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Surface plasmon and guided modes excitation of cholesteric liquid crystal layer

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The features of optical excitation of surface plasmon and guided modes in nematic liquid crystal layer (NLCL) are well studied. This problem has never been considered for cholesteric liquid crystal layer (CLCL). There are a lot of open questions, in spite some considerations have been recently performed. The aim of this work is to answer some questions by a theoretical study. A series of guided modes and surface plasmon are excited in CLCL at the condition of attenuated total reflection. The structure we consider has two main differences, compared with the nematic liquid crystal cell: i) the twist angle is a function of layer's thickness; ii) the pitch of the helical structure defines how the wavelength "sees" the refractive index profile of the liquid crystal layer. These special features presume that the critical angles for extraordinary modes are different than that of NLCL. We propose to use "effective critical angle" defined in terms of pitch length. The effective critical angle explains very well the dependence of number of guided modes on tilt angle and on pitch.

Keywords: Surface plasmon, guided mode, chiral anisotropic media

INTRODUCTION

Some early studies have treated the surface plasmon polariton (SPP) behavior at the interface metal layer/nematic liquid crystal (LC). In this context a series of papers of J.R.Sambles has to be acknowledged [1- 9], for example. These studies have been focused not only on SPP features, defined by the adjacent anisotropic medium but on the interaction SPP/guided modes in LC layer. These detailed studies have shown that the coupling SPP/guided mode is very sensitive to the surface director tilt profile near to the metal layer. In all studies nematic LC layer has been used. This is understandable - the nematic LC have been an object of great interest because of their application in LC display - the technology has required a precise knowledge of all LC characteristics.

Recently, the problem has been formulated in opposite direction – is it possible to obtain specific plasmon response by introducing anisotropic dielectric into the plasmon structure [10-14]. Two dimensional rotation of LC on a metal surface was studied in [15] as a first step toward the considering a cholesteric LC. Such kind of analysis was completed in [16] but comprehensive study has yet not been achieved.

Our research [17-19] has focused on the influence of the parameters of chiral anisotropic layer, adjacent to the metal layer, on the plasmon characteristics and on the possibility of controlling plasmon propagation.

Unlike our previous study, this paper is focused on the conditions for guided modes excitation in cholesteric liquid crystal layer and on the interaction plasmon/guided modes. This is the first time to our knowledge that such problem is considered for a chiral anisotropic structure.

THE STRUCTURE

The chosen structure consists in high-index glass prism with a deposed on gold layer, chiral liquid crystal layer, and a low index glass substrate (Fig.1). The prism refractive index must be greater that the highest index inherent to the LC, whereas the lower-index glass substrate must have an index lower than the lowest index inherent to the LC. The LC is uniaxial and specified by permittivities parallel and perpendicular to the director – $\varepsilon_{\parallel}$ and $\varepsilon_{\perp}$, respectively. In such structure there exist a range of incident angle defined by the critical angle of high-index prism and the effective index of the LC and the critical angle of high-index prism and low index substrate. In this range the guided modes

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in LC layer are excited because of evanescent optical field.

We suppose $\varepsilon_{||} > \varepsilon_{\perp}$ ($\Delta\varepsilon = \varepsilon_{||} - \varepsilon_{\perp}$) and the director is defined by tilt θ and twist φ (Fig. 1). The twist in CLCL is a function of thickness φ=f(z). The prism and the substrate are homogeneous with the permittivity ε_1 and ε_3, respectively.

The incidence angles range over which guided modes are excited is [20]:

$$\beta_1 < \beta < \beta_3 \quad (1)$$

Where β_1 and β_3 are critical angles defined as [20]:

$$\beta_1 = \sin^{-1}(\varepsilon_3 / \varepsilon_1)^{1/2} \quad (2)$$

$$\beta_3 = \sin^{-1}\left[\frac{\varepsilon_{||}\varepsilon_{|}}{\{\Delta\varepsilon(\cos(\theta)\cot(\alpha) - \sin(\theta)\sin(\phi))^2 + \varepsilon_{\perp}(1+\cot^2(\alpha))\}|_{\min}}\right]\frac{1}{\varepsilon_1} \quad (3)$$

