Journal of Optics

PAPER

# Spectral and polarization properties of a ‘cholesteric liquid crystal—phase plate—metal’ structure

To cite this article: S Ya Vetrov *et al* 2016 *J. Opt.* **18** 015103



IOP Publishing Journal of Optics
J. Opt. 18 (2016) 015103 (7pp) doi:10.1088/2040-8978/18/1/015103

# Spectral and polarization properties of a 'cholesteric liquid crystal—phase plate—metal' structure

S Ya Vetrov[1,2], M V Pyatnov[2] and I V Timofeev[1,3]

[1] L V Kirensky Institute of Physics, Siberian Branch of the Russian Academy of Sciences, Krasnoyarsk 660036, Russia
[2] Institute of Engineering Physics and Radio Electronics, Siberian Federal University, Krasnoyarsk 660041, Russia
[3] Laboratory for Nonlinear Optics and Spectroscopy, Siberian Federal University, Krasnoyarsk 660041, Russia

E-mail: MaksPyatnov@yandex.ru

Received 6 August 2015, revised 4 November 2015
Accepted for publication 11 November 2015
Published 11 December 2015

**Abstract**

We investigate the localized surface modes in a structure consisting of the cholesteric liquid crystal layer, a phase plate, and a metal layer. These modes are analogous to the optical Tamm states. The nonreciprocal transmission of polarized light propagating in the forward and backward directions is established. It is demonstrated that the transmission spectrum can be controlled by external fields acting on the cholesteric liquid crystal and by varying the plane of polarization of the incident light.

Keywords: photonic band gap materials, cholesteric liquid crystals, localized states, optical filters, optical waveguides

(Some figures may appear in colour only in the online journal)

## 1. Introduction

The surface electromagnetic states in photonic-crystal structures have been attracting the attention of researchers for a long time [1]. In recent years, there has been an increased interest in a special type of localized electromagnetic states excited at the normal incident of light, which are called the optical Tamm states (OTSs) [2]. Such states are analogous to the Tamm surface states in condensed matter. They can be excited between two different photonic crystals with overlapping band gaps [3] or between a photonic crystal and a medium with negative permittivity $\varepsilon$ [4, 5]. In experiments, the OTS manifests itself as a narrow peak in the transmission spectrum of a sample [6, 7].

The surface modes and OTSs are promising for applications in sensors and optical switches [8], multichannel filters [9], Faraday- and Kerr-effect amplifiers [7, 10], organic solar cells [11], and absorbers [12]. Symonds *et al* [13] experimentally demonstrated a laser based on the Tamm structure consisting of quantum wells embedded in a Bragg reflector with a silver-coated surface. Gazzano *et al* experimentally showed the possibility of implementing a single-photon source on the basis of confined Tamm plasmon modes [14]. Several studies have investigated the optical Tamm states in magnetophotonic crystals [7, 15–17]. The hybrid states were studied in [18–21]. Gester *et al* investigated the electro-optically tunable Tamm plasmon exciton polaritons [22]. Savelev *et al* [23] predicted that the edges of a finite one-dimensional array of dielectric nanoparticles with a high refractive index could support evanescent OTSs.

Treshin *et al* [24] proposed and implemented the extremely high efficiency transmission of light through a nanohole in a gold film, when the hole was placed in the light field at the interface between the film and a one-dimensional photonic crystal. This effect is related to the field amplification at the interface between the superlattice and the metal film due to the occurrence of the OTS.

An important problem in optoelectronics is the fabrication of materials with spectral properties controlled by external factors. A special class of one-dimensional photonic

 

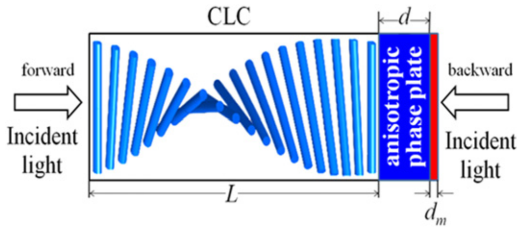


**Figure 1.** Schematic of the CLC layer–phase plate–metal layer structure.

crystals is formed by cholesteric liquid crystals (CLCs), which have unique properties: a wide passband, strong nonlinearity, and high sensitivity to external fields [25, 26]. By varying temperature and pressure and by applying electromagnetic fields and mechanical stresses, one can, e.g., vary the cholesteric helix pitch and, consequently, the band gap position. A qualitative difference between CLCs and other kinds of photonic crystals (PCs) is that their diffraction reflectivity is selective to polarization. Circularly polarized light propagating along the helix normal, with the polarization direction coinciding with the direction of rotation of the CLC, experiences Bragg reflection. The Bragg reflection occurs in the wavelength range between $\lambda_1 = pn_o$ and $\lambda_2 = pn_e$, where $p$ is the helix pitch and $n_o$ and $n_e$ are the ordinary and extraordinary refractive indices of the CLC, respectively. This circular polarization is called diffracting. Light with the opposite circular polarization does not experience the Bragg reflection. This polarization is called nondiffracting.

