

Surface plasmon resonance on the surface: metal - liquid crystal layer

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Abstract. Surface plasmon resonance (SPR) is widely used in different types of optical detection schemes and for light manipulation at sub-wavelength scale. Usually Kretschmann configuration is used for effective SPR excitation. There are a lot of experimental and theoretical investigations about the influence of the dielectric, adjacent to the metal, on SPR. However, till now the influence on liquid crystal layer, adjacent to the metal, is not considered to our best knowledge. The purpose of the present paper is to cover this gap. We simulate the influence of thin layer of liquid crystal, adjacent to the metal, on the SPR characteristics. For this purpose Maxwell equations are numerically solved for layer structure: prism/gold/liquid crystal/air. The light reflection spectra are calculated for chiral structure of ferroelectric smectic C (SmC*) liquid crystal layer. The angular and wavelength response are considered. Special attention is paid to SPR excitation for variation of tilt angle and different angle of incident light. The influence of SPR of the pitch length and cell thickness is also considered.

1. Introduction

Plasmonics are envisaged as a platform for future integrated photonics architectures which have the unique capability of providing sub-wavelength light confinement [1]. The functionality required for real light routing and switching applications also demand circuit elements that can be externally tuned via control mechanism, such as thermo-, electro-optic or non-linear effects. In this context, a family of tunable photonic devices has been based on the use of nematic liquid crystals [LC], inherently anisotropic materials, whose properties can be controlled by applying an electric field. Their high optical anisotropy and their extremely low power consumption have favored their use in numerous photonic platforms [2], such as tunable resonators [3], gratings [4], photonic crystals [5], or phase shifters [6], and they are also currently being explored as an efficient means of controlling nanoplasmonic resonant structures [7]. In the context of guided-wave plasmonics, LC-tunable waveguides of various designs have been proposed for low-power variable attenuators [8], phase-shifters [9], switches [10], filters [11], tunable lenses [12], beam steering [13], or modulators [14]. An important application of guided-wave plasmonics structures is sensor applications.

We focus our attention on simulation of influence of liquid crystal layer on SPR excitation which could increase the field of application. The simulation is performed for p-polarized light and for ferroelectric liquid crystal (FLC) in a chiral smectic C phase (SmC*). The SmC* structure is one in which the molecules in each layer are tilted with respect to the layer normal by an angle θ . The tilt angle projection on the layer's plane slowly processes about a direction parallel to the layer normal



resulting in a helical structure with a pitch p [15]. Our simulations are based on a theoretical model obtained by solving Maxwell equations in 4x4 matrix form for an anisotropic media [16].

We consider SmC* liquid cell which was studied in details in [17]. Regarding the structure of liquid crystal cell and molecules orientation we use the notations adopted in [17].

2. Reflection spectra at metal/ ferroelectric SmC* LC

In our simulations the physical parameters are as follows: prism ($\varepsilon_p = 2.89$), gold thin film with thickness $d = 50\text{nm}$, anisotropic layer with thickness $d = 500\text{nm}$ and $d = 1400\text{nm}$, air. The permittivity of gold is according [18].

2.1. Anisotropic layer with thickness $d = 500\text{nm}$

To reveal the specific influence of LC layer on SPR excitation, firstly we study the plasmon resonance with usual anisotropic layer, adjacent to Au layer, with permittivity equal to LC permittivity.

2.1.1. Reference anisotropic layer with thickness $d = 500\text{ nm}$

This simulation clearly identifies the plasmon resonance. Figure 1 shows the reflection spectra for p-polarized light as a function of incident angle at incident wavelength $\lambda = 632.8\text{nm}$. The resonance observed at incident angle $\varphi = 66^\circ$ has a width of few degree, typical for surface plasmon excited at the gold/anisotropic layer interface. Observed resonance at incident angle $\varphi = 46^\circ$ is narrow, typically for waveguide mode propagating in the anisotropic layer. It is worthy to mention that for reference anisotropic layer with $\varepsilon_x = 2$, $\varepsilon_y = 2$, $\varepsilon_z = 3$ plasmon mode cannot be excited.