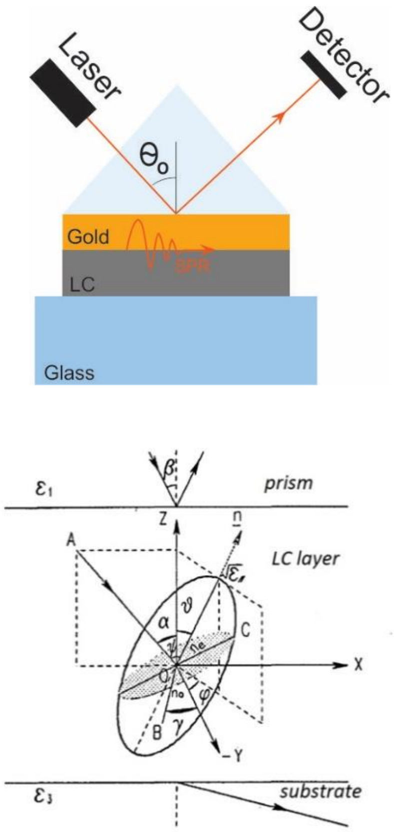

Fig. 1. Configuration of the structure and orientation of the principle axes of the local dielectric tensor ellipsoid defined by Euler angles in some chiral molecular layer.

The first critical angle is defined by the lowest refractive index of the substrate. The second critical angle is defined by the propagation constant of the extraordinary mode. For this mode the refractive index n_e depends on α and φ. While we are interested on the maximum value of the incidence angle, the denominator of (3) has to be minimized for a specific value of α. Thus, the dependence of α is cancel and the critical angle is a function only on tilt and twist.

CRITICAL ANGLE OF CLCL

A point worthy of note is that (3) is in the case of nematic LC. The question now is: how it is possible to extend (3) for chiral structure? We propose an idea to generalize (3) following the physics behind the light propagation in chiral LC. The optical field "seas" the twist structure when the pitch *p* is longer and compatible to the wavelength of incident light (λ = 632 nm). That why it is important to model numerically a CLCL with thickness *d* compatible to the wavelength. For the case *p* = *d* (i.e. $\phi \in [0, 2\pi]$) the optical field will follow the twist of LC molecule. Then, the extraordinary mode has some effective refractive index n_e corresponding to the continuously changed φ in the range 0 - 2π. Consecutively, (3) has to be changed to reflect this feature. Reasonably, the new form of the denominator in (3) is:

$$\int_0^{2\pi}\{\Delta\varepsilon(\cos(\theta)\cot(\alpha) - \sin(\theta)\sin(\phi))^2 + \varepsilon_{\perp}(1+\cot^2(\alpha))\}d\phi \quad (4)$$

then the minimization is provided for (4).

NUMERICAL SIMULATIONS

On the purpose to check our model we simulated guided modes and SPP excitation in nematic and cholesteric LC layer in the structure shown in Fig.1 for different tilt angle as a function of incident angle.

The simulations are based on a theoretical model, obtained by solving Maxwell equations in 4x4 matrix form, for an anisotropic medium [21]. The reflectance of the layered structure for incident p-polarized light, is presented in Fig. 2. For the prism we used permittivity ε_1 = 4.84 and for the substrate ε_3= 2.25. The gold film is with a thickness d_{Au} = 50nm. The permittivity of gold is according [22]. The thickness of LC layer is *d*=620 and the tilt angle is $\theta = 70^0$.

The spectra for nematic layer (Fig. 2a) at twist angle φ=π and φ=2π are the same because the molecule orientations are identical to the lab coordinate system.