In our previous study [27], we demonstrated the possibility of the implementation of localized surface states in a structure with the CLC. These states are analogous to the OTSs for scalar structures. We failed to obtain the surface state at the CLC/metal interface at the normal incidence of light. The difficulty is due to the wave polarization change upon reflection from a metal and to the existence of Bragg reflection for a certain polarization. To localize light, it is necessary to change the wave phase between the CLC and metal. To do so, we proposed to use a quarter-wave phase plate.

In this study, we continue investigations of the properties of OTSs in the system with a CLC. We demonstrate the effects that take place during propagation of light in the backward direction. We investigate the transmission spectra upon variation in the CLC helix pitch and calculate the transmission spectra for the linearly polarized radiation.

## 2. Model description and determination of transmission

The investigated structure consists of a thin right-hand CLC layer, a quarter-wave anisotropic plate, and a metal film (figure 1). The plate is cut parallel to the optical axis and shifts the wave phase by $\pi/2$. At the interface between the CLC and the phase plate, the cholesteric director, i.e., the preferred direction of molecules, is oriented along the optical axis. The CLC layer thickness is $L = 2\ \mu$m, the helix pitch is $p = 0.4\ \mu$m, and the ordinary and extraordinary refractive indices are $n_o = 1.4$ and $n_e = 1.6$, respectively. The phase plate thickness is $d = 0.75\ \mu$m, and its refractive indices are $n'_o = n_o$ and $n'_e = n_e$. The parameters of the phase plate satisfy the relation

$$2\pi\left(n'_e - n'_o\right)d/\lambda = \pi/2 \tag{1}$$

The phase plate is coupled with a silver film with thickness $d_m = 50$ nm. The permittivity of the metal is specified in the form of the Drude approximation

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

where $\varepsilon_0 = 5$ is the constant that takes into account the contribution of interband transitions of bound electrons, $\hbar\omega_p = 9$ eV is the plasma frequency, and $\hbar\gamma = 0.02$ eV is the reciprocal electron relaxation time [28]. The structure is surrounded by a medium with refractive index $n$ equal to the average refractive index of the CLC.

The optical properties and field distribution in the structure were numerically analyzed using a 4 × 4 Berreman transfer matrix at the normal incidence of light on the sample [29, 30]. The equation describing the propagation of light with frequency $\omega$ along the $z$ axis of the cholesteric is

$$\frac{d\Psi}{dz} = \frac{i\omega}{c}\Delta(z)\Psi(z), \tag{3}$$

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

## 3. Results and discussion

### 3.1. Optical localized states

In our previous paper [27], the transmission spectrum of the structure under consideration was shown. Figure 2(a) shows the maximal transmittance at a wavelength corresponding to the localized state at different thicknesses of the metal $d_m$. The inset shows the transmission spectrum of the CLC and the entire structure at $d_m = 50$ nm. The Bragg reflection region lies between 560 and 640 nm. At these wavelengths, the real part of the permittivity of silver is negative. At the wavelength corresponding to the CLC band gap, a narrow transmission peak is observed. The electric field intensity distribution in the sample for the diffracting polarization is illustrated in figure 2(b). The light is localized near the metal film with the maximum electric field value at the interface between the phase plate and metal. The decay of the localized mode field in the metal is caused by the negative permittivity of the metal film, while the decay of this field in the CLC is caused by Bragg reflection at the CLC/plate interface.

Consider the occurrence of localization between the CLC and the metal (figure 3). First, we explain why the light cannot be localized between the CLC and the metal without the quarter-wave phase plate.

