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Measurement of chromatic dispersion of liquid in a wide spectral range based on liquid-prism surface plasmon resonance sensor

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ABSTRACT

We present, in this work, a new method to measure the chromatic dispersion of liquid based on the surface plasmon resonance sensor. The liquid sample is serving as the liquid prism at the same time. Both angular and spectral interrogations are used in the experiments. The chromatic dispersions of six kinds of liquids with the wavelengths from 450 nm to 1050 nm are obtained, respectively. The experimental data are also compared with the data of Abbe refractometer, and they are in good agreement. The method provides a practical application for measuring the chromatic dispersion of liquid in a wide spectral range.

1. Introduction

The chromatic dispersion is the physical property of a substance that describes the wavelength dependence of its index of refraction. The chromatic dispersion of liquid is an important optical parameter in practice, and measurement of refractive index is very important in various applications, such as in characterization of optical materials [1], nonlinear optics [2], environmental pollution monitoring and chemistry. The measuring methods for refractive index include spectroscopic ellipsometry [3], prism minimum deviation method [4–6], Abbe refractometer [7], interferometry method [8–12], diffraction gratings [13], surface plasmon resonance (SPR) [14,15], optical fiber [16] and optical low-coherence tomography [17], etc.

In particular, surface plasmon resonance (SPR) technique is an optical method for measuring the refractive index of material adsorbed on a metal, and it has the capability for real-time measurement with high detection sensitivity. The most common Kretschmann-Raether configuration [18] (also known as the attenuated total reflection configuration) is widely used in SPR sensors. In practice, the liquid can also be used as the prism in Kretschmann-Raether configuration, and the corresponding results are identical to the solid prism when they have the same refractive index [19]. Different from the solid prism, liquid prism is the sample for measurement at the same time. It is because the condition of SPR is sensitive to the refractive index of liquid prism (or solid prism [20]). For spectral interrogation, the liquid prism SPR configuration will not consider the chromatic dispersion of prism specially. The liquid prism SPR sensor based on the angular and spectral interrogations [21] are used in this work to measure the chromatic dispersion of liquid. The experimental system is calibrated by the standard sample water, and the experimental data are also compared with the data of Abbe refractometer. The results show that the liquid prism SPR sensor is an efficient, simple and practical method for the measurement of chromatic dispersions of liquids.

2. Experimental setup

The experimental setup of liquid-prism SPR sensor is shown in Fig. 1a. The liquid box is fastened to the vertical rotator. The collimated broadband light beam (THORLABS, SLS201/M, 200 nm–2600 nm) passes through a Glan prism and generates p polarized beam. The reflected light from the liquid box is focused to the spectrograph (Ocean Optics USB 4000 200–1100 nm) with a convex lens. The rotator and the spectrograph are controlled with computer synchronously. The details of the cuboids liquid box and the sensing chip are shown in Fig. 1b. The BK7 glass slide with a thickness of 170 μm (Agar scientific) is put on the hollowed out side of the box, and a mirror is put on the bottom of the liquid box. The sections of the liquid box and the sensing chip are shown in Fig. 1c. The glass slide is oriented towards the liquid, and the metal film (50 nm Au film or 55 nm Ag film in this experiment) is oriented towards air, respectively. The top of the box is open for introducing the liquid. The incident light is set vertical to the liquid level, and it is always normal to the liquid level when the liquid box is turned. The light spot of the incident light is just on the center of the rotator, so it is stationary when the rotator turns a certain angle. The emergent light reflected twice in the right angle is parallel to the incident light always, so the reflected light is a beam of parallel light when the box is

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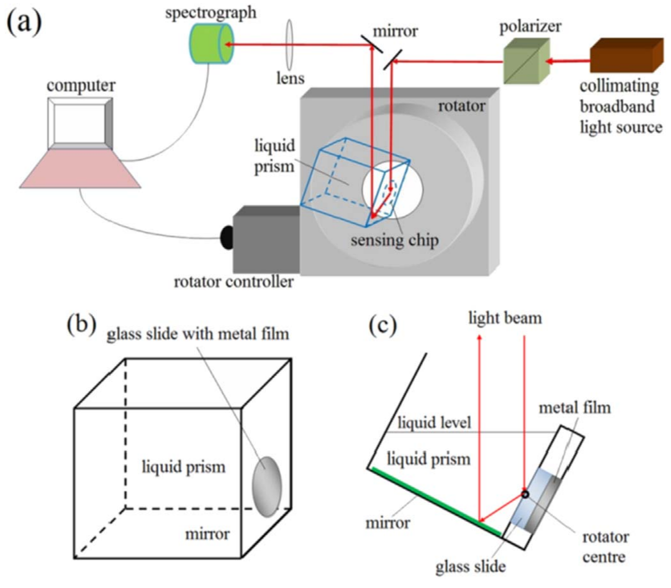

Fig. 1. (a) Experimental setup of the liquid-prism SPR sensing configuration. (b) The details of the liquid box and the sensing chip. (c) The sections of the liquid box and the sensing chip.

turned, and it is easy to collect with a convex lens.

