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Photonic Density of States of a Stack of Cholesteric Liquid Crystal and Isotropic Medium Layers

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Abstract. We calculated the photonic density of states (PDS) of the eigen polarizations in the system composed of a stack of layers of a cholesteric liquid crystal and an isotropic medium. The reflection spectra and PDS peculiarities, as well as the peculiarities of absorption and emittance were investigated. We obtained the dependences of the PDS as a function of parameters characterizing absorption and gain. It was shown that the subject system can be used in lasers for obtaining low threshold lasers with the emittance wavelength tunable in wide ranges. The system also can work as a multi-position trigger.

1. Introduction

Recently the science of optical and laser materials has been in great interest. The photonic crystals (PCs) and metamaterials have been in wide application as laser cavities. The lasing in cholesteric liquid crystals (CLCs) and PCs goes on being intensely investigated (see, for instance, [1, 2] and the wide literature cited therein). The possibilities of decreasing the lasing threshold in the CLC and multilayer systems with CLC layers have been studied theoretically [3-5] and experimentally [6]. Reference [7] experimentally investigated some novel hybrid structures composed of a dye-doped low-molecular-weight CLC sandwiched into a multilayered polymer CLC films with right- and left-hand polymer CLC layers and they evaluated the lasing characteristics of this system. It was shown that a lasing with an extremely reduced threshold can be observed. In the papers [8, 9] it was reported the observation of continuous wave lasing in the dye doped CLC, and the effect of losses and gain on the photonic density of states (PDS) was calculated. On the other hand, recently the PCs with multi-photonic band gap (PBG) have been of great interest.

In this paper we investigate the influence of absorption, amplification, layer thickness, dielectric borders, local dielectric anisotropy etc on the PDS of the stack of the CLC and an isotropic medium layers. The urgency of the problem is the fact that the lasing threshold is significantly lowered in the multi-layer systems with CLC layer(s).

2. Results and discussion

The problem was solved by the Ambartsumian's layer addition modified method [4]. The ordinary and extraordinary refractive indices of the CLC sublayers (with thicknesses d_1) are taken to be: $n_o = \sqrt{\varepsilon_2} = 1.4639$ and $n_e = \sqrt{\varepsilon_1} = 1.5133$ (ε_1, ε_2 are the principal values of the local dielectric permittivity tensor of the CLC); the CLC sub-layer helix is right handed and its pitch is: p = 420 nm.

Thus, if the right circularly polarized (RCP) light is normally incident onto a single CLC layer, it has a PBG (which is in the range of λ = 614.8 ÷ 635.6 nm), and the light with the left circular polarization (LCP) does not have any PBG. The refraction coefficient, n, of the isotropic layers (with thicknesses d_2) is chosen as: $n=\sqrt{\varepsilon}=1.7$.

In figure 1, the reflection spectrum for s =100 (s is the sub-sublayers number in the system) in the normal incident case is presented. The incident light polarizations coincide with the polarization of the first (the solid curve) and the second (the dotted curve) eigen polarizations (EPs). The EPs of the system are circular and the modules of the ellipticities of the EPs differ from the unit mainly in the PBGs. Outside of these ranges the modules of the ellipticities are practically equal to the unit.

