УДК 532.783

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LOCALIZED MODES AND THEIR EFFICIENT MANIFESTATION IN OPTICS OF CHIRAL LIQUID CRYSTALS

ЛОКАЛИЗОВАННЫЕ МОДЫ И ИХ ПРОЯВЛЕНИЕ В ОПТИКЕ ХИРАЛЬНЫХ ЖИДКИХ КРИСТАЛЛОВ

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A brief survey on investigations of localized optical modes (edge modes (EM) [1,2] and defect modes (DM) [1,3]) in chiral liquid crystals (CLC) as well as the original results on the analytic theory of edge and defect modes are presented.
Key words: *photonic liquid crystals, edge modes, defect modes, low-threshold lasing.*

Представлен краткий обзор исследований локализованных оптических мод (краевые моды (EM) [1, 2] и дефектные моды (DM) [1,3] в хиральных жидких кристаллах (CLC), а также оригинальные результаты, относящиеся к аналитической теории краевых и дефектных мод.
Ключевые слова: *фотонные жидкие кристаллы, краевые и дефектные моды, низкопороговая лазерная генерация.*

The main experimental results which have to be understood and explained for lasing at localized optical modes are unusually low lasing threshold for DFB lasing [1] and existence of the anomalously strong absorption effect [4] in CLC at the localized mode frequency. The analytic study is facilitated by the choice of the problem parameters. Namely, for DM a defect layer (with the averaged dielectric susceptibility equal to the average dielectric susceptibility of the CLC) sandwiched between two CLC layers inserted in an isotropic medium with the dielectric constant equal to the average dielectric constant of the CLC is studied. The chosen model allows one to get rid off the polarization mixing at the external surfaces of the localized mode structure (LMS) and to reduce the corresponding equations to the equations for light of circular diffracting in the CLC polarization only. The dispersion equations determining connection of the EM and DM frequency with the CLC layers parameters and other parameters of the LMS are obtained. Schematic of the boundary problem for EM is presented at fig. 1.

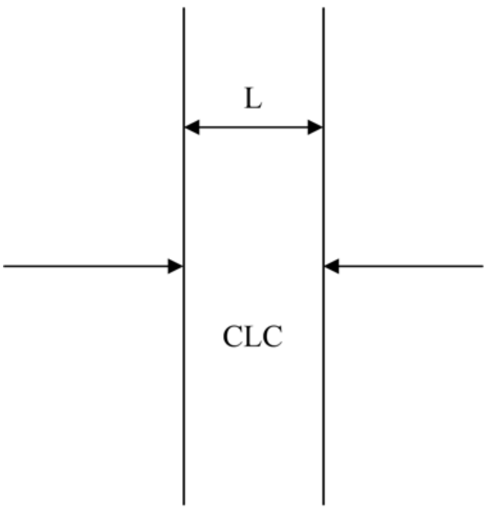

Fig. 1.

Analytic expressions for the transmission and reflection coefficients of the LMS are presented and analyzed. For EM (fig. 1) amplitude reflection R(L) and transmission T(L) coefficients for light of diffracting circular polarization are:

$$R(L)= i\delta\sin qL/\{(q\tau/\kappa^2)\cos qL +i[(\tau/2\kappa)^2+ (q/\kappa)^2-1]\sin qL\}$$

$$T(L)=\exp[i\tau L/2](q\tau/\kappa^2)/\{(q\tau/\kappa^2)\cos qL +i[(\tau/2\kappa)^2+ (q/\kappa)^2-1]\sin qL\}, \qquad (1)$$

where $\kappa =\omega\varepsilon_0^{1/2}/c$, $q = \kappa\{1+(\tau/2\kappa)^2-[(\tau/\kappa)^2 + \delta^2]^{1/2}\}^{1/2}$, $\varepsilon_0 =(\varepsilon_\parallel+ \varepsilon_\perp)/2$, $\delta =(\varepsilon_\parallel- \varepsilon_\perp)/(\varepsilon_\parallel+ \varepsilon_\perp)$ is the dielectric anisotropy, and $\varepsilon_\parallel$, $\varepsilon_\perp$ are the local principal values of the LC dielectric tensor and $\tau=4\pi/p$, where p is the cholesteric pitch, is the reciprocal lattice vector of the CLC spiral. The dispersion equation:

$$\mathrm{tg}\, qL= i(q\tau/\kappa^2)/[(\tau/2\kappa)^2+ (q/\kappa)^2-1] \qquad (2)$$

determines the discrete frequencies of the EM which are complex quantity for finite L (i.e. correspond to a EM finite life-time). Under the condition $(L\delta/pn) \gg 1$ the life-time of the EM (where n is the EM number) is given by

$$\tau_m \approx (1/4)(\varepsilon_0^{1/2}L/c)(L\delta/pn)^2. \qquad (3)$$

Hence, for sufficiently thick CLC layers as their thickness L increases the EM life-time τ_m increases as the third power of the thickness and is inversely proportional to the square of the EM number n connected with the EM frequency by the relation $qL=n\pi$. The distribution of the EM energy in the layer for the n = 1,2,3 is shown at fig. 2 (L/p=200, the number of maxima at each curve coincides with n).

