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Localized Optical States in a Liquid-Crystal Structure Adjacent to a Metal[1]

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Abstract—The spectrum of light transmission through a structure consisting of a metallic layer and a cholesteric liquid crystal with an induced planar defect is calculated. The possibility of existence of localized states at the metal–dielectric interface of this system is demonstrated. The transmission spectra at different positions of the defect in the structure are studied.

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At present, much attention on the part of researchers is being devoted to studying the surface electromagnetic states in photonic-crystal media [1]. This is due to both a number of intriguing fundamental phenomena observed in these states and their high application potential. A special type of localized electromagnetic surface states, in which the field exponentially weakens on both sides of the interface, is the optical Tamm state (OTS) [2]. This state is an optical analog of the Tamm bound electronic states on the crystal surface. The OTS can be excited between two different photonic crystals with overlapping band gaps at normal incidence of light [2, 3] or between a photonic crystal and a medium with the negative permittivity [4, 5]. The OTS excited at the interface with a metal is also called “Tamm plasmon polariton.” The OTS can be experimentally observed as a narrow resonance in the optical transmission or reflection spectrum of a sample [6]. Proposed and implemented applications of OTS include organic solar cells [7], lasers [8], sensors [9], and absorbers [10].

Materials with controlled spectral characteristics are often needed for application. Among such photonic-crystal materials are cholesteric liquid crystals (CLCs), which are chiral organic structures [11, 12]. CLCs are formed by strongly anisotropic extended molecules. Chirality of molecules induces rotation of their long axes, which results in the formation of a spatial helical structure. By changing the temperature or pressure or applying electromagnetic fields and stresses, one can change, e.g., the cholesteric helix pitch and, thereby, the band-gap position. In contrast to scalar photonic crystals, the CLCs exhibit the polarization-selective diffraction reflection. In particular, if circularly polarized light incident along the helix axis has the polarization direction coinciding with the CLC twist direction, it experiences the Bragg reflection. The Bragg reflection region lies 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 CLC refractive indices. The light with the opposite circular polarization does not experience the diffraction reflection.

As was shown previously [13–15], the OTS localized at the interface between the CLC and metal is difficult to obtain at the normal incidence of light. This is related to the polarization features of light reflection from the CLC and metal. In CLCs, only the light with the circular polarization of the same direction as the helix twist is reflected. In this case, the reflected light retains the circular polarization direction. The light with the opposite circular polarization does not experience the diffraction reflection. The metal, on the contrary, reflects light of any polarization; however, upon reflection, a phase difference appears, which leads to polarization diffracting for the CLC, i.e., that coinciding with the helix-twist direction, becoming nondiffracting and vice versa. Taking into account the aforementioned peculiarities of light localization

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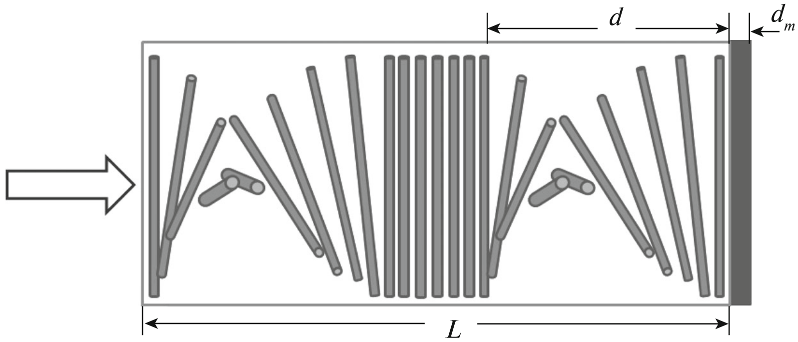

Fig. 1. Schematic of the investigated structure.

between the CLC and metal, we have proposed to retain the light polarization upon reflection from the metal using a phase-changing material embedded between the metal and CLC [13, 14]. A quarter-wave phase plate was considered as such an element. In [15], we investigated a structure consisting of a metallic layer and oppositely twisted CLC layers. The OTS localized at the interface between the CLC and metal-type anisotropic mirror was described [16]. The proposed methods allow localizing light using complex CLC structures. In this study, we propose a new method for localizing light between the CLC and metallic film. The specific feature of the proposed model is that it consists of only a cholesteric and a metal.

Some authors [17–21] have studied CLC systems with an anisotropic defect layer. The authors of [21] designed optical CLC cells with electrodes formed perpendicular to the CLC helix axis. Using such cells, they managed to untwist the CLC helix in the middle of the layer and, thereby, form a planar defect. Hsiao et al. [18] used the thermodielectric effect to induce a local strain at the center of a one-dimensional periodic helical structure.

Based on these studies, we investigated a structure consisting of a metallic film and a CLC with the planar defect (Fig. 1). The CLC-layer thickness was L = 11 μm, the helix pitch was p = 0.4 μm, and the ordinary and extraordinary refractive indices were n_o = 1.45 and n_e = 1.55, respectively. At these parameters, the CLC band gap lies between 580 and 620 nm. In the middle of the layer, the CLC helix is untwisted at a length of 3 μm, which is analogous to a quarter-wave anisotropic defect positioned there. The structure is surrounded by a medium with the refractive index equal to the averaged CLC refractive index. The thickness of the metallic film was d_m = 50 nm, and its permittivity was specified by the Drude approximation

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

where $\varepsilon_0 = 5$ is the ion-core contribution, $\hbar\omega_p = 9$ eV is the plasma frequency, and $\gamma = 0.02$ is the reciprocal relaxation time [22]. These are the parameters of silver.