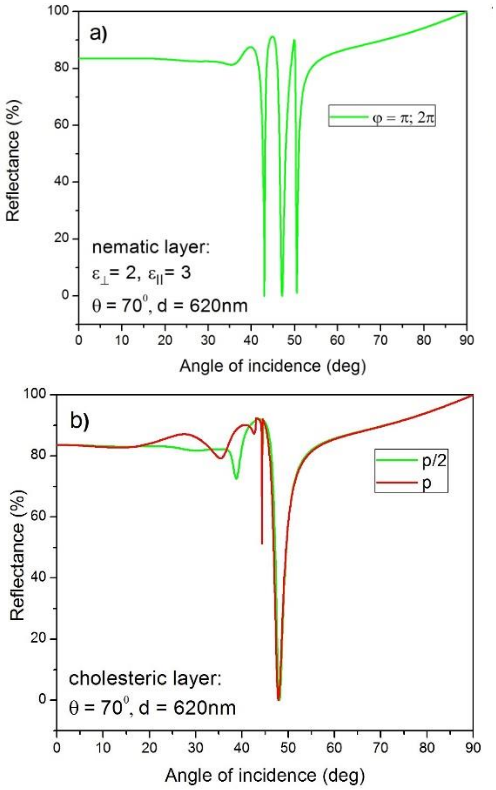

Fig. 2. Reflection spectra of p- polarized light as a function of incident angle for structures with a) nematic and b) cholesteric layer. All other parameters of the structures are identical.

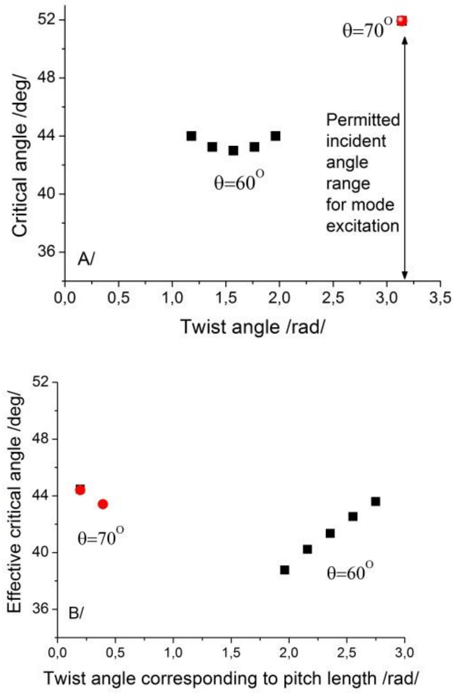

Fig. 3. a) Critical angle as a function of twist angle for nematic layer and b) Effective critical angle as a function of twist angle, corresponding to pitch length, for cholesteric layer at different tilt angles.

For cholesteric layer (Fig. 3b) calculation are performed for half pitch (p/2 - $\phi \in [0, \pi]$) and for one pitch (p - $\phi \in [0, 2\pi]$). The results are compatible with Fig. 2a because the final orientations of molecules are identical. For cholesteric SPP is well observed. The spectra related to the mode excitation are slightly different, in spite the final orientations of molecule are identical, what demonstrate the effect of molecule continuous rotation "seen" by the optical field.

According to our previous results [19] SPP has to be observed in the both structures. It is reasonable to suggest that the guided modes excited in the nematic LC layer mask SPP. Obviously, the conditions for mode excitation in nematic and in cholesteric structures are different. Following the model for the nematic [20] and our model for cholesteric layer expressed by (4), we analyzed the range of incident angle (1). The low limit β_1 is the same for both structures. However, β_2 are different what is shown in Fig.3. The critical angle for nematic structure is close to 52^0 at $\varphi=\pi$ as shown in Fig. 3a. This defines a wide window of incident angles (from 33.8^0 according to (1)) which covers the plasmon resonance angle ($\approx 49^0$). This explains the spectra at Fig. 2a – guided modes are excited and they completely destroy SPP.

