Controlled Photonic Surface Modes in 'Cholesteric Liquid Crystal — Phase Plate — Metal' Structure

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Abstract— Light transmission spectrum has been calculated for a 'cholesteric liquid crystal-phase plate-metal' structure. It is shown that the system can have an isolated waveguide surface mode with characteristics efficiently controllable by external fields acting on the cholesteric. This mode is similar to optical Tamm state. We observed anisotropy of transmission of the structure under consideration in the propagation of light of a certain polarization in forward and backward directions. This property is inherent in optically chiral media, such as the cholesteric liquid crystal.

1. INTRODUCTION

Surface electromagnetic waves in photonic crystals have long attracted the attention of researchers [1]. Optical Tamm state (OTS) is especially promising surface phenomenon. This state is electromagnetic analogue of the Tamm electronic state in solid state physics. OTS can be excited between two different photonic crystals having overlapping band gaps [2] or between a photonic crystal and a medium with negative dielectric constant [3, 4]. This state can be observed when incident waves are normal to the PC layers. Experimentally, OTS appears in the form of a narrow resonance in the spectra of reflection and transmission [5].

In recent years the series of devices based on OTS was proposed and carried out: optical switches [6], multichannel filters [7], organic solar cells [8], absorbents [9] and others. Recently the OTS laser structure was proposed and experimentally realized. It consists of quantum wells embedded in a Bragg reflector whose surface is covered with a layer of silver [10].

Most of the proposed devices have the disadvantage that they are not tunable. Correcting of this deficiency is possible using materials with spectral properties controlled by external fields. One such promising photonic material is a cholesteric liquid crystal (CLC). Applying external fields (electric, magnetic, ultraviolet radiation) can change the position of the Bragg reflection band of this material [11, 12]. A characteristic feature of the CLC is the strong dependence of its properties on the polarization of light. In CLC there is a photonic band gap for light propagating along the CLC helix with a circular polarization coinciding with the twist of the CLC helix. Light of opposite circular polarization does not undergo diffractive reflection and passes through the CLC medium almost unaffected., The light wave of such polarization does not change the sign of its polarization when reflected from CLC.

2. RESULTS AND DISCUSSION

In this Paper, we show a possibility to realize optical surface states, similar to optical Tamm states, in a structure with CLC [13] and study their characteristics unique to chiral media. Unlike the case with OTS observed at a PC — metal interface, we could not to obtain a surface state at a CLC — metal interface under normal incidence of light. The one difficulty is to change wave polarization reflected from the metallic surface. The other difficulty is that Bragg reflection exists not for every arbitrary polarization. For light localization between CLC and metal to occur, we need to change the phase of the wave. To this end, between CLC and metal we introduce an anisotropic quarter-wave plate cut parallel to the optical axis and shifting the wave phase by $\pi/2$. Cholesteric molecules at the CLC — phase plate interface align along the optical axis. The proposed structure is shown in Fig. 1. The system consists of a CLC layer of thickness L, phase plate of thickness d and refractive coefficients n'_e, n'_o, such that $2\pi(n'_e - n'_o)d/\lambda = \pi/2$, and metal.

Optical properties and field distribution in the structure were numerically analyzed on the basis of Berreman's 4×4 transfer matrix for normal incidence [14]. Light propagating along z axis with frequency ω is given by

$$\frac{d\Psi}{dz} = \frac{i\omega}{c}\Delta(z)\Psi(z), \tag{1}$$

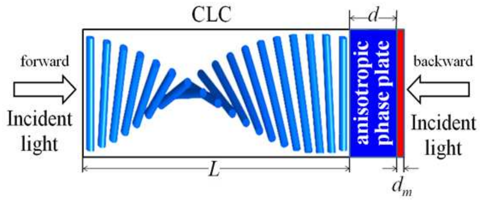

Figure 1: Schematic of the 'CLC – phase plate — metal' structure.

