Surface modes in "photonic cholesteric liquid crystal–phase plate–metal" structure

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The 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. The degree of localization of surface modes and the transmission coefficients have been found to differ considerably for the light of different polarizations. © 2014 Optical Society of America

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In recent years, along with the bulk properties [1], there has been extensive research on surface electromagnetic waves in one-dimensional photonic crystals (PCs) [2]. In addition to propagating surface waves, it is possible to obtain a state in the form of a standing surface wave that will have a zero wave number along the surface and will not transfer any energy. This state can be observed when incident waves are normal to the PC layers [3,4]. In that case, Maxwell's equation for the electric field will be an exact analogue of the one-electron Schrödinger equation for a semi-infinite crystal, which is resolved as a Tamm surface state. Therefore, an electromagnetic analogue of the Tamm electronic state is called an optical Tamm state (OTS), or alternatively, a Tamm plasmon polariton. OTS can be excited between two different PCs having overlapping band gaps [5,6] or between a PC and a medium with negative dielectric constant [3,7]. At the Tamm state frequency, a narrow transmittance peak is observed arising from tunneling of light through the Tamm state.

The range of potential applications of interface modes and OTS includes sensors and resonant optical filters [4], polariton lasers [8], optical switchers [9], multichannel filters [10], Faraday rotation amplifiers [11], Kerr effect amplifiers [12], organic solar cells [13], and absorbers [14]. A number of various devices using Tamm plasmons have been proposed and experimentally realized recently, e.g., a laser based on the Tamm structure in [15]. The underlying structure consists of quantum wells embedded in a Bragg reflector surface coated with a silver layer. In [16], the authors observed hybrid states in the organic microcavity with an embedded silver layer. These states were due to coupling between photon modes of the cavity and Tamm plasmons. A parabolic dispersion dependence of hybrid states was obtained experimentally. Also observed was splitting of orthogonally polarized resonances. The experimental results were confirmed numerically and on the basis of the developed analytical model. A possibility of lasing in a microcavity with two metal layers placed inside an active region is shown theoretically in [17]. A region of optically active organic material is confined between two layers of silver and surrounded by Bragg reflectors. Microcavity eigenmodes are formed with participation of Tamm plasmons. To observe the lasing, low attenuation of the microcavity optical eigenmode was achieved by using metal layers in the nodes of the electric field of the optical mode. Metal layers inside the resonator can serve as contacts for the laser electrical pumping.

An important challenge of PC optics is to invent new materials with parameters that would be easily controllable by external factors. Cholesteric liquid crystals (CLCs) are a special class of one-dimensional chiral PCs exhibiting unique properties such as a wide passband, strong nonlinearity, and high sensitivity to external fields [18,19]. These structures are formed by highly anisotropic elongated molecules. Because of the chirality, molecules tend to form a spiral structure. The spatial modulation of permittivity in CLC is associated with reorientation of anisotropic liquid crystal molecules. Long molecular axes are orthogonal to the helical axis of CLC. The structure period equal to half the pitch of the helix may be comparable with the light wavelength. The difference between extraordinary n_e and ordinary n_o refractive indices is a measure of optical anisotropy in CLC. The characteristic feature of chiral liquid crystals is the strong dependence of their properties on polarization of light. For normal incidence, that is when light propagates along the helix axis, there is an exact solution of Maxwell's equations. It is well known that there is a photonic band gap for light with the same direction of circular polarization as the CLC twist. Light with a frequency in the band gap cannot propagate and is reflected. The Bragg reflection region, or alternatively the bandgap region, lies in the wavelengths range between $\lambda_1 = pn_o$ and $\lambda_2 = pn_e$, where p is the helical pitch of the CLC.

In this Letter, we show the possibility of realizing optical surface states in a structure with CLC. Unlike the case with OTS observed at a PC–metal interface, it does not seem possible 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 does not exist for some polarizations. For light

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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. The structure is surrounded by a medium with the refractive index n equal to the average refractive index of CLC. For the case under consideration $n'_o = n_o$, $n'_e = n_e$ Fresnel reflection from the CLC–metal interface is assumed to be negligibly weak.