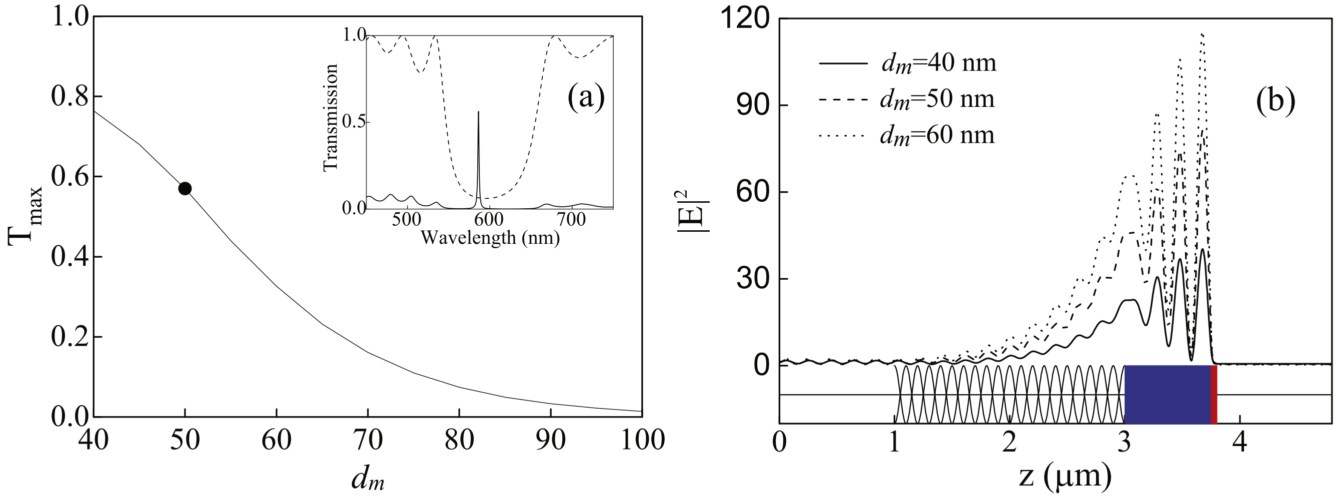


**Figure 2.** (a) Transmission coefficients at a wavelength corresponding to localized state ($\lambda = 586$ nm) for different values of the thickness of the metal film $d_m$. The inset shows the transmission spectrum of a cholesteric liquid crystal (dashed line), and the entire structure (solid line) with $d_m = 50$ nm. (b) Spatial distribution of the field local intensity in the sample normalized to the input value for three values of $d_m$ ($\lambda = 586$ nm).

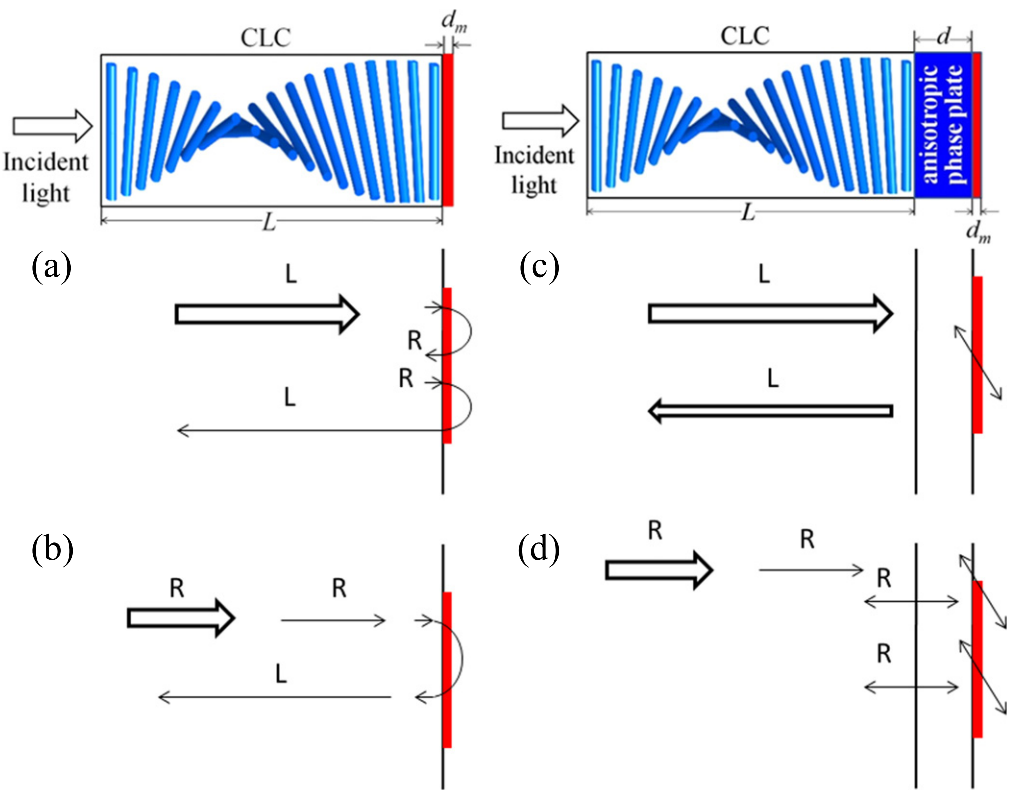


**Figure 3.** Localization of light for right-hand (R) and left-hand (L) polarizations in the structures consisting of (a), (b) the CLC and metal layers and (c), (d) the CLC layer, phase plate, and metal layer.

