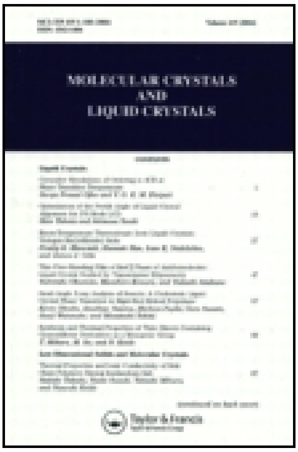

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Electric Field Tuning of Surface Plasmon Resonance Using Vertical Alignment Liquid Crystals on a Silver Grating Structure

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We report electric field tuning of surface plasmon resonance (SPR) by controlling the polarization state of incident light using vertical alignment liquid crystal (VA-LC) layer. Excitation of SPR depends on the polarization state of incident light and incident angle. We fabricated a metallic grating structure in order to excite SPR, and then we investigated the applied voltage dependence of reflection spectrum. Continuous tuning of SPR is achieved as a result of the polarization change of incident light by controlling the birefringence of the LC layer.

Keywords Electric field tuning; surface plasmon resonance; vertical alignment liquid crystal

1. Introduction

Surface plasmons (SPs) are transverse magnetic (TM) electromagnetic waves propagating along a metallic surface resulting from a collective oscillation of free electrons of the metal [1]. They are excited on metallic surface with TM-polarized incident light using prism configuration, such as Otto or Kretschmann-Raether configuration, or grating structures [2–4]. Such surface plasmon resonance (SPR) occurs at a wavelength λ_{inc} ($=2\pi/k_{inc} = 2\pi c/\omega$) determined by Eqs. (1) and (2).

$$k_{sp} = n_d k_{inc} \sin\phi + m\frac{2\pi}{\Lambda} \quad (\mathrm{m} = 0, \pm1, \pm2, \cdots), \tag{1}$$

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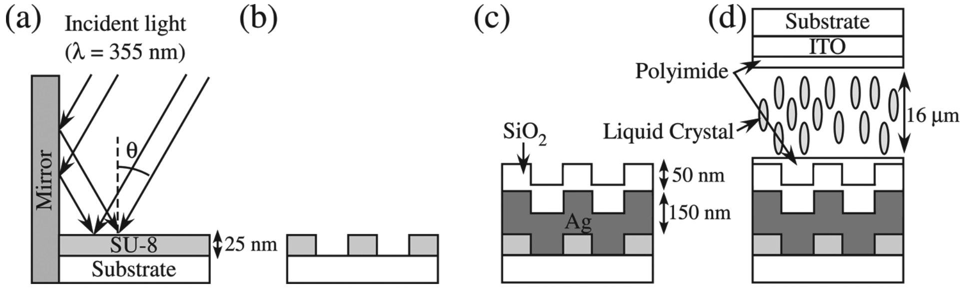

Figure 1. The fabrication procedure of plasmonic structure: (a) Lloyd-mirror configuration, (b) polymer grating structure, (c) metallic grating structure with SiO_2, and (d) metallic grating structure with VA-LC layer.

$$k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_d \times \varepsilon_m(\omega)}{\varepsilon_d + \varepsilon_m(\omega)}}. \tag{2}$$

Here k_{sp} is wavenumber of SPs, φ is incident angle of the light, m is diffraction order, λ is grating pitch of the metallic structure, $\varepsilon_m(\omega)$ is dielectric function of metal, ε_d ($=n_d^2$) is dielectric constant of the material placed on the metallic surface and c is light speed in vacuum. At the resonance wavelength, the incident light is absorbed in metallic structure. These SPR are employed in passive devices, such as biosensor because the wavenumber of the SPs significantly depends on the dielectric constant of the material placed on the metallic surface [5].

A tunable SPR device can control the properties of reflection light and be applied in active devices, such as reflective displays [6]. The tunable SPR devices using liquid crystals (LCs) were suggested two methods, one is modulating the dielectric constant of the material placed on the metallic surface and the other is controlling polarization direction of the incident light [6–8]. We previously reported a tunable SPR device based on rotating the polarization direction of the incident light using a twisted nematic liquid crystal layer [8]. However, the polarization rotating mechanism only allowed on-off switching of the SPR. For applications, a gradual control of SPR is required. In this paper, we proposed a tuneable SPR device based on controlling the polarization state of the incident light using a grating structure and a vertical alignment (VA)-LC layer. The polarization state can be changed continuously by applying an electric field across the VA-LC layer, and so a continuous electrical tuning of the SPR is possible.

We also propose a method to control the excitation of SPR independently at two wavelengths using the VA-LC layer. In case of incident angle $\varphi \neq 0°$, excitation wavelength separate to short wavelength side and long wavelength side. The polarization state of light passing through the material having birefringence is different depending on the wavelength, so we demonstrated independently control of SPR using VA-LC layer at oblique incidence.