The transmission spectra and field-intensity distribution in the structure were studied using the matrix technique for calculating layered anisotropic Berreman structures [23].

As was demonstrated in [20, 21], the presence of a half-wave defect layer in the CLC structure leads to the loss of the polarization dependence of the diffraction reflection. It means that the CLC starts reflecting light of any polarization rather than only the circularly polarized radiation with the direction coinciding with the CLC helix twist. Figure 2 shows the calculated transmission spectrum of the circularly polarized light for the investigated system CLC–half-wave defect–CLC–metal. At the frequencies of the Bragg reflection zone in the crystal, several transmission peaks occurred. Note that these peaks are observed at both circular polarizations.

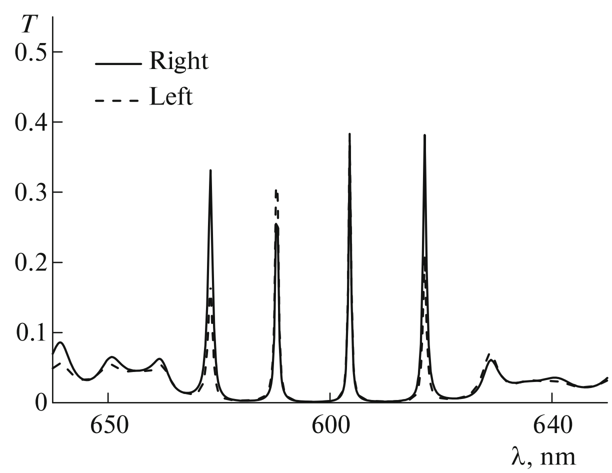

Fig. 2. Transmission spectrum of the structure for circularly polarized incident light.

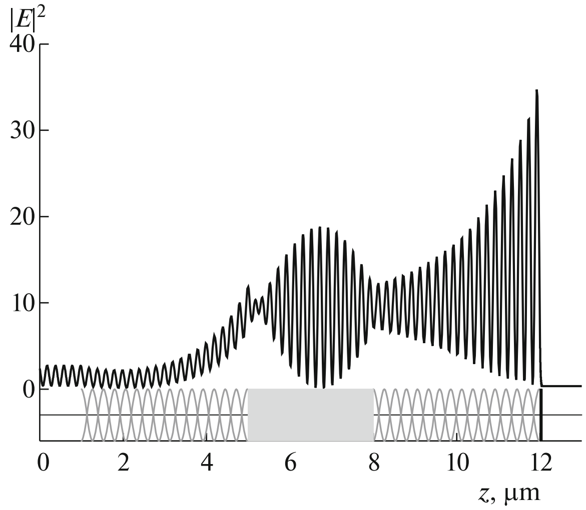

Fig. 3. Electric-field-intensity distribution for right-hand circular polarization of the incident light at a wavelength of 603.5 nm.

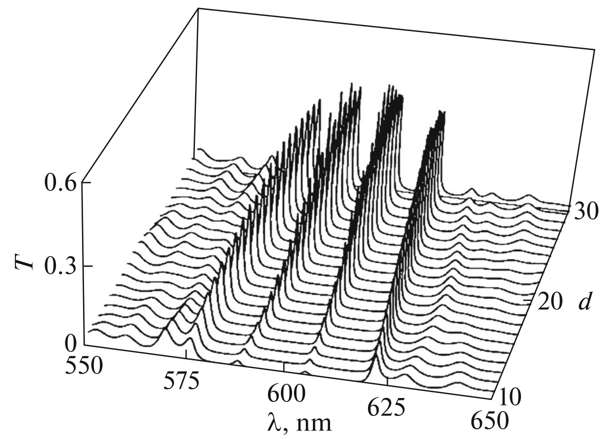

Fig. 4. Dependence of the transmission spectrum for right-hand circular polarization on number of periods d between the defect and metal.

Each peak in the spectrum corresponds to the localized state. Figure 3 shows the electric-field-intensity distribution for the right-hand circular polarization at a wavelength of 603.5 nm. At the rest of the frequencies, the field distribution is analogous. The field is mainly localized at the metal–CLC interface. The localized-mode field attenuation inside the metal is caused by the negative permittivity of the metallic film, whereas the field attenuation inside the CLC results from the Bragg reflection. Note that the field is partially localized on the defect with the maximum in the middle of the half-wave layer. This is due to the fact that the system under study can be considered as a composition of several resonators. The planar defect can be considered as one of them.

Let us investigate the variation in the properties of the structure with the planar defect position in the CLC. The calculated transmission spectrum at different positions of the defect relative to the CLC center is shown in Fig. 4. It can be seen that the transmission spectrum significantly depends on the defect position in the CLC. As the distance between the defect and metal decreases, the resonances gradually vanish. As the distance increases, the peaks move closer to each other and the transmission at their frequencies grows. This originates from the fact that the reflectance of the CLC layer depends on its thickness. At small CLC layer thicknesses, the majority of the light between the metal and defect passes through this layer, changes its orientation when passing through the half-wave defect, and exits from the second CLC layer. Thus, the light localization is affected mainly by the CLC part located between the defect and metallic film.

Thus, we demonstrated the existence of surface electromagnetic states localized in the structure containing a silver film and CLC with a half-wave planar defect. This defect can be induced, e.g., by applying an external electric field perpendicular to the CLC helix axis. It was established that at this geometry the light with any polarization of the incident wave is localized with the maximum field intensity at the metal–CLC interface. Different ellipticities of the waves passing through the CLC and their polarization properties lead to different transmittances for each polarization. It was shown that the transmission spectrum of the investigated structure significantly depends on the defect position in the CLC.

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