We will investigate four cases:

(1) The left-hand circularly polarized light enters the CLC and passes through it freely. Upon reflection from the metal, left-hand circular polarization transforms into right-hand circular polarization. Upon reflection from the CLC, the right-hand circular polarization is retained. Upon repeated reflection from the metal, right-hand circular polarization transforms into left-hand polarization and the light propagates backward through the crystal (figure 3(a)).

(2) The right-hand diffracting-polarized light enters the CLC. Part of the light passed through the CLC retains its polarization, but upon reflection from the metal the right-hand circular polarization transforms into left-hand circular polarization and the light passes freely through the CLC structure in the backward direction (figure 3(b)).

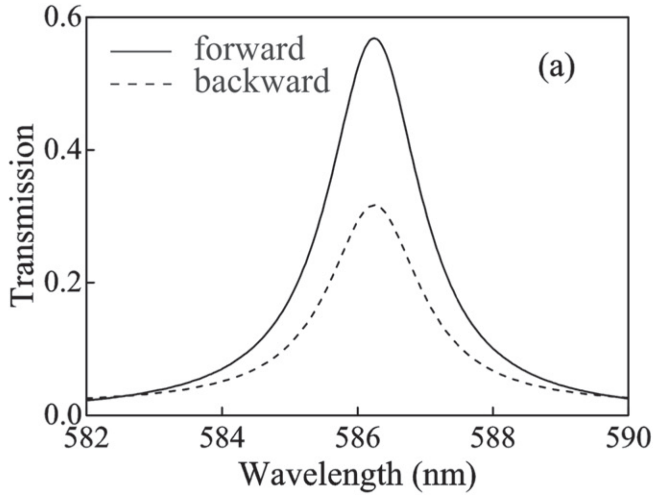


**Figure 4.** Transmission spectrum of the structure for incident waves with (a) right-hand and (b) left-hand circular polarization. The solid line corresponds to the forward incidence on the CLC, and the dashed line to the backward incidence on the metal.

Now consider the effect of the quarter-wave plate on the polarization of light.

(3) The left-hand circularly polarized light enters the CLC. The light passes freely through the CLC. The light passed through the plate acquires linear polarization. Upon reflection from the metal, the linear polarization is retained. The light passed through the plate in the backward direction acquires left-hand circular polarization. After that, the light propagates backward through the CLC (figure 3(c)).
(4) The right-hand diffracting-polarized light enters the CLC. Part of the light passed through the CLC retains its polarization. The light passed through the plate acquires linear polarization. Upon reflection from the metal, the linear polarization is retained. The light passed backward through the plate acquires right-hand circular polarization. Upon repeated reflection from the CLC, the light retains its right-hand circular polarization (figure 3(d)). Thus, the light is localized between the CLC and the metal.

### *3.2. Transmission nonreciprocity*

For a long time, the cholesteric liquid crystals have been attracting the attention of researchers who want to effectively manipulate light. One of the promising effects in structures consisting of CLCs and anisotropic elements is the different transmission spectra for light of a certain polarization propagating in the forward and backward directions. This phenomenon was demonstrated, in particular, by Hwang *et al* [31]. The authors proposed an electric-field-tunable optical diode based on two identically twisted CLCs separated by the nematic liquid crystal layer. In these diodes, the transmission spectra for diffracting-polarized light propagating in the forward and backward directions were qualitatively different.

We established that the analogous effect takes place in the investigated model. Figure 4 presents the transmission spectra of the structure at the wave incidence on the CLC and on the metal film for right- and left-hand circularly polarized light. When light with the diffracting polarization propagates forward, the transmittance is 0.57; when it propagates backward, the transmittance is 0.34. Thus, we deal with transmission nonreciprocity. It was observed that when left-hand circularly polarized light enters the structure, its spectrum changes. The transmittances in the forward and backward directions are 0.09 and 0.32, respectively. It should be noted that this effect cannot be implemented in scalar structures.

To elucidate the origin of this effect, we consider the light polarization dynamics at the incidence on the CLC (figures 5(a) and (b)) and on the metal (figures 5(c) and (d)).