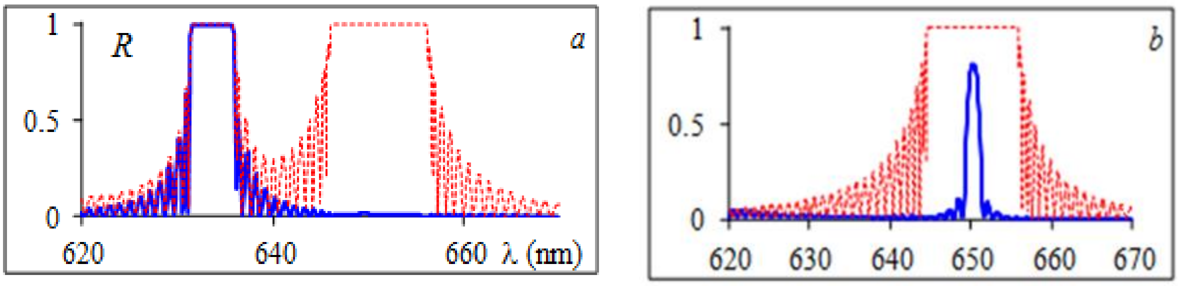

Figure 1. The spectrum of reflectance at normal light incidence. The incident light has (solid line) the first EP and (dashed line) the second EP. d_2=1000 nm. *a*: d_1=1200 nm. *b*: d_1= 3*p*.

As it is seen from figure 1, in contrast to the case of the single CLC layer, this system has multi-PBGs. There are PBGs of two types, namely, the one that does not depend on the incident light polarization and the other that is selective with respect to the incident light polarization. Moreover, if the CLC sublayer thicknesses are multiples of the helix pitch, then the selective reflection regions overlap the non-selective regions (figure 1*b*), otherwise these regions are separate (figure 1*a*).

Now we consider the absorption/radiation peculiarities and the PDS of the stack of the CLC and the isotropic medium layers. The divergence in the PDS at the band edges in the single CLC layer and at defect modes in the CLC with defects in its structure was shown theoretically and experimentally in [4, 5, 10]. Some new and important results for the PDS of CLC layer, as well as for the CLC-NLC structure were obtained in [11–13]. The investigation of the PDS peculiarities is important because of the following. For the laser emission it has been shown that, for instance, analyzing the case of the Fabry-Perot resonator, the threshold gain, $g_{\rm th}$, can be related directly to the PDS, that is, ρ, as in [12]: $g_{th}\propto n/(d\rho)$, where n is the refractive index inside the resonator of the length d, and ρ is the maximum PDS. Furthermore, according to the space-independent rate equations, the slope efficiency of lasers can be shown to be inversely proportional to the threshold energy and, therefore, directly proportional to ρ [14].

For the isotropic medium case we have: $\rho_{iso}=n_s/c$, where n_s is the refractive index of the system surrounding medium, and c is the speed of light in vacuum. Both the losses and the gain can be incorporated through introducing an imaginary part to the CLC dielectric permittivity tensor components and to the isotropic medium dielectric permittivity.

Let the CLC and the isotropic medium layers be doped with dye molecules. Then this system is an amplifier in the presence of a pumping wave, i.e. we are discussing a planar resonator with active elements. The presence of the dye leads to the change of local refraction indices of the system sub-layers. In this case, in the presence of the pumping wave, the effective imaginary parts of the local refraction indices in the CLC ($n''_{o,e}$) and those of the isotropic layers (n'') are negative ($n_{o,e}=\sqrt{\varepsilon_{1,2}}=n'_{o,e}+in''_{o,e}$, $n=\sqrt{\varepsilon}=n'+in''$), and all they characterize the gain. In the case of the absence of the pumping wave (when the imaginary parts of the local CLC indices, $n''_{o,e}$, and those of the isotropic layers, n'', are positive), the quantity, A=1–(R+T), characterizes the light energy absorbed by the system, while, in the case of amplification, the value of $|A|$ characterizes the radiation emitted by the system (we assumed that the incident light intensity is unit, $I_0 = 1$).