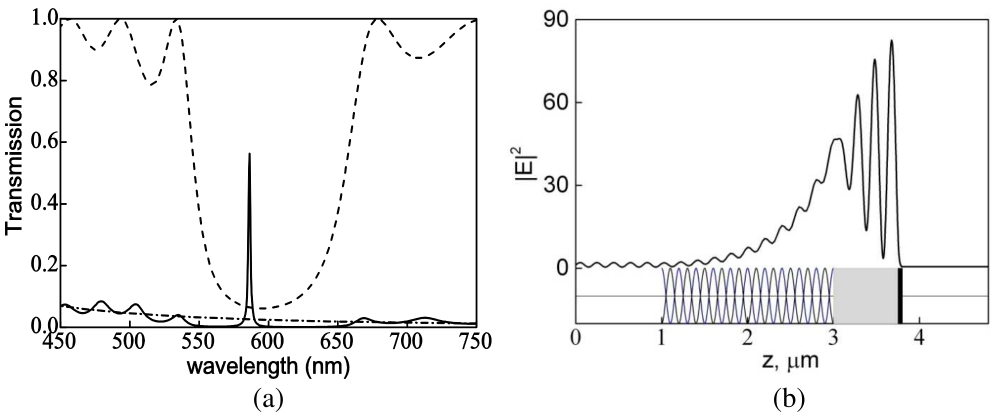

Figure 2: (a) Transmission versus wavelength with light incidence normal to CLC (dashed line), to the silver film (dash-dotted line) and to the 'CLC — phase plate — metal' structure (solid line). (b) Distribution of the squared modulus of the electric field intensity $|E(z)|^2$ in the 'CLC — phase plate — metal' structure for $\lambda = 586.5\,\text{nm}$. Field is normalized to the input field equal to unity.

where $\Psi(z) = (E_x, H_y, E_y, -H_x)^T$ and $\Delta(z)$ is the Berreman matrix dependent on the dielectric function and incident wave vector.

The parameters used in this study are as follows: ordinary and extraordinary refractive indices of the phase plate and CLC were taken to be $n_o = 1.4$ and $n_e = 1.6$, respectively. The CLC layer helix is right handed and there is a photonic band gap for light with right-hand, diffracting polarization. The pitch is $p = 0.4\,\mu\text{m}$, thickness of the CLC layer is $L = 2\,\mu\text{m}$, thickness of the phase plate is $d = 0.75\,\mu\text{m}$. The phase plate is coupled with a silver film having the thickness $d_m = 50\,\text{nm}$. The permittivity of silver can be expressed as the Drude model:

$$\varepsilon(\omega) = \varepsilon_0 - \frac{\omega p^2}{\omega(\omega + i\gamma)}, \tag{2}$$

where $\varepsilon_0 = 5$ is the background dielectric constant, $\hbar\omega_p = 9\,\text{eV}$ is the plasma frequency, and $\hbar\gamma = 0.02\,\text{eV}$ is the plasma collision rate.

Figure 2(a) shows individual transmission spectra of the CLC, silver film and the structure under consideration. The CLC transmission spectrum clearly exhibits a band gap for right-hand circular polarization of light. The figure shows that a peak of the waveguide surface mode in the transmission spectrum (solid line) occurs when an anisotropic quarter-wave plate controlling the phase of light waves is introduced between CLC and metal. Fig. 2(b) shows distribution of the electric field for the wavelength corresponding to maximum transmission in the 'CLC — phase plate — metal' structure shown in Fig. 2(a). Attenuation of the field of the localized mode inside metal is associated with negative permittivity of the metal film whereas inside CLC it is associated with Bragg reflection at the CLC — phase plate interface.

By varying parameters of the system we can control position of the transmission peak via an isolated surface waveguide mode. Strong dependence of the helical pitch, e.g., on temperature, as compared to other structural elements, can be used to effectively control frequency of the transmission peak associated with tunneling of light through the surface state.

Figure 3 shows the reflection spectrum versus the period of the CLC. It can be seen that the peak shift to longer wavelengths is almost directly proportional to the increase of the period.

Now consider the propagation of light through the sample in the backward direction when the light is incident normally on the metal layer at the right side in Fig. 1. When light propagates in the forward direction transmittance for light diffracting right polarization is equal to 0.57, in the opposite direction the transmittance is equal to 0.34. Thus, we observe the anisotropy of the transmission (Fig. 4). It should be noted that this effect is essentially impossible in scalar structures.

To understand the mechanism of occurrence of this effect, consider the evolution of the polarization of light falling on the CLC and metal. Both cases are shown in Fig. 5.

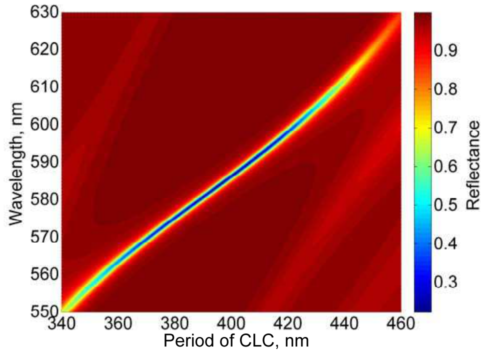

Figure 3: The reflection spectrum of structures for different periods of the cholesteric helix.