When light with right-hand diffracting polarization enters the CLC, part of the light passed through the crystal approximately retains its polarization at the CLC output. After passing through the quarter-wave plate, the light acquires linear polarization. The unabsorbed part of light leaves the metal. Upon reflection from the metal, the linear polarization is retained. After passing backward through the metal, the light acquires right-hand circular polarization. Upon repeated reflection from the CLC, the light retains its right-hand circular polarization. Again, the linearly polarized light leaves the metal (figure 5(a)).

For the backward incidence of light (figure 5(c)), the situation is qualitatively different. It appears that half of the light that is not absorbed by or reflected from the metal is reflected from the cholesteric layer due to the linear polarization.

The situation is similar for the nondiffracting left-hand polarization (figures 5(b) and (d)). Since at the incidence of light on the metal, light with both circular polarizations propagates similarly, we can expect that the transmittances corresponding to the OTSs for the left- and right-hand polarizations will almost coincide, which was confirmed by our calculations (figure (4)).

The structure under study can be used as a polarization optical diode. The advantages of this optical diode are its tunability and ease of manufacture, since it consists of only three elements.

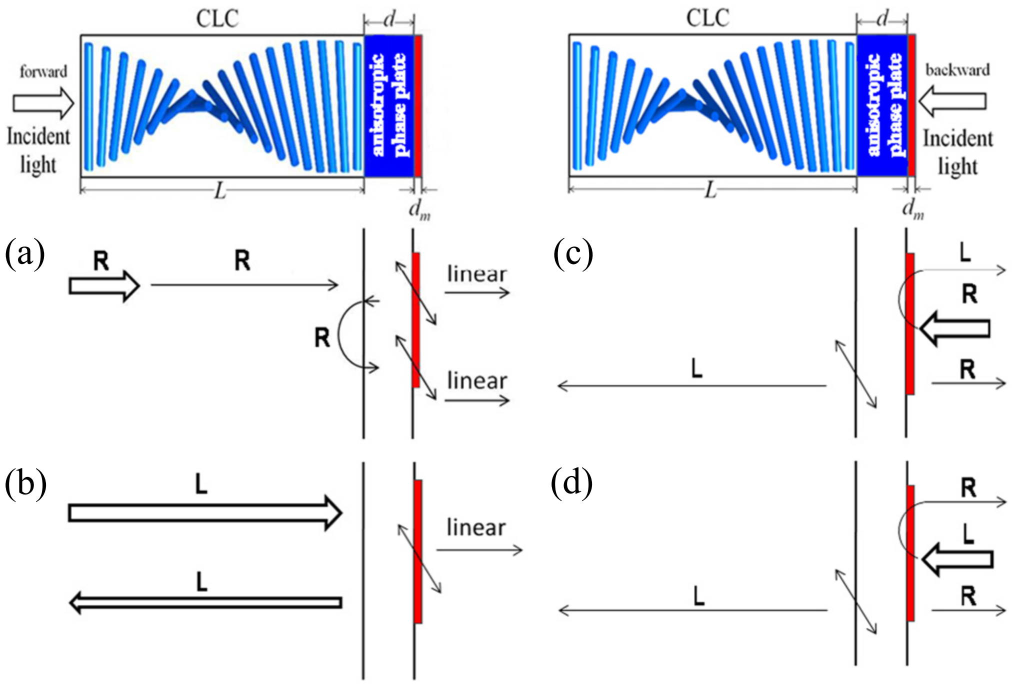


**Figure 5.** Light polarization dynamics at the incidence (a), (b) on the CLC and (c), (d) on the metal. R and L are the right- and left-hand circular polarization and 'linear' is the linear polarization.