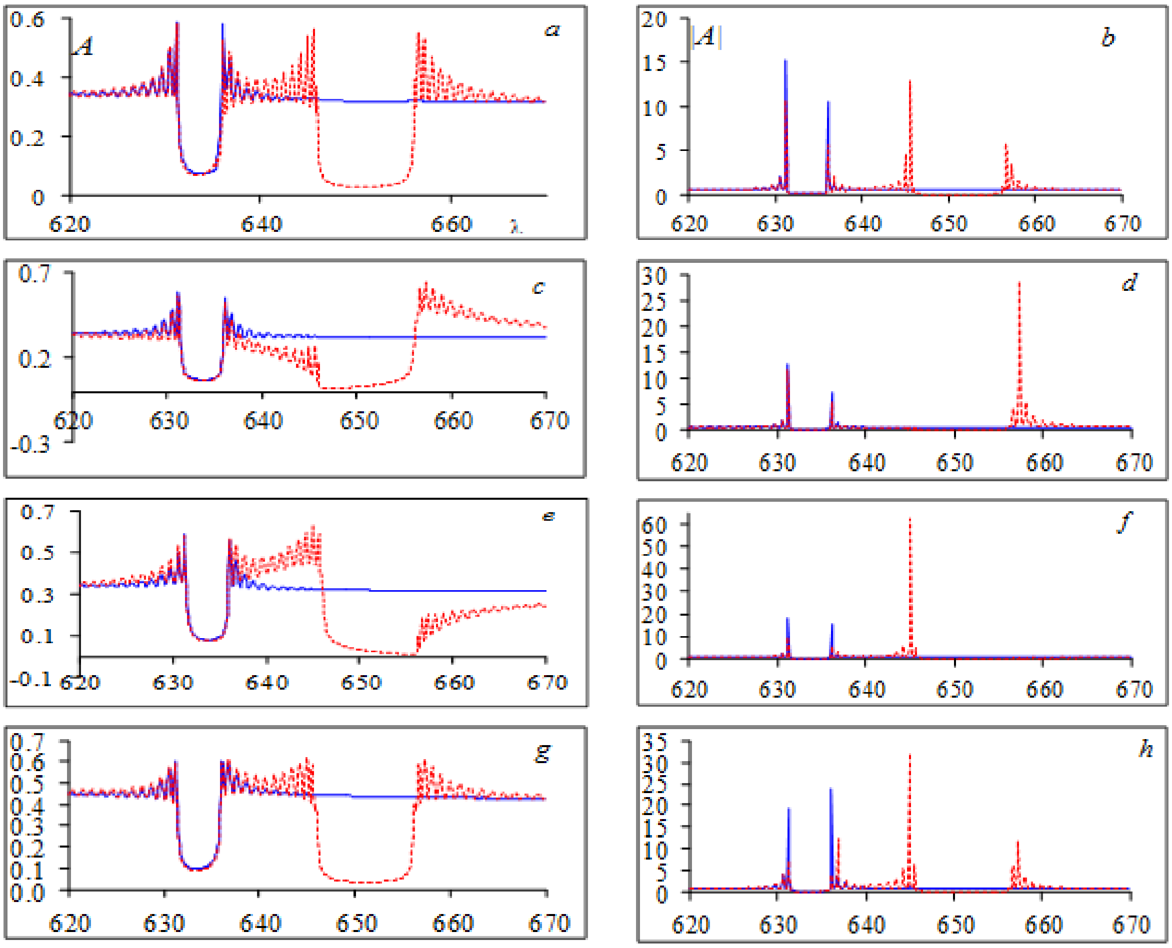

Figure 2. The absorption A (the left column) and the emittance, $|A|$ (the right column) spectra. *a*: $\varepsilon''_1 = \varepsilon''_2 = 0.001$, $\varepsilon'' = 0$. *b*: $\varepsilon''_1 = \varepsilon''_2 = -0.001$, $\varepsilon'' = 0$. *c*: $\varepsilon''_1 = 0.002$, $\varepsilon''_2 = 0$, $\varepsilon'' = 0$. *d*: $\varepsilon''_1 = -0.002$, $\varepsilon''_2 = 0$, $\varepsilon'' = 0$. *e*: $\varepsilon''_1 = 0.$, $\varepsilon''_2 = 0.002$, $\varepsilon'' = 0$. *f*: $\varepsilon''_1 = 0.$, $\varepsilon''_2 = -0.002$, $\varepsilon'' = 0$. *g*: $\varepsilon''_1 = \varepsilon''_2 = 0$, $\varepsilon'' = 0.002$. *h*: $\varepsilon''_1 = \varepsilon''_2 = 0$, $\varepsilon'' = -0.002$. The other parameters are the same as in figure 1*a*.