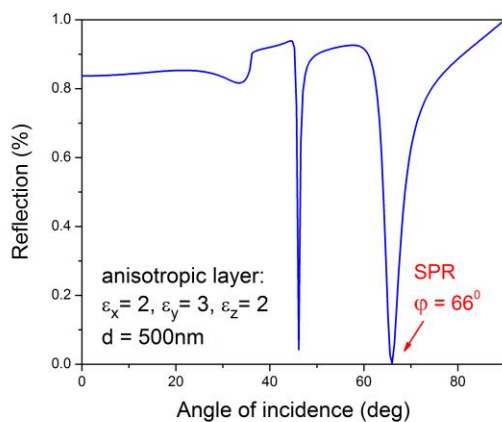


Figure 1. Reflection spectra for p-polarization light as a function of incident angle. Configuration: prism ($\varepsilon_p = 2.89$), Au layer with thickness $d = 50\text{nm}$, anisotropic layer ($\varepsilon_x = 2$, $\varepsilon_y = 3$, $\varepsilon_z = 2$) with thickness $d = 500\text{nm}$, air, for incident wavelength $\lambda = 632.8\text{nm}$.

2.1.2. Ferroelectric SmC* LC layer with thickness $d = 500\text{nm}$

Now we compare LC layer with reference anisotropic layer. The both layers have the same thickness and permittivity. The specific parameters of LC layer are pitch $p = 500\text{ nm}$ (e.g. number of period $Np = 1$) and tilt angle θ (in notation of [17]). Figure 2 is analogues to figure 1 in the case of ferroelectric SmC* LC layer. The corresponding information about structure parameters is reported in the caption.

The feature of SmC* LC layer (helical structure with a pitch p) leads to plasmon resonance shift (figure 2a) compared with reference anisotropic layer (figure 1) from 66 deg to 68 deg. The other resonances in figure 2a are waveguide modes. The tilt angle $\theta = 90^\circ$ (figure 2b) strongly influences SPR: the plasmon resonance disappears. This can be explained simply – a molecule rotation converge the anisotropic layer with $\varepsilon_x = 2$, $\varepsilon_y = 3$, $\varepsilon_z = 2$ to layer with $\varepsilon_x = 2$, $\varepsilon_y = 2$, $\varepsilon_z = 3$ were plasmon mode cannot be excited as mention in point 2.1.1.

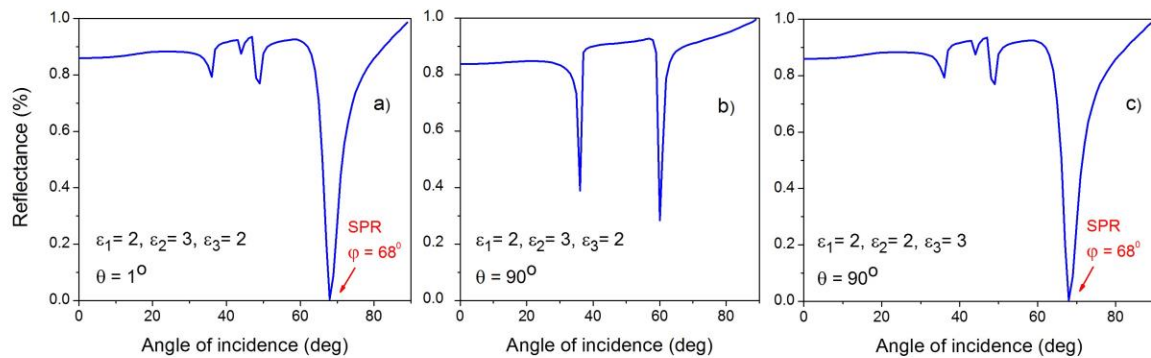


Figure 2. Reflection spectra as a function of incident angle φ for different configuration: LC ($\varepsilon_1=2$, $\varepsilon_2=3$, $\varepsilon_3=2$), $p=500\text{nm}$, $Np=1$ for tilt angle a) $\theta=1^\circ$ and b) $\theta=90^\circ$; c) LC ($\varepsilon_1=2$, $\varepsilon_2=2$, $\varepsilon_3=3$), $p=500\text{nm}$, $Np=1$ for tilt angle $\theta=90^\circ$ and incident wavelength $\lambda=632.8\text{nm}$.

