

LETTER

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# Lasing in cholesteric liquid crystal cells with an isotropic defect layer inside

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## Abstract

The photonic density of states (PDS) of eigen polarizations (EPs) in cholesteric liquid crystal (CLC) cells with a defect layer inside are calculated. The dependences for the PDS and light intensity in the defect layer on the parameters characterizing absorption and gain are obtained. We investigated the possibility of connections between the PDS and the density of the light energy accumulated in the system. The influence of the defect layer and CLC layer on the PDS are investigated. It is shown that the PDS is maximum when the defect is in the center of the system. We also showed that the subject system can work as a low threshold laser, a multi-position trigger, filter, etc.

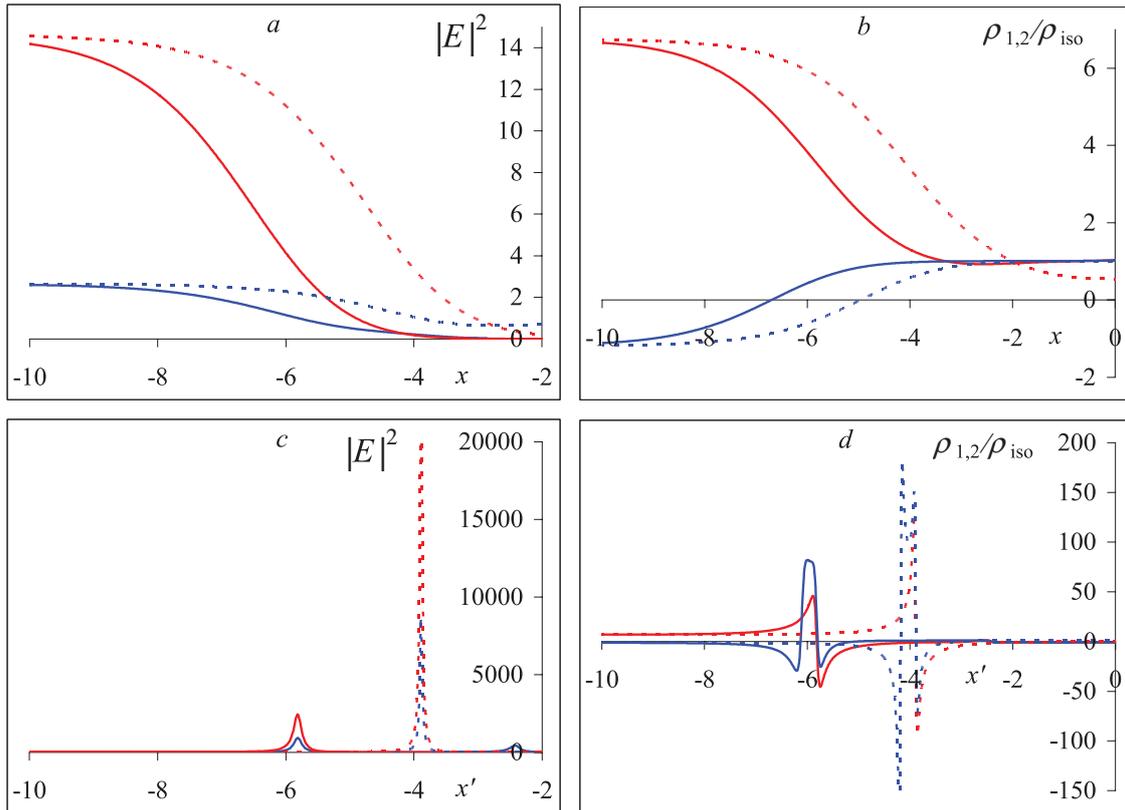
Keywords: photonics, photonic density of states, laser excitation threshold, cholesteric liquid crystals, defect mode, photonic band gap