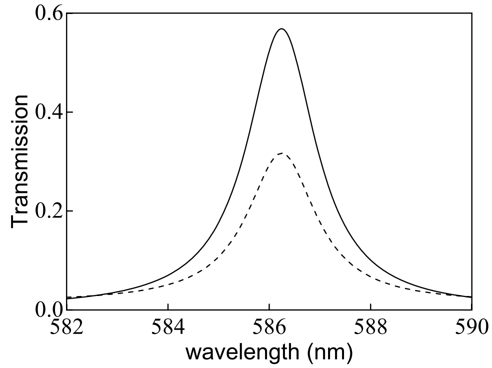

Figure 4: The transmission spectrum of the structure for the right circular polarization: solid line — for light incident on the CLC; dashed line — for light incident on the metal.

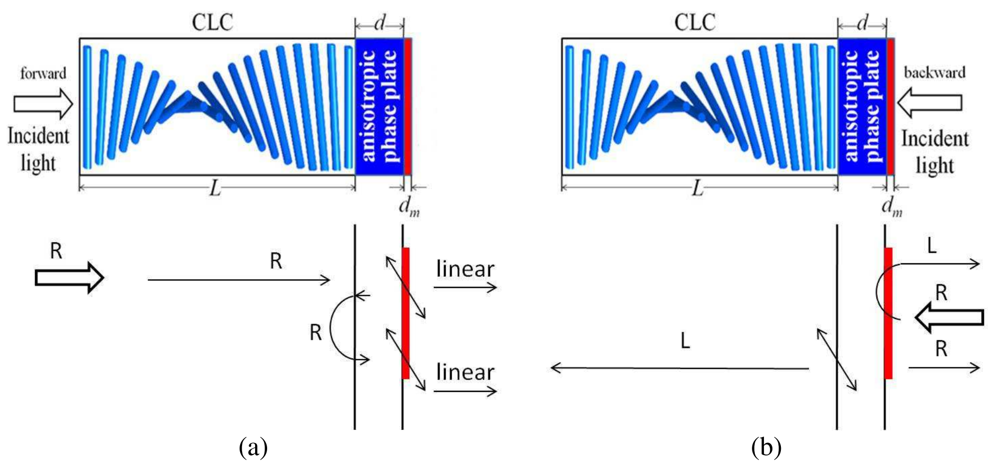

Figure 5: The evolution of polarization for light incident on the (a) CLC and (b) metal, R — right-hand circular polarization, L — left-hand circular polarization, linear — linear polarization.

If at the thin layer of CLC the diffracting right-handed polarized light falls down, it keeps its polarization at the output of the CLC. After passing through the quarter-wave plate, the light becomes linearly polarized. The unabsorbed part of the light comes out of metal layer. Upon reflection from the metal the linear polarization is concerved. After have passed through the plate in the opposite direction, the light gets the right-handed circular polarization. When reflected from CLC the light retains the right-handed circular polarization. Again the light of linear polarization comes out of the metal layer (Fig. 5(a)).

When light is incident on the metal (Fig. 5(b)), the situation is qualitatively different. In this case, the half of the light, unabsorbed and unreflected from the metal layer, is reflected from the cholesteric layer because it is linearly polarized.

For this reason, the structure considered in this paper may be used as a polarizing optical diode. The advantage of this optical diode is its tunability and ease of manufacture, as it consists of just three elements.

3. CONCLUSION

In summary, we have demonstrated existence of surface electromagnetic states localized in the system containing CLC as a structural element. Spectral properties of such a system can be efficiently controlled due to high sensitivity of CLC structural parameters to external factors. Because of changes in polarization of the wave reflected from metal and because of special polarization properties of CLC we have to use a phase plate between CLC and the metal layer. A possibility to control the passband position by varying the thickness of the CLC pitch by external fields has been demonstrated. We also note that the resultant surface mode is essentially an eigenmode of the microcavity where CLC layer and the metal film act as mirrors. Consequently, it is possible to realize lasing in a microcavity using optically active material as a phase plate.

It was established that the transmission spectra of the propagation of light in the forward and backward direction are different. This property is inherent in optically chiral media, which include CLCs. On this basis, we proposed the construction of the polarization of the optical diode based on surface photon modes.

Note also that it is hard to create direct contact between CLC and metal. This requires the use of orientant which is a layer of anisotropic material. Therefore orientant can simultaneously be a quarter phase plate, picking up the thickness correspondent to the localized state.

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