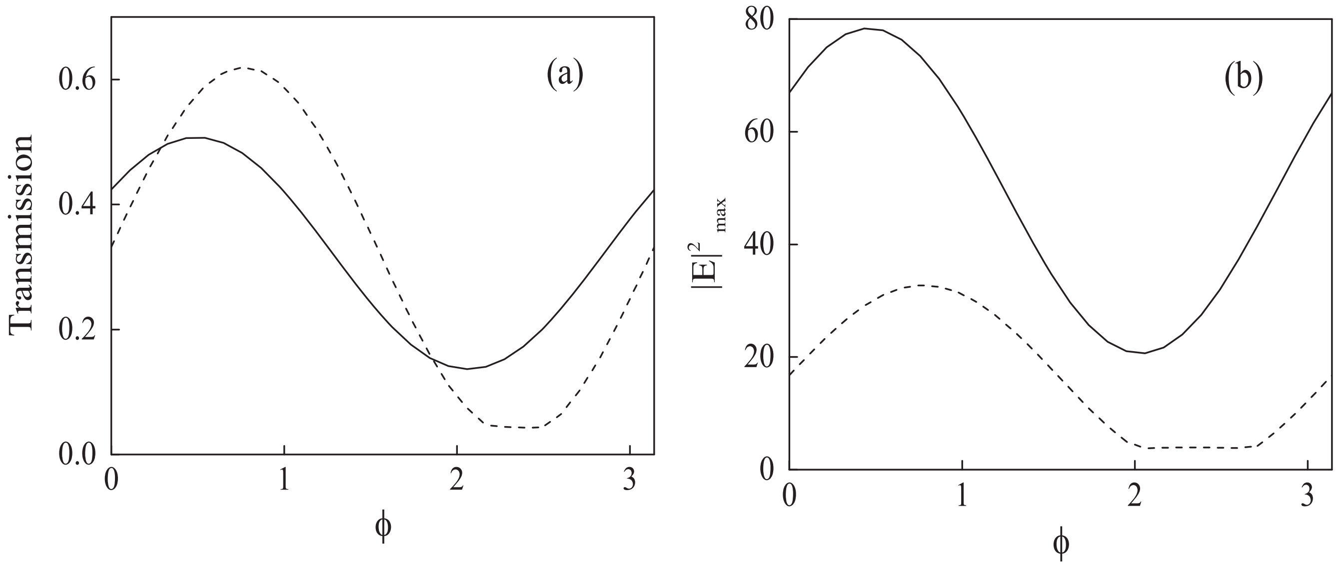


**Figure 6.** (a) Transmittances corresponding to the localized state at different $\varphi$ for the light incident on the CLC (solid line) and on the metal (dashed line). (b) Electric field intensity at the phase plate–metal interface at different $\varphi$ for the light incident on the CLC (solid line) and on the metal (dashed line).

### *3.3. Controlling the transmission spectrum of the structure*

In contrast to scalar structures, the transmission spectra of the CLCs can be easily and effectively controlled, because the transmission spectra of the CLCs are different for different polarizations and the helix pitch of all or part of the CLC can be changed by an external field [32–34]. The change in the CLC helix pitch will change the position of the Bragg reflection region in the crystal.

As was shown in [27], the localized mode is excited in the sample by light of different polarizations, which make different contributions to the excitation. This effect is explained by the fact that light of both circular polarizations excites a localized mode by transforming the polarizations at the dielectric interfaces. As a result, any polarization of the light becomes elliptic, to different extents, at the CLC output, depending on the initial polarization and the crystal thickness.

In this study, we investigated the transmission of linearly polarized light by the structure. It was established that the transmittance of the structure at the frequency corresponding to the OTS depends on the angle $\varphi$ between the optical axis of

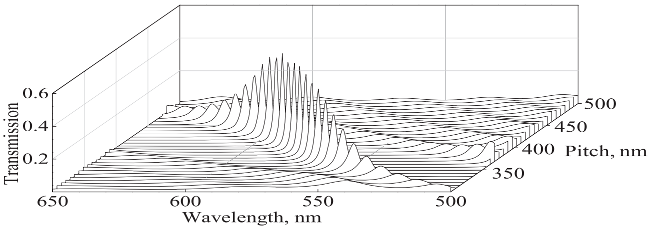


**Figure 7.** Transmission spectrum of the structure versus cholesteric helix pitch.

the phase plate and the polarization plane of polarization of the incident linearly polarized light (figure 6(a)).

It can be seen from the plots that the transmission maxima at the propagation of light in the forward and backward directions are shifted relative to each other. For the backward incidence of light, the transmittance of the structure is maximum at an angle of 45° between the plane of polarization of the incident light and the optical axis of the phase plate. This is caused by transformation of linear polarization to circular polarization as the light propagates through the quarter-wave phase plate. Consequently, all the light that reaches the CLC will pass through it.

Figure 6(b) shows the dependence of the maximum squared absolute value of the electric field for different angles $\varphi$. Using this dependence, one can determine the polarization at which the radiation is most effectively localized in the system. It can be seen that the localization at the frequency corresponding to the localized state at the light incidence on the CLC greatly exceeds the localization at the light incidence on the metal film.

As mentioned above, an important advantage of the CLC over other photonic crystals is its high sensitivity to external fields. Varying the parameters of the system, we can control the position of the transmission peak corresponding to the OTS. The stronger temperature or applied voltage dependences of the helix pitch as compared to the analogous dependences of other structural elements can be used to effectively control the frequency of the transmission peak related to light tunneling through the localized state (figure 7).

## 4. Conclusions

We have demonstrated the existence of surface states similar to the OTSs localized in the structure that contains a cholesteric liquid crystal and a silver layer. The variation of wave polarization upon reflection from the metal and the special polarization properties of the CLC led us to introduce the anisotropic quarter-wave element between the cholesteric and metal layers. The origin of light localization in the investigated system was explained in detail.