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

## 1. Introduction

Photonic crystals (PCs) consisting of artificial or self-organizing periodic structures have opened up possibilities for novel physics and device applications. PCs as laser cavities have been the focus of intense research in recent decades. Lasing in these structures takes place either due to the distributed feedback mechanism or defect modes (in PCs with defects), where spontaneous emission is inhibited in the wavelengths inside the photonic band gaps (PBGs) except at the band edges or defect modes where the photonic density of states (PDS) is large. Especially attractive is the use of cholesteric liquid crystals (CLCs) as band edge lasers which is connected with the fact that the macroscopic properties of CLCs can be manipulated by external stimuli. Lasing in CLCs and PCs has been intensely investigated (see, for instance [1–4], and the wide literature cited therein). The possibilities of decreasing the lasing threshold in CLCs and multilayer systems with CLC layers have been studied both theoretically [5–7] and experimentally [8]. In the following three papers [9–11] the effect of loss and gain on the PDS was reported. Dolganov reported in

[12] that a highly sensitive method was used to determine the PDS, as well as a drastic increase in the PDS near the PBG borders, and oscillations related to Pendellösung beatings were observed. It was reported in [13] about the design and fabrication of a wedge structured CLC film incorporating a spatial gradient of a chiral dopant concentration. A continuous spatial laser tuning in a broad visible spectral range with a tuning resolution less than 1 nm is demonstrated, which renders a CLC-based micron-sized laser an important continuously tunable laser device [13]. In the review article [14] the ways of employing CLCs in tunable dye lasers were discussed. The investigations in this direction have been continuing intensively because the CLCs exhibit new wonderful and multilateral peculiarities all the time (see, for example [15–24]). The performance of light emitting liquid crystal devices may be significantly improved by using more advanced optical structures. To develop new optical architectures one must have at one's disposal a fundamental understanding of absorption-emission processing and the PDS and their other important optical peculiarities, as well as accurate numerical design tools for their calculation.



**Figure 1.** The dependences (a, c) of the total field intensity  $|E|^2$  aroused at the left border of the defect layer and (b, d) the relative PDS  $\rho_{1,2}/\rho_{\text{iso}}$  (a, b) on the absorption parameter  $x = \ln(\text{Im } \varepsilon_m)$  and (c, d) on the parameter  $x' = \ln(-\text{Im } \varepsilon_m)$  characterizing gain at the given defect mode wavelength ( $\lambda = 631.5$  nm) for the diffracting (the red or light gray lines) and non-diffracting (the blue or dark gray lines) EPs. The dashed lines correspond to  $n_o'' = n_e'' = 0$  and  $n'' \neq 0$ , that is, when absorption/gain is absent in the CLC sublayers and it exists in the defect layer; and the solid lines correspond to the case when  $n_o'' = n_e'' \neq 0$  and  $n'' = 0$ , that is, if absorption/gain exists in the CLC sublayers and is absent in the defect layer. The CLC layer thickness is:  $d = 44p$ , the defect layer thickness is:  $d' = 1000$  nm.

In this letter we discuss the lasing peculiarities of a CLC layer with an isotropic defect layer inside.