We characterize the degree of the arrangement of the dipole transition momentums of the guest molecules by the order parameter, S_d, defining it through the average of cosϑ: $S_d = 3\langle \cos\vartheta \rangle / 2 - 1/2$, where ϑ is the angle between the local optical axis and the dipole transition momentum of the guest molecules. The possible maximum value of this order parameter is the unit, $S_d = 1$, and it corresponds to the ideal orientation of the transition dipole momentums along the local optical axis; and the isotropic orientation of the transition dipole momentums corresponds to the value, $S_d = 0$, while the minimum value, $S_d = -0.5$, corresponds to the distribution of those momentums in the plane that are perpendicular to the local optical axis.

In figure 2, the spectra of absorption, A (the left column) and those of the emittance, $|A|$ (the right column) are presented. The first row corresponds to the isotropic absorption and gain in the CLC layers, and the second and third ones are for the anisotropic absorption and gain in the CLC layers (assuming that the absorption and gain in the isotropic layers are absent); finally, the fourth row corresponds to the absorption and gain in the isotropic layers if they are absent in the CLC layers. The solid lines correspond to the first EP, and the dashed ones are for the second EP. As it is seen from figure 2, in the diffraction reflection regions suppression of absorption and emittance takes place. In the presence of anisotropic absorption and gain in the CLC layers, complete suppression of absorption and emittance take place at one of the PBG border, and there is an anomalously strong absorption and emittance at the other border. These indicate that at these parameters of the system, in the PBGs selective with respect to the polarization of incident light and nearby the region of the single CLC layer PBG, the modulation of the total field in the CLC layers is the same as that in the single CLC layer.

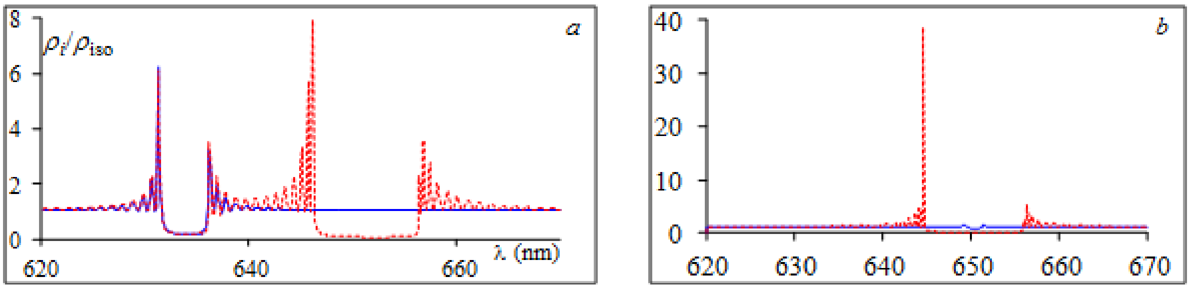

Figure 3. The spectra of the relative PDS ρ_i / ρ_{iso}. The incident light has the first EP (i=1, solid line) and the second EP (i=2, dashed line). The parameters are the same as in figure 2.