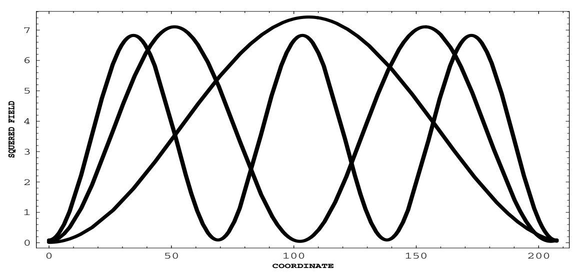

Fig. 2

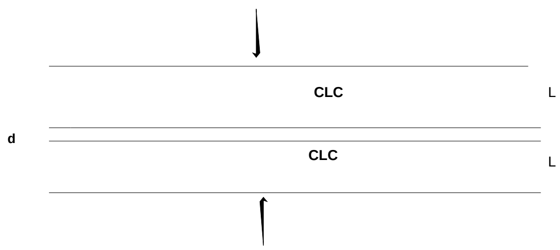

Fig. 3

The studies of DM [3] for LMS presented at fig. 3 result in the following. To be specific as defect layers d were considered isotropic, birefringent, absorbing and amplifying layers in a perfect CLC structure. The transmission $|T(d,L)|^2$ and reflection $|R(d,L)|^2$coefficients for DM structure (fig. 3) with an isotropic defect layer for light of diffracting circular polarization are:

$$|T(d,L)|^2=|[T_eT_d\exp(ikd)]/[1-\exp(2ikd) R_dR_u]|^2,$$

$$|R(d,L)|^2=|\{R_e+R_u T_eT_u\exp(2ikd)/[1-\exp(2ikd) R_dR_u]\}|^2, \qquad (4)$$

where $R_e(T_e)$, $R_u(T_u)$ and $R_d(T_d)$ are the amplitude reflection (transmission) coefficients of the CLC layer (see fig. 1) for the light incidence (fig. 3) at the outer (top) layer surface, for the light incidence at the inner top CLC layer surface from the inserted defect layer and for the light incidence at the inner bottom CLC layer surface from the inserted defect layer, respectively.

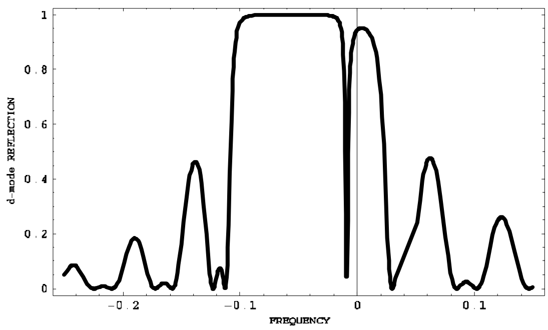

Fig. 4.

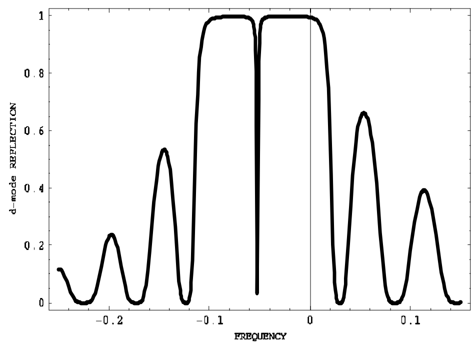

Fig. 5.

Calculations of reflection coefficient ($\delta = 0{,}05$, $l = 200$, $l = L\tau = 2\pi N$, where N is the director half-turn number at the CLC layer thickness L) for isotropic defect layer presented at fig. 4 ($d/p = 0{,}1$) and fig. 5 ($d/p = 0{,}25$) reveal strong dependence of the DM frequency (corresponding to the reflection minimum) on d. At fig. 4 and in all figures below the parameters of LMS are the same as at fig. 4 and at the frequency axis the frequency deviation from the stop band edge is plotted (normalized by the Bragg frequency multiplied by δ).