## 2. Results and discussion

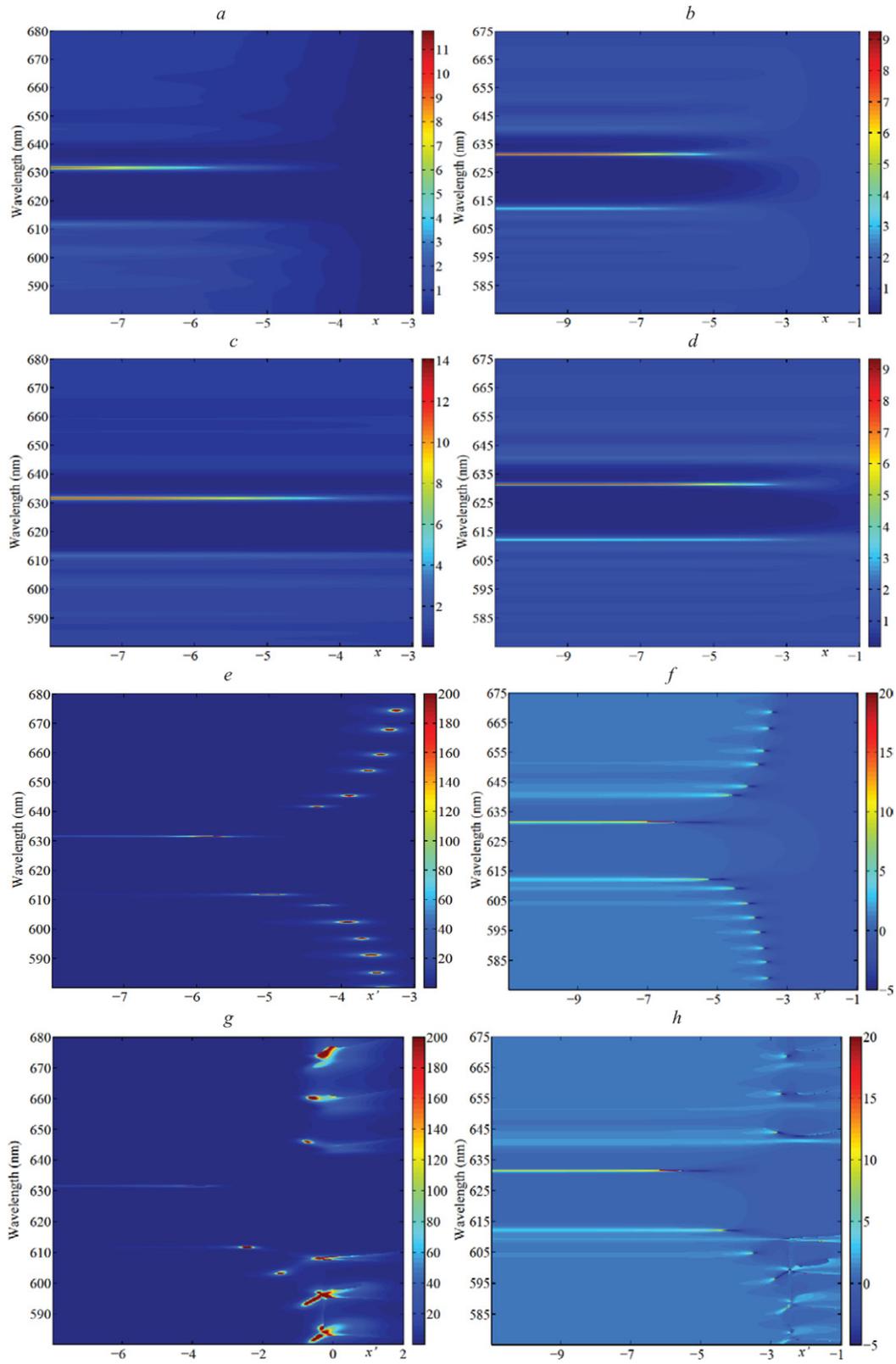
A CLC with an isotropic defect can be treated as a three-layer system: Two CLC layers (CLC(1) and CLC(2)) and an isotropic layer (IL) between them (or a Fabry–Perot resonator with diffraction mirrors and an IL filling). The ordinary and extraordinary refractive indices of the CLC layers are taken to be  $n_o = \sqrt{\varepsilon_2} = 1.4639$  and  $n_e = \sqrt{\varepsilon_1} = 1.5133$ ;  $\varepsilon_1, \varepsilon_2$  are the principal values of the CLC local dielectric tensor. The CLC layer helix is right handed and its pitch is:  $p = 420$  nm. These are the parameters of the CLC cholesteryl-nonanoate–cholesteryl-chloride–cholesteryl-acetate (20:15:6) composition at the temperature  $t = 25$  °C. Hence, the light normally incident onto a single CLC layer, with the right circular polarization (RCP), has a PBG (which is in the range of  $\lambda = 614.8 \div 635.6$  nm), and the light with the left circular polarization (LCP) does not have any. The defect IL refractive index was taken to be  $n = 1.8$ . The problem was solved by Ambartsumian’s layer addition modified method [25]. We investigated the peculiarities of the absorption, emission, and PDS of this system for eigen polarizations (EPs). The EPs are

the two polarizations of incident light, which do not change when light transmits through the system.

