, the reflectance decreases significantly because the energy of the incident light is used for the SPR excitation. This reflectance curve versus the incident angle of the laser is called the SPR curve. From equation (1), we can find that the SPR curve shifts to the lower or higher angles due to the resonance conditions, which depend on the refractive index of the adjacent medium (ex. water). This means that the reflected light reflects oscillating refractive index of water caused by ultrasonic waves. By observing the reflected light, then, we can observe ultrasonic waves.

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3. Experimental Method

3.1 Sensor configuration

A Kretschmann-type SPR sensor was fabricated by depositing a thin Ag film (48 nm thick) on a glass prism (BK7, refractive index 1.519) by electron beam evaporation (Fig. 1).

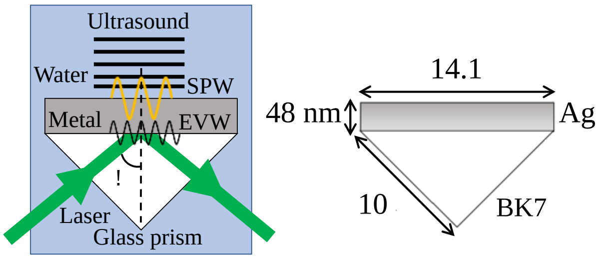

Fig. 1 An image of SPR sensor and the fabricated SPR sensor.

3.2 Experimental conditions.

First, a SPR curve was obtained by measuring the reflected light of a CW laser beam (Torus mpc-300 Laser Quantum, wavelength 532 nm) with a power meter (S120B, THORLAB).

Next, the SPR sensor system was installed in a water tank (Fig. 2). The focus type ultrasonic transducers (B2K20I and B5K20I PF40, JAPAN PROBE) were used to transmit pulse waves at 2 or 5 MHz to the surface of the SPR sensor. The laser beam diameters were 0.41 mm (condition A) or 1.26 mm (condition B). The reflected light from the SPR sensor was input to a differential photodiode (PDB435A, THORLABS). The output of the diode was amplified by an amplifier (NF, SA-420F5). The AC component of the output was observed with an oscilloscope (DPO7254C, Tektronix). The focused ultrasound was also observed using a needle-type ultrasonic transducer (UT) (HNR-1000, Onda, effective diameter 1.00 mm).

4. Results and discussion

4.1 The SPR curve

The SPR and sensitivity curves are shown in Fig. 3.

The intensity of the input light to the photodiode (including the DC component) was kept constant in the sensitivity curve measurement following the Nuster's sensitivity equation [3]. The sensitivity curve showed two peaks near the resonance angle. However, the sensitivity decreased sharply between them. The slope of the SPR curve at the SPR angle was almost zero, where changes in the reflected light (the AC component) was small, and resulted in the low sensitivity.

4.2 Relationship between sensing diameter and frequency response

The observed ultrasonic waves by the SPR sensor (incident angle: 73.07 deg (Fig. 3)) and UT are shown in Fig. 4. The waveforms were in good agreement. However, the maximum amplitude of the observed waves in condition B (SPR 1.26 mm) was found with a small delay. The amplitude spectra obtained from the waves are shown in Fig. 5. They were normalized by the spectra of the waves observed by UT. The spectra of condition A (SPR 0.41 mm) showed better sensitivity at higher frequencies, due to the smaller sensing diameter. The delay of the maximum amplitude in condition B is considered to come from the frequency response in the high-frequency region. Similarly, the maximum amplitude was very slightly delayed in condition A, although the laser beam diameter (0.41 mm) was smaller than the effective diameter (1.00 mm) of UT. The sensing diameter of condition A on the metal surface was ellipse (short diameter: 0.41 mm, long diameter: 1.42 mm). The long diameter may be a cause of the slight delay. The response at high frequencies can be improved by controlling the beam diameter.

5 Summary

In this study, the effect of sensing diameter on the frequency response of the SPR sensor were investigated. The frequency response was improved by decreasing the light beam diameter. Since there is a trade-off between the sensing diameter and sensitivity, an appropriate sensing diameter should be selected for the frequency used.

Reference

1. F. Yang et. al: Photoacoustic. 24 (2021) 100305.
2. E. Kretschmann et. al: Z. Naturforsch. 23a (1968) 2135.
3. R. Nuster et. al: Opt. Exp. 15 (2007) 6095.

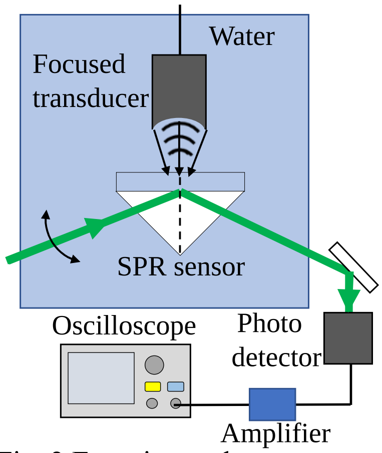

Fig. 2 Experimental system.

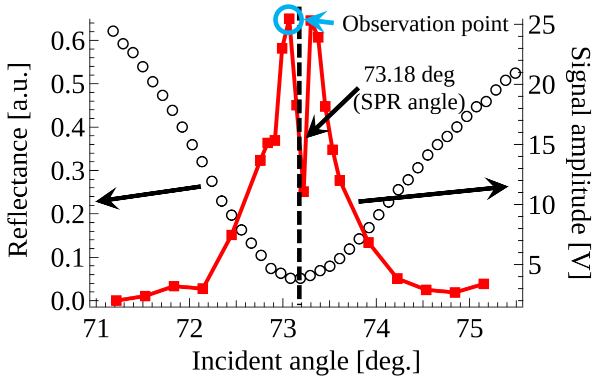

Fig. 3 SPR and sensitivity curve.

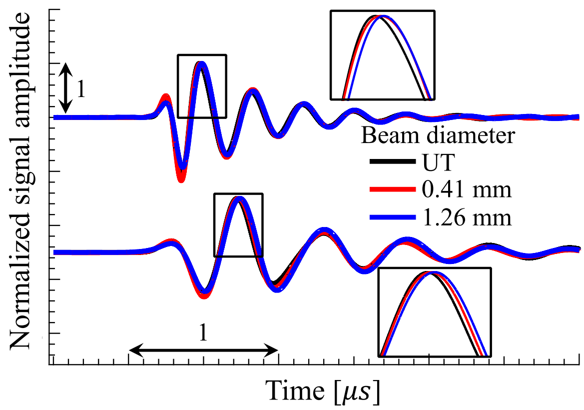

Fig. 4 Comparison of the measured ultrasonic waves by SPR sensors and an ultrasonic transducer.

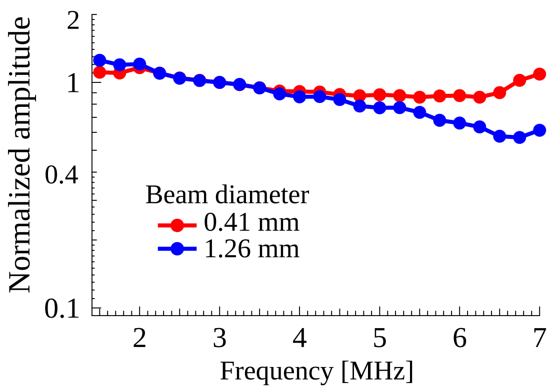

Fig. 5 Comparison of the measured ultrasonic wave spectra by SPR sensors.