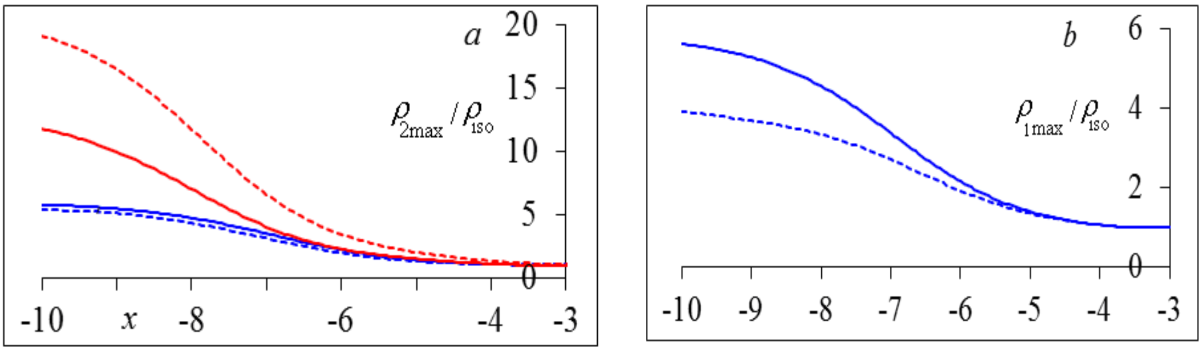

Figure 4. The dependence of the maximum, $\rho_{1,2\max} / \rho_{iso}$, of the PDS of the first (b) and the second (a) EPs at the short (the solid lines) and long (the dashed lines) wavelength edges on the parameter, $x = \ln(\operatorname{Im}\varepsilon_m)$, characterizing absorption. The isotropic absorption in the CLC layers is considered and the isotropic layers are assumed non-absorbing. The blue (dark) lines correspond to the nonselective PBG, and the red (light) lines are for the selective one.

Now we pass to the PDS. In figure 3, the spectra of ρ_i / ρ_{iso} are presented in the above said two cases considered in figure 1. As it is known, in the single CLC layer the value of ρ_i / ρ_{iso} for the diffracting EP has two principal maxima nearby the PBG borders (the short wavelength edge (SWE) maximum and the long wavelength edge (LWE) one), meanwhile, it is constant for the non-diffracting

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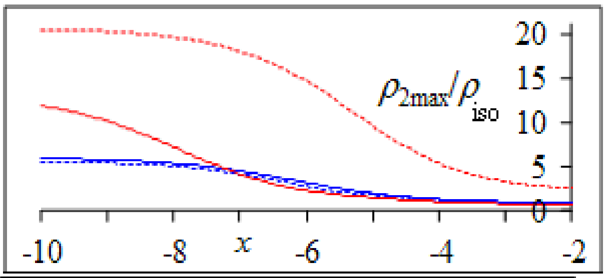
EPs. As it is seen from figure 3, for the incident wave with the first EP, the value of ρ_i / ρ_{iso} has two principal maxima nearby the non-selective PBG borders, and they are essentially weaker in the second case, that is in the case when the CLC sublayer thicknesses are multiples of the helix pitch. For the incident wave with the second EP, the value of ρ_i / ρ_{iso} has four principal maxima both nearby the selective and non-selective PBG borders in the first case (that is, if the CLC layers thicknesses are not multiples of the helix pitch) and there are only two of them in the second case. Note that in the last case the PDS near the SWE reaches essentially larger values.

Now we investigate the influence of the absorption and gain on the PDS. We consider only the first case when the CLC layers thicknesses are not multiples of the helix pitch. In figure 4, the dependences of the maximum $\rho_{1,2\max} / \rho_{iso}$ of the PDS of the first (*b*) and the second (*a*) EPs at the short (the solid lines) and long (the dashed lines) wavelength edges on the parameter, $x = \ln(\operatorname{Im}\varepsilon_m)$, characterizing the absorption, are presented. The case of the isotropic absorption in the CLC layers is considered and the isotropic layers are assumed to be not absorbing. The blue (dark) lines correspond to the shortwave PBG border, and the red (light) lines are for the long wavelength one.

As it is seen from figure 4, the PDS decreases dramatically with the increment of the parameter, $x = \ln(\operatorname{Im}\varepsilon_m)$, characterizing the absorption.



Fgure 5. The same as in figure 4*a*; the dependences for the anisotropic absorption if an imaginary term is included only in the dielectric constant parallel to the CLC local director.