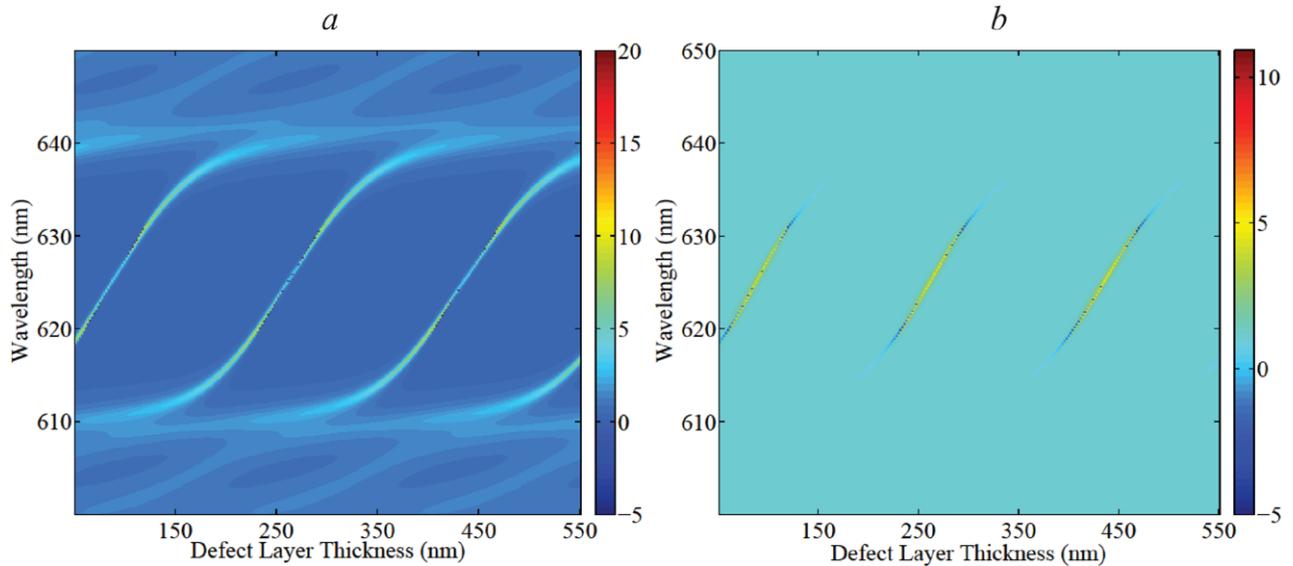
The presence of a thin defect in the CLC structure is known to initiate a defect mode in the PBG [26, 27]. First we investigate some new peculiarities of the PDS for this system. The investigation of the PDS  $\rho$  is important because of the following. For laser emission it has been shown that, for instance, analyzing the case of the Fabry–Perot resonator, the threshold gain  $g_{\text{th}}$  can be directly related to the maximum PDS  $\rho_{\text{max}}$ , that is,  $g_{\text{th}} \propto n/\rho_{\text{max}}d$ , where  $n$  is the refractive index inside the resonator of the length  $d$  [28]. 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  $\rho_{\text{max}}$  [29]. The PDS, i.e. the number of wave vectors  $k$  per unit frequency,  $\rho(\omega) = dk/d\omega$ , is the reverse of the group velocity and can be defined by the expression [29]:

$$\rho_i(\omega) \equiv \frac{dk_i}{d\omega} = \frac{1}{d} \frac{\frac{du_i}{d\omega} v_i - \frac{dv_i}{d\omega} u_i}{u_i^2 + v_i^2}, \quad i = 1, 2 \quad (1)$$