Optical properties and field distribution in the structure were numerically analyzed on the basis of Berreman's 4×4 transfer matrix for normal incidence [20,21]. Light propagating along the z axis with frequency ω is given by

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

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 $p = 0.4$ μm, thickness of the CLC layer is $L = 2$ μm, and thickness of the phase plate is $d = 0.75$ μm. The phase plate is coupled with a silver film having the thickness $d_m = 50$ nm. The permittivity of silver can be expressed as the Drude model

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

where $\varepsilon_0 = 5$ is the background dielectric constant, $\hbar\omega_p = 9$ eV is the plasma frequency, and $\hbar\gamma = 0.02$ eV is the plasma collision rate [22]. For the assumed CLC parameters, the band gap is between 560 and 640 nm.

Figure 2 shows the individual transmission spectra of the CLC, silver film, and the structure under consideration (Fig. 1). The CLC transmission spectrum clearly exhibits a band gap for right-hand circular polarization of light. The transmission spectrum of the silver film is designated by a dashed line. 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. 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. For the given plate thickness, the maximum transmission coefficient is 0.57. It should be noted that the wavelength of the localized mode is very sensitive to the phase plate thickness. For example, even for $d = 0.78$ μm the mode frequency is shifted by 13.5 nm.

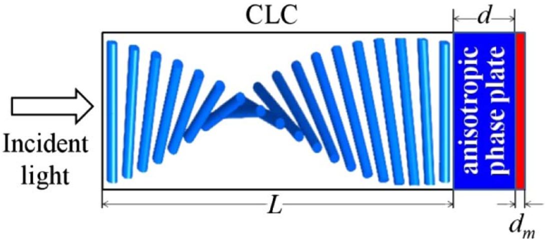

Fig. 1. Schematic of the "CLC–phase plate–metal" structure.

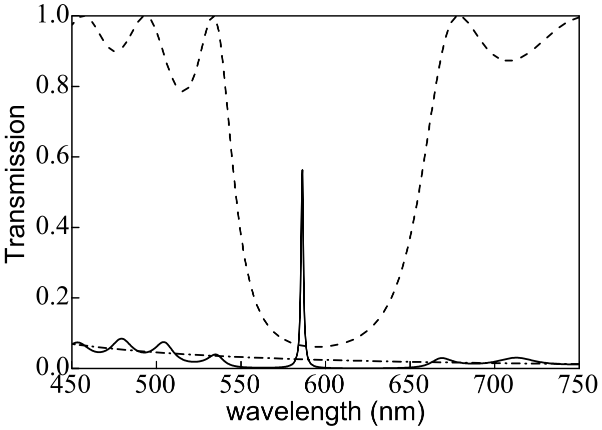

Fig. 2. Transmission versus wavelength with light incidence normal to CLC (dashed line), to the silver film (dash-dotted line), and to the "CLC–phase plate–metal" structure (solid line).

Figure 3 shows the distribution of the electric field for the wavelength corresponding to maximum transmission in the "CLC – phase plate – metal" structure shown in Fig. 3. Light is localized near the metal film and the highest electric field is observed at the phase plate–metal interface.

We have found that a localized mode is excited in the sample, to a different extent, by light of various polarizations. This can be explained by polarization conversion at the dielectric border. Any polarization of the light transmitted through CLC will be slightly elliptical compared to the initial polarization. Figure 4 shows transmission

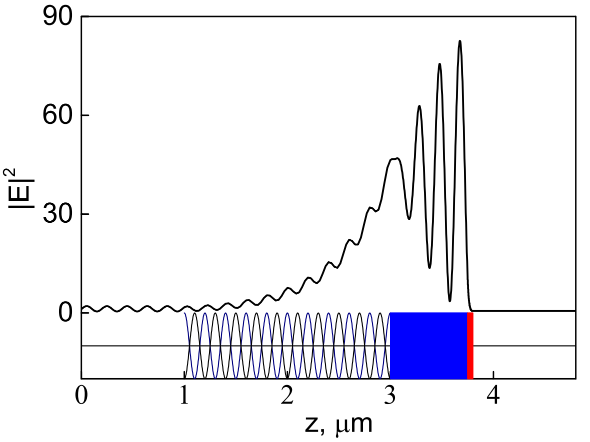

Fig. 3. Distribution of the squared modulus of the electric field intensity $|E(z)|^2$ in the "CLC–phase plate–metal" structure for $\lambda = 586.5$ nm. Field is normalized to the input field equal to unity.