It is difficult to form a direct contact between the CLC and the metal. To do so, one should apply localizers in the form of layers of an anisotropic material. The anisotropic material can simultaneously serve as a quarter-wave phase plate. Varying the thickness of this plate, one can implement the localized state.

We showed that the transmission spectra for light propagating in the forward and backward directions are different; i.e., we deal with the transmission nonreciprocity. Therefore, the investigated structure can be used as a polarization optical diode based on surface photonic modes.

We demonstrated that the transmission spectrum of such a system can be effectively controlled. At any polarization of the incident wave, the light is localized with the maximum field intensity at the interface between the plate and the metal. However, different ellipticities of the waves passed through the CLC and their polarization properties lead to different transmittances for each polarization.

Varying the plane of polarization of the linearly polarized incident radiation, one can easily change the transmittance at the wavelength corresponding to the localized state. We studied the dependence of the transmission maxima on the angle between the optical axis of the phase plate and the plane of polarization of the incident light. Using this dependence, we determined the angles at which the transmission of the system is maximum. It was found that light transmitted forward localizes more strongly than light transmitted backward.

We showed that the transmission peak position can be controlled by varying the CLC helix pitch with the use of external fields.

To sum up, note that the observed surface state is, in fact, the eigenmode of the microcavity with the CLC layers and metal plane working as mirrors. Consequently, it becomes possible to induce laser generation in a microcavity by using the phase plate from an optically active material.

## Acknowledgments

This work was supported by the Russian Foundation for Basic Research, project no. 14-02-31248, and the Ministry of Education and Science of the Russian Federation, Government program, project no. 3.1276.2014/K.

## References

[1] Vinogradov A P, Dorofeenko A V, Merzlikin A M and Lisyansky A A 2010 Surface states in photonic crystals *Phys. -Usp.* **53** 243–56

[2] Kavokin A, Shelykh I and Malpuech G 2005 Optical Tamm states for the fabrication of polariton lasers *Appl. Phys. Lett.* **87** 261105

[3] Kavokin A V, Shelykh I A and Malpuech G 2005 Lossless interface modes at the boundary between two periodic dielectric structures *Phys. Rev.* B **72** 233102

[4] Kaliteevski M, Iorsh I, Brand S, Abram R A, Chamberlain J M, Kavokin A V and Shelykh I A 2007 Tamm plasmon-polaritons: possible electromagnetic states at the interface of a metal and a dielectric Bragg mirror *Phys. Rev.* B **76** 165415

[5] Vetrov S Y, Bikbaev R G and Timofeev I V 2013 Optical Tamm states at the interface between a photonic crystal and a nanocomposite with resonance dispersion *J. Exp. Theor.* P **117** 988–98

[6] Sasin M E, Seisyan R P, Kalitteevski M A, Brand S, Abram R A, Chamberlain J M, Egorov A Y, Vasil'ev A P, Mikhrin V S and Kavokin A V 2008 Tamm plasmon polaritons: slow and spatially compact light *Appl. Phys. Lett.* **92** 251112

[7] Goto T, Dorofeenko A V, Merzlikin A M, Baryshev A V, Vinogradov A P, Inoue M, Lisyansky A A and Granovsky A B 2008 Optical Tamm states in one-dimensional magnetophotonic structures *Phys. Rev. Lett.* **101** 113902

[8] Zhang W L and Yu S F 2010 Bistable switching using an optical Tamm cavity with a Kerr medium *Opt. Commun.* **283** 2622–6

[9] Zhou H, Yang G, Wang K, Long H and Lu P 2010 Multiple optical Tamm states at a metal–dielectric mirror interface *Opt. Lett.* **35** 4112–4

[10] Vinogradov A P, Dorofeenko A V, Erokhin S G, Inoue M, Lisyansky A A, Merzlikin A M and Granovsky A B 2006 Surface state peculiarities in one-dimensional photonic crystal interfaces *Phys. Rev.* B **74** 045128

[11] Zhang X-L, Song J-F, Li X-B, Feng J and Sun H-B 2012 Optical Tamm states enhanced broad-band absorption of organic solar cells *Appl. Phys. Lett.* **101** 243901

[12] Gong Y, Liu X, Lu H, Wang L and Wang G 2011 Perfect absorber supported by optical Tamm states in plasmonic waveguide *Opt. Express* **19** 18393–8