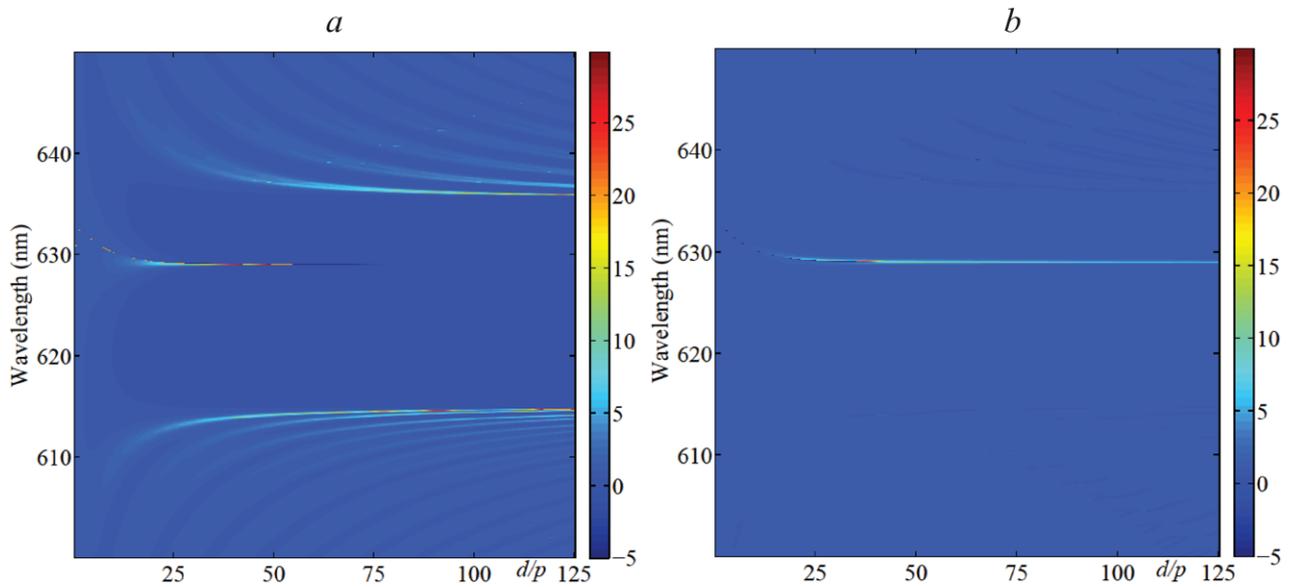
where  $d$  is the whole system thickness,  $\omega$  is the incident light frequency, and  $u_i$  and  $v_i$  are the real and imaginary parts of the transmission amplitudes;  $t_i(\omega) = u_i(\omega) + jv_i(\omega)$  are the transmission amplitudes for the incident light with the two



**Figure 2.** The evolution (a, c) of the total field intensity  $|E|^2$  spectra and (b, d) the PDS  $\rho_l/\rho_{iso}$  spectra if (a, b, c, d) the absorption parameter  $x = \ln(\text{Im } \epsilon_m)$  increases and if (e, f, g, h) the gain parameter  $x' = \ln(-\text{Im } \epsilon_m)$  increases, for the diffracting EP. (a, b, e, f) correspond to the case if  $n''_o = n''_e = 0$  and  $n'' \neq 0$ , and (c, d, g, h) correspond to the case if  $n''_o = n''_e \neq 0$  and  $n'' = 0$ . The parameters are the same as in figure 1.



**Figure 3.** The density plots for the PDS spectra versus the defect layer thickness.  $d' = 3000$  nm. The other parameters are the same as in figure 1.



**Figure 4.** The density plots for the PDS spectra versus the CLC layer thickness.  $d' = 2380$  nm. The other parameters are the same as in figure 1.

EPs, and  $j$  is the imaginary unit. For the single CLC layer the two EPs practically coincide with the two circular (right and left) polarizations. The values  $i = 1, 2$  correspond to the diffracting and non-diffracting EPs, respectively. For a CLC layer with a defect layer inside a jump of EPs takes place at the defect mode. For the isotropic case we have:  $\rho_{\text{iso}} = n_s/c$ , where  $n_s = \sqrt{\varepsilon_s}$  is the refractive index of the media surrounding the system and  $c$  is the speed of light in vacuum.