2. Experimental Methods

Figure 1 shows the fabrication method of the sample used in this study. The polymer grating structure was fabricated using holographic lithography with Lloyd–mirror configuration. A thin layer of a photoresist (SU-8 2005) was formed by spin-coating the material at 4000 rpm for 30 seconds, and was irradiated by a frequency–tripled Q-switched Nd:YAG laser with wavelength, pulse width and repetition rate of 355 nm, 20 ns, 10 Hz respectively. The grating pitch Λ fabricated with Lloyd-mirror configuration is determined by Eq. (3),

$$\Lambda = \frac{\lambda}{2\sin\theta}, \tag{3}$$

where λ is the wavelength of the incident light, and θ is the angle of the incidence beams from the normal of the substrate. The photoresist was developed and then rinsed with diacetone alcohol and isopropyl alcohol in order to obtain the grating structure. 150 nm of Ag and 50 nm of SiO_2 were deposited on the fabricated polymer grating structure in order to excite SPR and prevent oxidation of Ag. Figure 2 shows an atomic force microscopy (AFM) image of the metallic grating structure fabricated at $\theta = 30°$ after deposition of Ag and SiO_2. From the cross-section profile of AFM image, the period and height were determined as 370 nm and 25 nm respectively. In order to induce vertical alignment of LC molecules, a vertical alignment layer (JALS-2021-R2:JSR) was spin-coated on the SiO_2 layer. As the counter substrate, a glass substrate coated with ITO was used. The vertical alignment layer was also spin-coated on the ITO and rubbed at 45° from the direction of the groove of the grating. A VA-LC cell was fabricated using the two substrates using 16 µm-thick spacer. The LC material used in this study was MLC-6610 (Merck) with negative dielectric anisotropy.

To observe excitation of SPR, the reflection spectrum was measured using a tungsten lamp (MHF-100 L:MORITEX) as incident light source at incident angle φ from normal of the substrate. In order to measure the polarization dependence of the incident light, TM or transverse electric (TE)-polarized light was entered to the sample in the nematic phase. A multichannel spectrometer (PMA-11:Hamamatsu Photonics) was used as a detector and rectangular voltage was applied between ITO electrode and metallic grating structure.

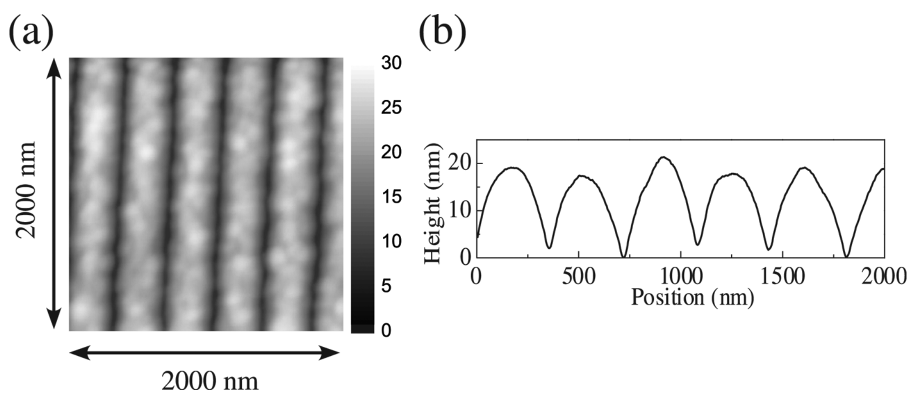

Figure 2. (a) AFM image of metallic grating structure with SiO_2, (b) cross-section profile of AFM image.

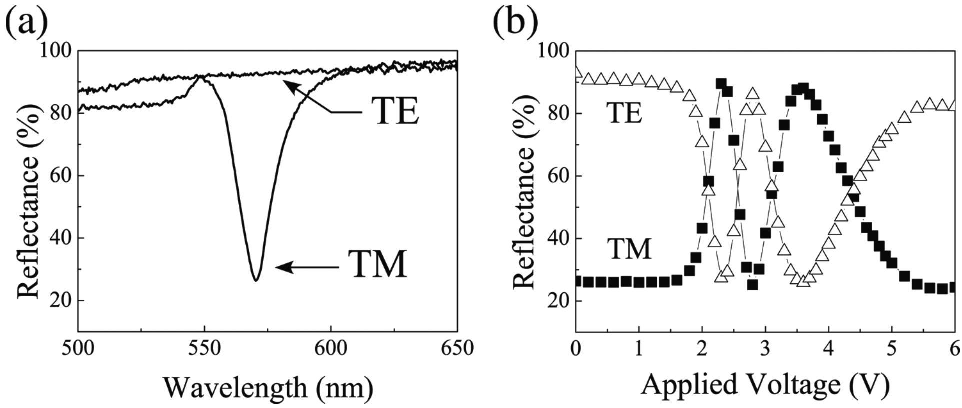

Figure 3. (a) Polarization dependence of reflection spectra of the metallic grating with VA-LC layer, (b) applied voltage dependence of reflectance at $\lambda = 570$ nm.