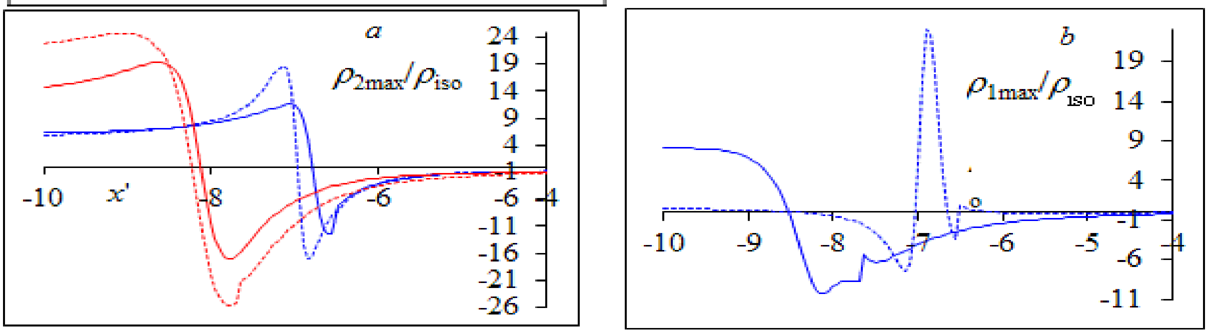


Figure 6. The same as in figure 5. The dependences of the maximum, $\rho_{1,2\max} / \rho_{iso}$, of the PDS of the first (*b*) and the second (*a*) EPs at the short (the solid lines) and long (the dashed lines) wavelength edges on the parameter, $x' = \ln(-\operatorname{Im}\varepsilon_m)$, characterizing the gain. The blue (dark) lines correspond to the nonselective PBG, and the red (light) lines are for the selective one.

An interesting situation is observed in the case of anisotropic absorption in the CLC sublayers. In figure 5, the same is presented as in figure 4*a*, that is, the dependences of the maximum, $\rho_{2\max} / \rho_{iso}$, on the parameter, *x*, for the anisotropic absorption if an imaginary term is included only in the dielectric constant parallel to the CLC sublayers local director. An interesting effect is observed here. If the absorption is weak, then the PDS for the selective with respect to the polarization PBG in its SWE is practically unaffected at first, when the loss is increased, while the PDS in the LWE is diminished sharply. Meanwhile, if an imaginary term is included only in the dielectric constant perpendicular to the local director, then the reverse takes place.

Now about the gain. In figure 6 the dependences of the maximum $\rho_{1,2\max} / \rho_{iso}$ of the PDS of the first (*b*) and the second (*a*) EPs at the short (the solid lines) and long (the dashed lines) wavelength edges on the parameter, $x' = \ln(-\mathrm{Im}\varepsilon_m)$, characterizing the gain are presented. If the gain (that is, the parameter, $x' = \ln(-\mathrm{Im}\varepsilon_m)$) increases, the maximum of the PDS increases too. The further increment of the gain leads to a resonance-like change of the maximum of the PDS; then the PDS diminishes. There exists a critical value of x' beyond witch the lasing mode is quenching and the feedback vanishes. The critical values of x' for SWE and LWE both for selective and non-selective PBGs are different. The existence of the critical value for the gain indicates the possibility of using the system as a trigger. Tuning the pumping intensity (for the corresponding density of the dye molecules), one can pass from the lasing regime to that of quenching.

3. Conclusions

We investigated the PDS peculiarities of the EPs for the stack of layers of a CLC and an isotropic medium layers both in the absence of absorption and gain and in their presence. It was shown that the subject system possesses multiple PBGs. There are PBGs of two types: the ones selective with respect to the incident light polarization and those non-selective to that. It can be shown that the change of the CLC sublayer thicknesses and the isotropic sublayer thicknesses leads both to the frequency overlapping of the PBGs and the width changes.

Taking into account the possibility of tuning the width, the number and the frequency location of these regions by the external fields (electric, magnetic, light, mechanical, heat, etc) or the possibility of changing the internal structure of the system, the system we offer seems having perspectives also for other fields of science and technologies.

The investigation of the influence of the gain on the PDS showed that if the gain is increased then the maximum of the PDS increases too; meanwhile, it decreases if absorption is present. Then, it was shown that in the presence of gain there exists a critical value of x' (the parameter characterizing the gain) beyond which the lasing mode is quenched and the feedback vanishes. Besides, the critical values for x' at the SWE and LWE are different.

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