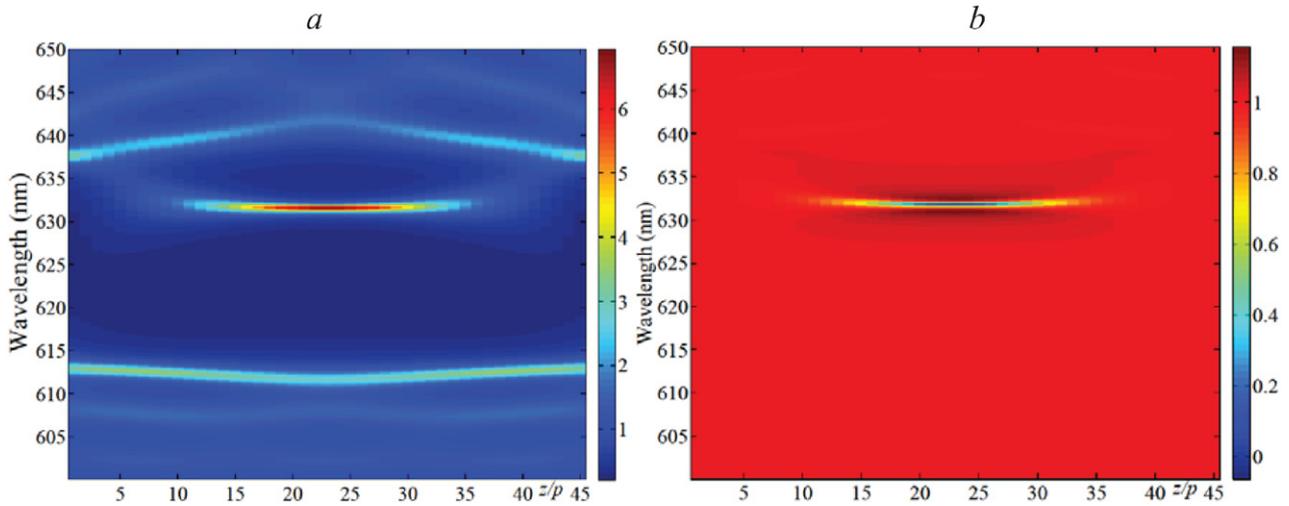
One must realize that the concept of the PDS introduced by equation (1) is not without controversy, especially in the case of non-periodic systems (for more detail about this see in [30]). Let us only note that although it is impossible to ascribe a direct physical meaning to the PDS in equation (1) in a general case, anyhow, it can be used as a parameter, which can provide some heuristic guidance in experiments for the PDS

dispersion-related effects. Moreover, as was shown in [9–12], equation (1) is applicable for finite PCs layers, even for cases with absorption and amplification (naturally, for weak ones).

Below we first show that this equation is applicable (at least qualitatively) to our (aperiodic) system both in the presence of absorption and amplification.

In [10, 11, 31], it was shown that in the absence of absorption, the PDS was proportional to the integral of the energy stored within the medium. Then in [10, 11], it was shown that it takes place both in the presence of absorption and gain.

In figure 1 the dependences (a, c) of the total field intensity  $|E|^2$  aroused at the left border of the defect layer and (b, d) the relative PDS  $\rho_{1,2}/\rho_{\text{iso}}$  (a, b) on the absorption parameter  $x = \ln(\text{Im } \varepsilon_m)$  and (c, d) on the parameter  $x' = \ln(-\text{Im } \varepsilon_m)$  characterizing the gain at the given defect mode wavelength



**Figure 5.** The density plots for the PDS spectra versus the defect layer position ( $z/p$ ). The parameters are the same as in figure 1.

$\lambda = 631.5$  nm are presented for the diffracting (the red or light gray lines) and non-diffracting (the blue or dark gray lines) EPs ( $\varepsilon_m = \frac{\varepsilon_1 + \varepsilon_2}{2}$  is the mean dielectric permittivity of CLC). The dashed lines correspond to the case if  $n_o'' = n_e'' = 0$  and  $n'' \neq 0$ , that is, if absorption/gain is absent in the CLC sublayers and is present in the defect layer; and the solid lines correspond to the case if  $n_o'' = n_e'' \neq 0$  and  $n'' = 0$ , that is, if absorption/gain is present in the CLC sublayers and is absent in the defect layer.

In figure 2 the evolution (*a*, *c*) of the total field intensity  $|E|^2$  spectra and (*b*, *d*) the relative PDS  $\rho_1/\rho_{\text{iso}}$  spectra when (*a*, *b*, *c*, *d*) the absorption parameter  $x = \ln(\text{Im } \varepsilon_m)$  increases and when (*e*, *f*, *g*, *h*) the gain parameter  $x' = \ln(-\text{Im } \varepsilon_m)$  increases are presented for the diffracting EP. (*a*, *b*, *e*, *f*) correspond to the case if  $n_o'' = n_e'' = 0$  and  $n'' \neq 0$ , and (*c*, *d*, *g*, *h*) correspond to the case if  $n_o'' = n_e'' \neq 0$  and  $n'' = 0$ .