Figure 2c shows the effect of changing the dielectric anisotropy of the LC molecule ($\varepsilon_1=2$, $\varepsilon_2=2$, $\varepsilon_3=3$) at tilt angle $\theta=90^\circ$, which leads to case analogues to figure 2a i.e. the LC layer has the same permittivity as shown in figure 2a. For negative anisotropy ($\varepsilon_2 > \varepsilon_3$) the variation of tilt angle from 1 deg to 90 deg leads to conversion of plasmon mode into waveguide mode (see figure 2a and figure 2b).

2.1.3. Wavelength dependence of plasmon resonance at LC layer thickness $d=500\text{nm}$

The conversion of plasmon mode into waveguide mode has supposed strong dependence of SPR on the tilt angle of LC molecule. To reveal this dependence as a function of wavelength we have simulated the reflection at the angle of SPR excitation ($\varphi=68^\circ$), shown in figure 3.

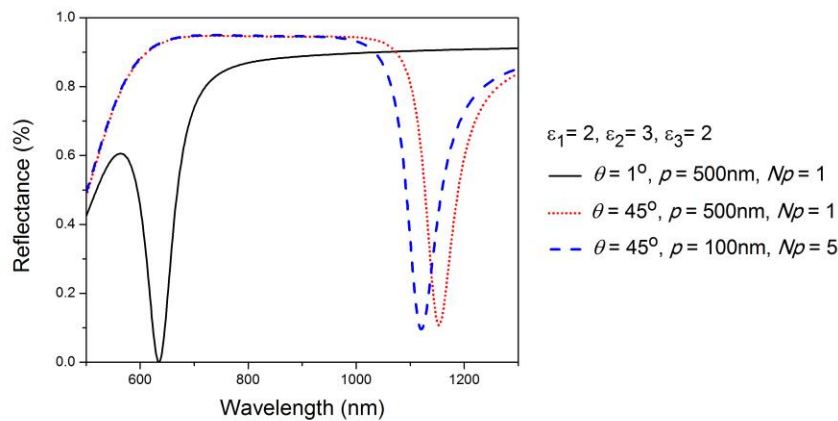


Figure 3. Reflection spectra as a function of wavelength for incident angle $\varphi=68^\circ$.

Increasing the tilt angle causes a strong SPR shift to longer wavelengths (figure 3 – dot line). Pitch length increasing makes this effect smooth (figure 3 – dashed line). For correct comparison LC layer thickness is fixed, but numbers of turns are different to get different pitch.

2.2. Anisotropic layer with thickness $d=1400\text{nm}$

The next step is to study the influence of thicker anisotropic layer. Keeping in mind that the penetration depth of plasmon is few hundred nanometers it is worthy to simulate LC layers with pitch

of compatible length. From common consideration one can expect that the number of waveguide modes will increase.

2.2.1. Reference anisotropic layer with thickness $d = 1400\text{nm}$

Following our approach from point 2.1 at thickness $d=500\text{nm}$, we start simulations with usual anisotropic layer. Indeed, our simulation, shown in figure 4, has confirmed the increased number of waveguide modes. The comparison of the results with figure 2 shows that the thickness of the anisotropic layer does not influence the position of the plasmon resonance.

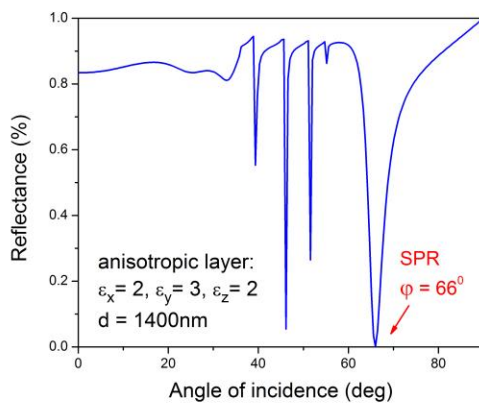


Figure 4. Reflection spectra for p-polarization light as a function of incident angle. Configuration: prism ($\varepsilon_p = 2.89$), Au layer with thickness $d = 50\text{nm}$, anisotropic layer ($\varepsilon_x = 2$, $\varepsilon_y = 3$, $\varepsilon_z = 2$) with thickness $d = 1400\text{nm}$, air, for incident wavelength $\lambda = 632.8\text{nm}$.