[13] Symonds C, Lheureux G, Hugonin J P, Greffet J J, Laverdant J, Brucoli G, Lemaitre A, Senellart P and Bellessa J 2013 Confined Tamm plasmon lasers *Nano Lett.* **13** 3179–84

[14] Gazzano O, Michaelis de Vasconcellos S, Gauthron K, Symonds C, Voisin P, Bellessa J, Lemaıˆtre A and Senellart P 2012 Single photon source using confined Tamm plasmon modes *Appl. Phys. Lett.* **100** 232111

[15] Dong H Y, Wang J and Cui T J 2013 One-way Tamm plasmon polaritons at the interface between magnetophotonic crystals and conducting metal oxides *Phys. Rev.* B **87** 045406

[16] Da H, Bao Q, Sanaei R, Teng J, Loh K P, Garcia-Vidal F J and Qiu C-W 2013 Monolayer graphene photonic metastructures: giant Faraday rotation and nearly perfect transmission *Phys. Rev.* B **88** 205405

[17] Khokhlov N E *et al* 2015 Photonic crystals with plasmonic patterns: novel type of the heterostructures for enhanced magneto-optical activity *J. Phys. D: Appl. Phys.* **48** 095001

[18] Kaliteevski M, Brand S, Abram R A, Iorsh I, Kavokin A V and Shelykh I A 2009 Hybrid states of Tamm plasmons and exciton polaritons *Appl. Phys. Lett.* **95** 251108

[19] Brückner R, Sudzius M, Hintschich S I, Fröb H, Lyssenko V G, Kaliteevski M A, Iorsh I, Abram R A, Kavokin A V and Leo K 2012 Parabolic polarization splitting of Tamm states in a metal-organic microcavity *Appl. Phys. Lett.* **100** 062101

[20] Afinogenov B I, Bessonov V O, Nikulin A A and Fedyanin A A 2013 Observation of hybrid state of Tamm and surface plasmon-polaritons in one-dimensional photonic crystals *Appl. Phys. Lett.* **103** 061112

[21] Kaliteevski M A and Lazarenko A A 2013 Reduced absorption of light by metallic intra-cavity contacts: Tamm plasmon based laser mode engineering *Tech. Phys. Lett.* **39** 698–701

[22] Gessler J, Baumann V, Emmerling M, Amthor M, Winkler K, Höfling S, Schneider C and Kamp M 2014 Electro optical tuning of Tamm-plasmon exciton-polaritons *Appl. Phys. Lett.* **105** 181107

[23] Savelev R S, Miroshnichenko A E, Sukhorukov A A and Kivshar Y S 2014 Optical Tamm states in arrays of all-dielectric nanoparticles *J. Exp. Theor. Phys. Lett.* **100** 430–3

[24] Treshin I V, Klimov V V, Melentiev P N and Balykin V I 2013 Optical Tamm state and extraordinary light transmission through a nanoaperture *Phys. Rev.* A **88** 023832

[25] Belyakov V A 1992 *Diffraction Optics of Complex Structured Periodic Media* (New York: Springer)

[26] Blinov L M 2011 *Structure and Properties of Liquid Crystals* (Dordrecht: Springer) ch 12

[27] Vetrov S Y, Pyatnov M V and Timofeev I V 2014 Surface modes in 'photonic cholesteric liquid crystal–phase plate–metal' structure *Opt. Lett.* **39** 2743–6

[28] Johnson P B and Christy R W 1972 Optical constants of the noble metals *Phys. Rev.* B **6** 4370–9

[29] Berreman D W 1972 Optics in stratified and anisotropic media: 4 × 4-matrix formulation *J. Opt. Soc. Am.* **62** 502–10

[30] Palto S P 2001 An algorithm for solving the optical problem for stratified anisotropic media *J. Exp. Theor. Phys.* **92** 552–60

[31] Hwang J, Song M H, Park B, Nishimura S, Toyooka T, Wu J W, Takanishi Y, Ishikawa K and Takezoe H 2005 Defect mode lasing from a double-layered dye-doped polymeric cholesteric liquid crystal films with a thin rubbed defect layer *Nat. Mater.* **4** 383–6

[32] Dolganov P V, Ksyonz G S and Dolganov V K 2013 Photonic liquid crystals: optical properties and their dependence on light polarization and temperature *Phys. Solid State* **55** 1101–4

[33] Rodarte A L, Cisneros F, Hirst L S and Ghosh S 2014 Dye-integrated cholesteric photonic luminescent solar concentrator *Liq. Cryst.* **41** 1442–7

[34] Hsiao Y-C, Wang H-T and Lee W 2014 Thermodielectric generation of defect modes in a photonic liquid crystal *Opt. Express* **22** 3593–9