The presented results show that at sharp changes of  $|E|^2$  and, consequently, also for the energy stored within the system, depending on the parameters  $x$  and  $x'$ , the expression  $\rho_1/\rho_{\text{iso}}$  also possesses sharp changes versus the same parameters. This means that equation (1) can also describe laser peculiarities of periodic systems with a defect in their structure. At the same time these figures give information about laser peculiarities of CLC layers with defects inside them in the presence of absorption and amplification. In particular, as can be seen in figure 1, the modulus of the PDS decreases dramatically with the increase of the absorption parameter  $x = \ln(\text{Im } \varepsilon_m)$ , as it takes place for a single CLC layer at the band gap border wavelengths. The maximum of the PDS increases with the gain increase. The further increase of gain leads to a resonance-like change with the maximum spikes in the PDS. There exists a critical value of  $x'$  beyond which the lasing mode is quenched and the feedback vanishes. Note that the critical values of  $x'$  for the case if gain is present in the CLC sublayers and that for the case if it is absent in the defect layer, and vice versa, are different. The existence of these critical values of gain indicates the possibility that the subject system can work as a trigger. Tuning the pumping intensity by a suitable dye molecule density or by the pump laser intensity, one can pass from the laser generation regime to the quenching one.

For a single CLC layer, as the gain increases in the absence of the defect layer, the maximum PDS shifts away from the PBG border, and this does not take place continuously, but in discrete steps [10, 11]. Note that when going away from the PBG borders, the critical value of  $x'$  (beyond which the lasing mode is quenched) increases. As seen in figure 2(e) if a defect layer is present and the gain increases, the PDS increases too, and then quenching takes place, although first it takes place for the defect mode wavelength. It should be noted that not all modes outside the PBG exist in the case if gain is absent in the CLC layers and it exists in the defect layer. Again, let us note that these changes also take place for  $|E|^2$ .

Then we considered the influence of the defect layer thickness on the relative PDS. In figure 3 the evolution of the relative PDS,  $\rho_{1,2}/\rho_{\text{iso}}$ , spectra when the defect layer thickness increases are presented for (*a*) the diffracting and (*b*) non-diffracting EPs. As is well known, the defect mode wavelength increases from a minimum to a maximum band gap value if the defect layer optical thickness increases. As we can see in this figure, for this change of the defect layer thickness, the relative PDS  $\rho_{1,2}/\rho_{\text{iso}}$  on the defect mode does not change smoothly, but with strong oscillations. This means that there exists a definite value of the defect layer thickness at which the lowest threshold lasing takes place.

Now we investigate the influence of the CLC layer thickness on the relative PDS. In figure 4 the evolution of the relative PDS spectra if the CLC layer thickness increases are presented for the (*a*) diffracting and (*b*) non-diffracting EPs. As is seen in the figure, although low threshold lasing takes place both for the diffracting and non-diffracting EPs only for small CLC layer thicknesses, nevertheless, for CLC layer large thicknesses it takes place only for the non-diffracting EPs.

Let us now consider how the position of the defect layer in the system affects the defect mode features. Figure 5 shows the dependences of the relative PDS on the defect position in the structure ( $z/p$ , where  $z$  is counted from the left boundary the CLC layer) for the (*a*) first and (*b*) second EPs. As is seen in the figure, laser generation with the least threshold takes place if the defect layer is in the CLC layer center. It can be

seen in the figure that the defect location also significantly influences the PBG width, essentially influencing the PBG border near where the defect mode is.

### 3. Conclusions

Let us note in conclusion that we investigated the lasing peculiarities of a CLC layer with a defect inside its structure. We showed that the PDS defined in [29] are also applicable (qualitatively, at least) to the subject system. In the case of the CLC layer with an isotropic defect layer inside on the defect mode, the  $\rho_{1,2}/\rho_{\text{iso}}$  is extreme at the defect mode wavelength, with a larger height than that at the PBG borders. This provides laser generation with a much lower threshold at the defect modes than that at the PBG borders. Then we investigated the influence of absorption and gain on the PDS and the light field intensity in the defect. Our investigation of the influence of the defect layer thickness on the PDS showed that at the defect layer thickness changes the relative PDS  $\rho_{1,2}/\rho_{\text{iso}}$  does not change smoothly, but with strong oscillations. Furthermore, when investigating the influence of the CLC layer thickness on the PDS we showed that although for small CLC layer thicknesses low threshold lasing takes place both for diffracting and non-diffracting EPs, nevertheless, for larger thicknesses it takes place only for the non-diffracting EPs. Finally, we investigated the defect location influence on the lasing peculiarities of the system.

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