3. Theory

The excitation condition of SPR is given [22] by:

$$k_0 n_p \sin\theta = \mathrm{Re}\left(k_0\left(\frac{\varepsilon_m\varepsilon_a}{\varepsilon_m+\varepsilon_a}\right)^{1/2}\right) \tag{1}$$

where k_0 is the wave vector of light in the vacuum, n_p is the refractive index of prism, θ is the incident angle of light, ε_m is the complex permittivity of the metal film, and ε_a is the permittivity of air. The right side of Eq. (1) is the real part of complex wave vector of surface plasmon wave (SPW) at metal-air interface. Here ε_m can be expressed as the plural form $\varepsilon_m = \varepsilon_{rm} + i\varepsilon_{im}$. If $\varepsilon_{rm} < 0$, $|\varepsilon_{rm}| \gg \varepsilon_{im}$ and $|\varepsilon_{rm}| \gg \varepsilon_a$ are all satisfied (e.g. Au in the wavelength larger than 530 nm and Ag in the wavelength larger than 430 nm), then the complex wave vector of SPW can be written as:

$$k_{\mathrm{SPW}} = k_0\left(\frac{\varepsilon_m\varepsilon_a}{\varepsilon_m+\varepsilon_a}\right)^{1/2} \approx k_0\left(\frac{\varepsilon_{rm}\varepsilon_a}{\varepsilon_{rm}+\varepsilon_a}\right)^{1/2} + ik_0\left(\frac{\varepsilon_{rm}\varepsilon_a}{\varepsilon_{rm}+\varepsilon_a}\right)^{1/2}\frac{\varepsilon_{im}\varepsilon_a}{2\varepsilon_{rm}(\varepsilon_{rm}+\varepsilon_a)} \tag{2}$$

and Eq. (1) is simplified as:

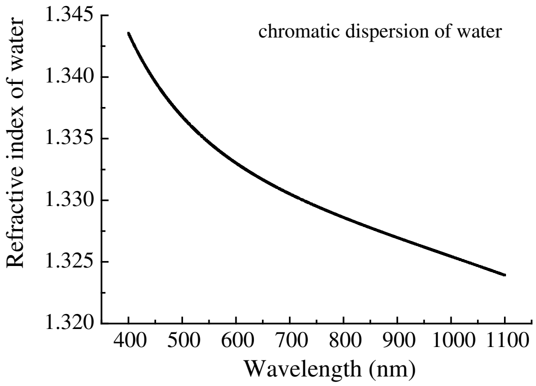

Fig. 3. The chromatic dispersion of water with the wavelength from 200 nm to 1100 nm, the temperature is 20 °C, and the atmosphere pressure is standard atmosphere pressure (0.1 MPa).

$$k_0 n_p \sin\theta \approx k_0\left(\frac{\varepsilon_{rm}\varepsilon_a}{\varepsilon_{rm}+\varepsilon_a}\right)^{1/2} \tag{3}$$

The model of liquid prism SPR sensor in this manuscript is shown in Fig. 2a, where n_l, n_g and n_a are the refractive indices of liquid, glass slide and air; k_x, k_g and k_{SPW} are the horizontal components of wave vectors in liquid, glass slide and metal film, respectively. θ is the incident angle of light, and φ is the refraction angle of light in the glass slide. According to Fresnel formula $n_l\sin\theta = n_g\sin\varphi$ between the sample and the glass, the wave vectors in two media are equal, i.e. $k_x = k_g$. Thus, the glass slide can be neglected, and the model in Fig. 2a can be simplified to the model in Fig. 2b. Finally, the wave vector in liquid k_l and the wave vector of SPW k_{SPW} are connected directly, and the theory of liquid prism SPR sensor can be described by Eq. (3) conveniently.

For spectral interrogation, k_0, n_l (or n_p) and ε_{rm} in Eq. (3) are all the functions of wavelength (here, the chromatic dispersion of air is neglected in a suitable wavelength range and it will not introduce additional errors). If the incident angle of broadband light θ and the real part of complex permittivity of metal film ε_{rm} in resonant wavelength are known in Eq. (3), then the refractive index of liquid n_l in the resonant wavelength can be known. In order to obtain the chromatic dispersion of liquid in a wide wavelength range, the incident angle of light θ should be changed to obtain another resonant wavelength, so the angular interrogation is required additionally in this experiment. The key factor to measure the chromatic dispersion of liquid exactly in this experiment is obtaining the accurate value of ε_{rm} in Eq. (3), and the complex permittivity of the metal film can be obtained elsewhere, such as literatures or hand books of optics. Here, the values of ε_{rm} for gold and silver films are determined by the standard sample water. The chromatic dispersion of water is studied widely and the expression of chromatic dispersion of water is a recognized formula. The chromatic dispersion formula of water is given by Sellmeier dispersion formula

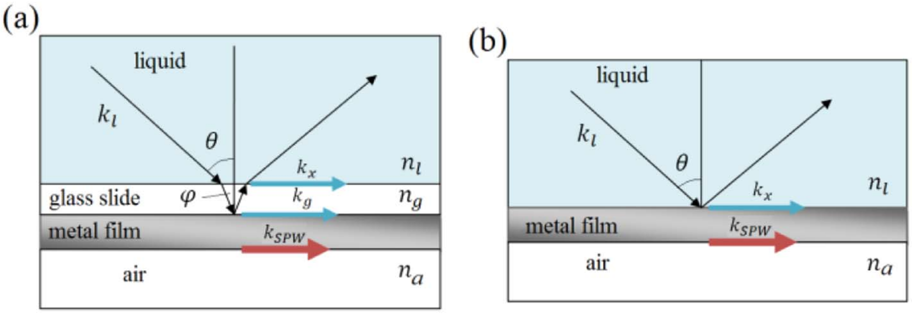

Fig. 2. (a) The model of liquid-prism SPR sensor. (b) The simplified model of liquid-prism SPR sensor.