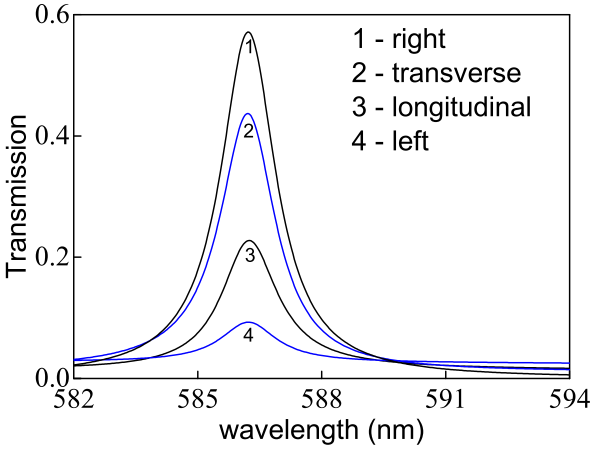

Fig. 4. Transmission spectra associated with different polarizations of light tunneling through the localized mode. The parameters are the same as in Fig. 2.

spectra in the localized mode for four typical polarizations of light, namely two circular polarizations (right and left) and two linear polarizations (with polarization plane transverse or longitudinal to the orientation of the molecules at the entrance to the cholesteric sample).

By varying parameters of the system we can control the 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 (Fig. 5).

Another possible option for control is the angle of light incidence on the sample. If the angle of incidence is different from zero, then there will be a nonzero wave vector in the direction tangent to layers of the structure. Therefore the surface mode turns into a propagating mode. Because of Bragg's law, the photonic band gap shifts to shorter wavelengths and becomes deformed with the increasing angle of incidence on CLC. Depending on the angle, there may appear a band gap for nondiffracting polarization [18]. The surface mode shifts with the band gap.

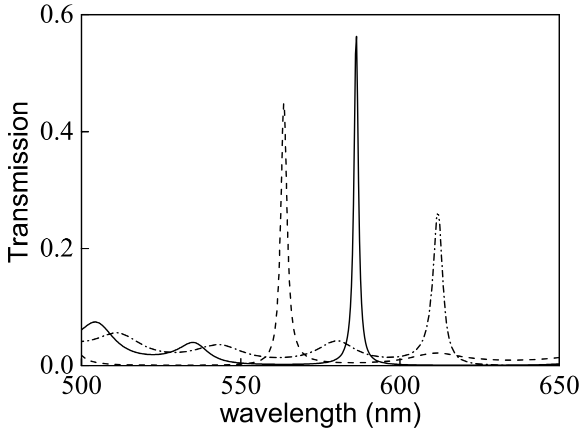

Fig. 5. Transmission spectrum of the "CLC–phase plate–metal" structure for different pitch of the CLC, $p = 0.4$ μm (solid line), $p = 0.36$ μm (dashed line), and $p = 0.44$ μm (dashed–dotted line).

The transmission coefficient of a surface mode depends on the thickness of CLC. An increased thickness will result in a decreased transmittance and a narrower width of the passband. The obtained dependence can be interpreted as an increase in the quality factor of the microcavity associated with increasing of the CLC layer.

In summary, we have demonstrated the 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. Light of any polarization will be localized near metal with the field intensity maximizing at the phase plate–metal layer interface. However, different degrees of ellipticity of transmitted waves and their polarization properties result in different transmission coefficients for each polarization. A possibility to control the passband position by varying the thickness of the phase plate or 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.

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