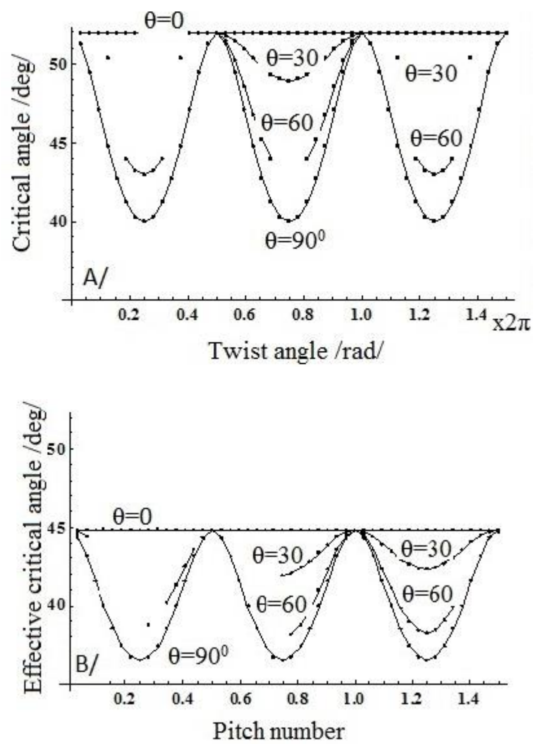

Fig. 4. a) Critical angle as a function of twist angle for different tilt angles for nematic layer; b) Effective critical angles as a function of pitch number for different tilt angles for cholesteric layer.

For cholesteric layer (Fig. 3b) the effective critical angle, calculated according (3) with modified denominator (4) does not exists at half pitch *p*/2. Hence, there is not a range of incident angles for which the mode excitation is permitted. That why the effective excitation of SPP is possible as shown in Fig. 2b. Moreover, this result confirms the correctness of our model for cholesteric structure.

Following our model one can expect that at short pitch length the optical field could not be able to follow the chiral stricture. The extraordinary modes will have some average effective n_e and the dependence on twist angle will be blurred. Hence, one can expect that *p* reduction increases the number of critical angles – the chiral structure is not a limiting factor. Indeed, this is the real behavior as illustrated in Fig. 4. Reasonably, the values of critical angles for nematic structure are symmetric against $\varphi=270^0$, as shown in Fig 4a, because the structure is symmetric. For cholesteric LC layer (Fig. 4b) the behavior is absolutely different – the number of effective critical angles increases with pitch number, as expected. It is worthy to note, that the values of effective critical angle for extraordinary modes in chiral structure are lower than the plasmon resonance angle. Hence, the excitation of SPP in CLCL is more effective than in nematic LC. Also, the range of incident angle for which guided mode excitation is permitted, is shorter than in for NLCL.

CONCLUSION

In this paper we study the conditions for guided modes excitation in CLCL and the interaction plasmon/guided modes. For the purpose we introduce a simple but effective extension of the model about guided modes excitation in NLCL. Our model introduces the “effective critical angle” following the physics behind the light propagation in chiral anisotropic medium. The correctness of the model is proved by numerical simulations regarding the mode and SPP excitation in such structures. We show that it is more effective to excite SPP in CLCL. The reported results are for a fixed tilt angle $\theta=70^0$, only. However, our study showed that different guided mode structures and interaction with SPP can be achieved for numerous tilt angles what can be used for exploration of cholesterc liquid-crystal layers parameters.

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ВЪЗБУЖДАНЕ НА ПОВЪРХНИНЕН ПЛАЗМОН И НАПРАВЛЯЕМИ МОДИ В СЛОЙ ОТ ХОЛЕСТЕРИЧЕН ТЕЧЕН КРИСТАЛ

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(Резюме)

Към момента добре са изучени особеностите на оптичното възбуждане на повърхнинни плазмони и направляеми моди в слой от нематичен течен кристал. Тези особености, обаче, не са изучени за случая на слой от холестеричен течен кристал. Съществуват много проблеми, свързани разпространението на светлина в анизотропна хирална среда, които не са решени, въпреки, че напоследък такива изследвания се провеждат. Целта на тази работа е да се отговори на някои въпроси чрез теоретично изследване. Моделирано е възбуждане на повърхнинен плазмон и направляеми моди в слой от холестиричен кристал при ъгли на падащата светлина, по-големи от ъгъла на пълно вътрешно отражение. Съществуват две съществени различия на структурата, която разглеждаме, от тази с нематичен кристал: 1/ ъгъла на завъртане е функция на дебелина на слоя; 2/ стъпката на хеликса определя до колко светлината с определена дължина на вълната е чувствителна към локалния показател на пречупване на течния кристал. Това предполага, че критичният ъгъл на възбуждане на „необикновените“ моди е различен от същия за нематичен слой. Ние възвеждане понятието „ефективен критичен ъгъл“, дефинирано в термините на дължина на стъпката на хеликса. Този ъгъл описва много добре зависимостта на броя на възбудените моди от ъгъла на наклона на молекулите и от стъпката на хеликса.