2.2.2. Ferroelectric SmC* LC with layer thickness $d = 1400\text{nm}$

Figure 5 is analogues to figure 4 in case of ferroelectric SmC* LC layer with permittivity $\varepsilon_1 = 2$, $\varepsilon_2 = 3$, $\varepsilon_3 = 2$, pitch $p = 1400\text{nm}$, number of periods $Np = 1$ and tilt angle as indicated in the caption of figure 5. The result shows that the existence of helical structure slightly shifts the plasmon resonance exactly at the same manner as in the case of thinner layer $d=500\text{nm}$.

By analogy to the case with LC layer at thickness $d = 500\text{nm}$, the effect of changing the dielectric anisotropy of the LC molecule ($\varepsilon_1 = 2$, $\varepsilon_2 = 2$, $\varepsilon_3 = 3$) at tilt angle $\theta = 90^\circ$ is the same (figure 5a and figure 5c are similar). For negative anisotropy ($\varepsilon_2 > \varepsilon_3$) a conversion of plasmon mode into waveguide modes is observed when the tilt angle is 90 deg (see figure 5a and figure 5b), as for LC thinner layer.

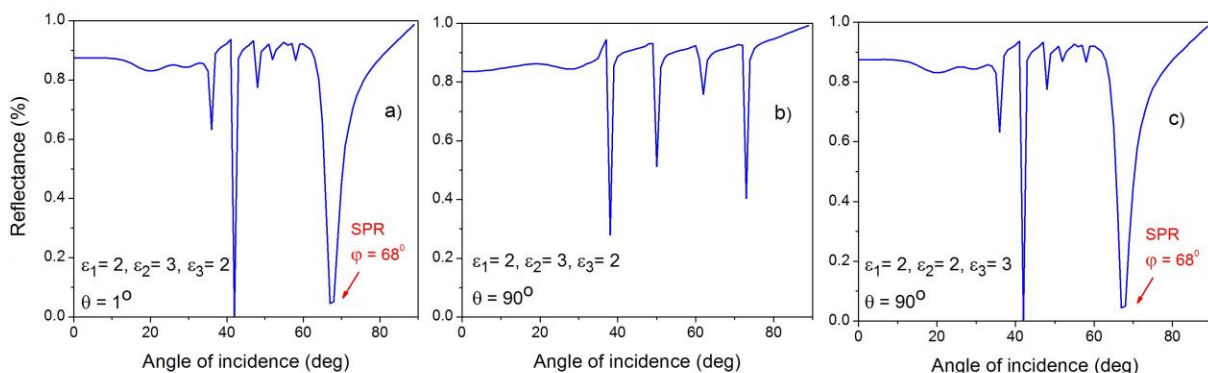


Figure 5. Reflection spectra as a function of incident angle. Configuration: LC ($\varepsilon_1 = 2$, $\varepsilon_2 = 3$, $\varepsilon_3 = 2$), $p = 1400\text{nm}$, $Np = 1$ for tilt angle a) $\theta = 1^\circ$ and b) $\theta = 90^\circ$; c) LC ($\varepsilon_1 = 2$, $\varepsilon_2 = 2$, $\varepsilon_3 = 3$), $p = 1400\text{nm}$, $Np = 1$ for tilt angle $\theta = 90^\circ$ and incident wavelength $\lambda = 632.8\text{nm}$.

2.2.3. Wavelength dependence of plasmon resonance at LC layer thickness $d = 1400$ nm

The wavelength dependence of SPR excitation has been simulated at the angle of SPR excitation ($\varphi = 68^\circ$). The result is shown in figure 6. Changing the tilt angle shifts the SPR at longer wavelengths (figure 6 – dot line). The pitch length influences strongly the condition of plasmon resonance (figure 6 – dashed line). Unlike the case of 500 nm this effect is much stronger – the conditions of plasmon resonance could be violated depending on the tilt angle. Observed resonances are very narrow and are not SPR. As in the case of thinner layer, here the pitch length is changed by increasing number of turns at fixed LC layer thickness.