3. Results and Discussion

3.1. *Continuous Tuning of Surface Plasmon Resonance*

Figure 3(a) shows the reflection spectra of the fabricated metallic grating with VA-LC layer. One dip in the reflection spectrum was observed for TM-polarized light at a wavelength determined by Eq. (1) with $\phi = 0°$, $m = \pm 1$. At zero voltage, the incident light only experienced the ordinary refractive index of the LC, and the polarization state remained unaffected. As a result, the dip in the reflection spectrum caused by SPR appeared only for TM-polarized incident light. Figure 3(b) shows the applied voltage dependence of the reflectance at $\lambda = 570$ nm. Above the Frederiks threshold at $\sim$2 V, the reflectance was seen to oscillate between high and low reflectance regime. This change in reflectance can be explained in terms of field-induced reorientation of the LC molecules. When the electric field is applied

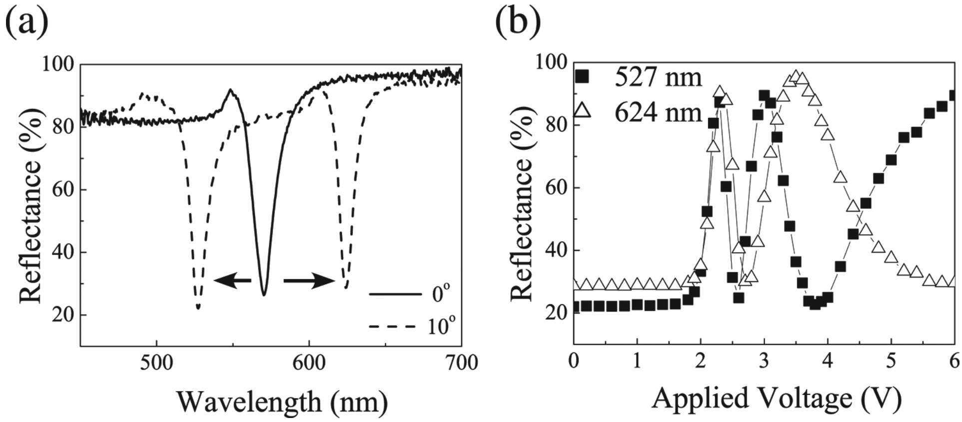

Figure 4. (a) Reflection spectra of TM-polarized incident light at $\theta = 0°$ and 10°, (b) applied voltage dependence of reflectance at $\lambda = 527$ nm and 624 nm at $\theta = 10°$.

normal to the substrate, LC molecules gradually align perpendicular to the electric field and along the rubbing direction. As a result, the birefringence of LC layer increases, causing a change in the polarization of light passing through the LC layer. Since SPR is excited only by the TM-field component, continuous tuning of SPR results from a continuous increase in birefringence and following change of the polarization state of incident light.

3.2. *Independently Control of Surface Plasmon Resonance at Two Wavelengths*

Figure 4(a) shows the reflection spectra with TM-polarized incident light at incident angle $\varphi = 0°$ and $\varphi = 10°$. In the case of $\varphi = 10°$, two coupling conditions can be considered ($m = \pm 1$), resulting in two SPR dips at two wavelengths ($\lambda = 527$ nm, 624 nm). Figure 4(b) shows the applied voltage dependence of the reflectance with TM-polarized incident light at $\lambda = 527$ nm and $\lambda = 624$ nm. At high voltage, different behaviours were observed for the two wavelengths. For example, light absorption caused by SPR appeared only for $\lambda = 527$ nm at 3.7 V. However, light absorption appeared only for $\lambda = 624$ nm at over 6 V. Phase difference δ of the light passing through the LC layer is explained by Eq. (4).

$$\delta = \frac{2\pi \Delta n d}{\lambda_{inc}}. \tag{4}$$

Here Δn and d are birefringence and thickness of the LC layer. The polarization state of light passing through the LC layer is different at each wavelength because of the wavelength dependence of δ. Therefore the excitation of SPR at two wavelengths can be controlled independently by amount of applied voltage.

4. Conclusion

We demonstrated a tunable SPR device using metallic grating structure and VA-LC layer. SPR could be controlled continuously by applied electric field because of the increase in the birefringence of LC layer. Moreover, the excitation of SPR at two wavelengths could be control independently at oblique incidence because of wavelength dependence of phase difference of the incident light. Excitation wavelength of SPR can be controlled by grating pitch and incident angle, so tuning of reflectance at arbitrary wavelength can be achieved by optimizing fabrication grating structure and thickness of VA-LC layer.

Acknowledgment

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