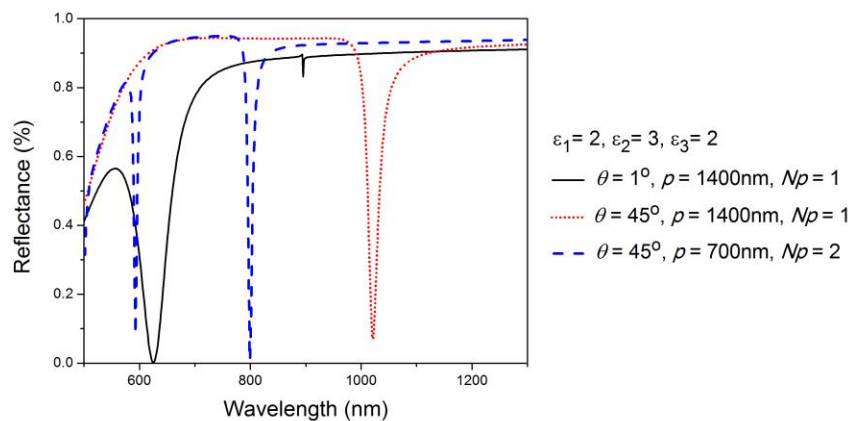


Figure 6. Reflection spectra as a function of wavelength for incident angle $\varphi = 68^\circ$.

The effect of tilt angle variation on SPR excitation is different for different LC layers thickness. This effect is illustrated in figure 7. The resonance shift can be used as criterion for tilt angle determination.

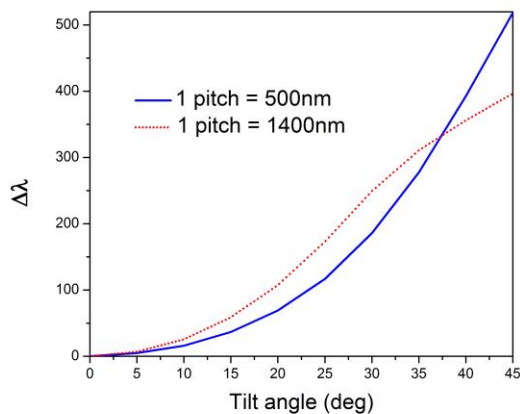


Figure 7. Plasmon resonance shift as a function of tilt angle. Configuration: LC ($\varepsilon_1 = 2$, $\varepsilon_2 = 3$, $\varepsilon_3 = 2$), $p = 500$ nm and $p = 1400$ nm, $Np = 1$ for incident angle $\varphi = 68^\circ$.

3. Discussion

The comparison between ordinary anisotropic layer and LC layer reveal the influence of LC layer feature on SPR: the helical structure slightly shift SPR while its influence on the waveguide modes can be neglected.

Not for all anisotropic layers SPR can be excited – the existence of evanescent field is obligatory and depends on the value of permittivity of different axes. In our geometry (following [17]) the SPR is

not possible for $\varepsilon_x = 2$, $\varepsilon_y = 2$, $\varepsilon_z = 3$. This case can be accomplished for LC molecule with negative anisotropy $\varepsilon_1 = 2$, $\varepsilon_2 = 3$, $\varepsilon_3 = 2$ at tilt angle 90 deg (see figures 2a and 2b and figures 5a and 5b). This effect explains the dependence of SPR wavelength excitation on the tilt angle and can be used for LC characterization (see figures 3, 6, and 7).

The pitch strongly influences SPR excitation conditions – they can be violated as in the case of LC layer with thickness $d = 1400\text{nm}$ (see figure 6). Probably, this is due to Bragg reflection and resonances shown in figure 6 correspond to Bragg reflection of higher order. This problem needs of more careful attention.

4. Conclusion

The reflection spectra of metal/ferroelectric SmC* LC interface as dependence of angle of incidence and wavelength has been theoretically investigated. The results show that, the tilt angle variation of LC changes the condition of SPR excitation including a conversion of plasmon mode to waveguide mode. Increasing the anisotropic layer thickness does not influence SPR, but new waveguide modes appear. SPR wavelength strongly depends on tilt angle variation. Pitch length variation causes SRR wavelength shift, the effect is more expressed for the case of thicker liquid crystal layer. Observed SPR can be used for liquid crystal characterization.

Acknowledgments

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