The DM frequencies ω_D (which are complex quantity for finite L, i. e. correspond to a finite DM life-time) are determined by the following dispersion equation:

$$\{\exp(2ikd)\sin^2 qL-\exp(-i\tau L)[(\tau q/\kappa^2)\cos qL+i((\tau/2\kappa)^2+(q/\kappa)^2-1)\sin qL]^2/\delta^2]\}=0. \qquad (5)$$

The maximum for the DM life time τ_D corresponds to the location of the DM frequency just at the middle of the stop band. For thick CLC layers in the LMS and the DM frequency at the middle of the stop band at the condition $|q|\, L \gg 1$ the life-time τ_D is:

$$\tau_D = (3\varepsilon_o^{1/2}/4)(L/c)\exp[2\pi\delta L/p], \qquad (6)$$

i. e. grows exponentially with the thickness increase. The coordinate distribution of DM intensity at DM frequency for infinitely thick CLC layers in the fig. 3 are presented at fig. 6 (with the distance normalized by p and $\delta = 0{,}05$; 0,1; 0,2 from the top to the bottom, respectively.

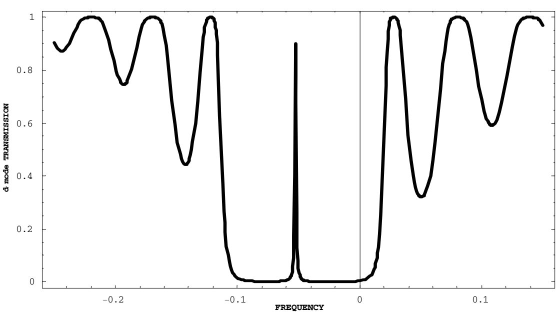

Fig. 6.

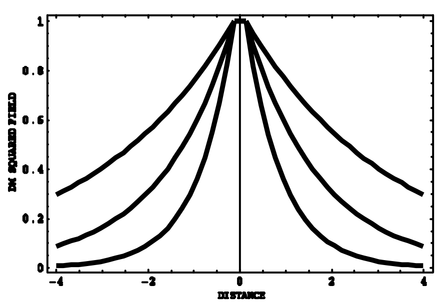

Fig. 7.

The localized EM and DM reveal themselves in a number of optical phenomena, the most known is DFB lasing. The lasing threshold for DFB lasing occurs to be lower than in the conventional lasing. The main corresponding results are as the following. An active media in lasing should be amplifying at the lasing frequency and absorbing at the pumping frequency. To take into account the absorption or amplification in the active media we define the ratio of the dielectric constant imaginary part to the real part of ε for the active media (CLC) as γ, i. e. $\varepsilon=\varepsilon_0(1+i\gamma)$ with positive and negative γ for absorbing and amplifying media, respectively. It happens that the lasing threshold for DFB lasing at the frequency of localized modes is decreasing with the CLC layers thickness increase. In a general case one has to solve numerically the dispersion equation (2) for EM and (5) for DM, respectively, relative to γ [2, 3]. In the case of thick CLC layers γ corresponding to the lasing threshold for DFB lasing may be found analytically [2, 3]:

$$\gamma = -\delta(n\pi)^2/(\delta L\tau/4)^3 \text{ for EM and } \gamma = -(4/3\pi)(p/L)\exp[-\pi\delta(L/p)] \text{ for DM.} \qquad (7)$$

The discussed here lowering of the lasing threshold is observed experimentally [1]. Another option to reduce the lasing threshold is connected with the anomalously strong absorption effect in CLC which reveals itself at the frequencies of localized modes in absorbing media [4]. The experimental observation of this option (to reduce the lasing threshold) was reported in [5] where the pumping frequency was coinciding with the EM frequency at the short wave length edge of the stop band and the lasing frequency was coinciding with the EM frequency at the long wave length edge of the stop band. Under these circumstances a low threshold lasing at the EM frequency and an enhanced absorption (at another EM frequency) were ensured simultaneously resulting in a further lowering of the lasing threshold.

Another effects are related to the LMS presented at fig. 3 in the case of active (birefringent, absorbing or amplifying) defect layers. It is shown [6, 7] that the layer birefringence reduces the DM life-time in comparison with the case of LMS with an isotropic defect layer and only at discrete values of LMS parameters it achieves the value of the corresponding LMS with an isotropic defect layer. The cause of it is the light polarization conversion in the defect layer resulting in transformation of the diffracting polarization light into light of nondiffracting polarization escaping from the LMS. In the case of a defect layer with low birefringence the transmission $|T(d,L)|^2$ and reflection $|R(d,L)|^2$ coefficients for DM structure (fig. 3) with a birefringent defect layer for light of diffracting circular polarization are:

$$|T(d,L)|^2 = |[T_e T_d \exp[ikd]\cos(\Delta\varphi/2)]/[1-\exp[i2kd]\cos^2(\Delta\varphi/2)R_d R_u]|^2, \qquad (8)$$

$$|R(d,L)|^2 = |\{R_e + R_d T_e T_u \exp[i2kd]\cos^2(\Delta\varphi/2)/[1-\exp[i2kd]\cos^2(\Delta\varphi/2)R_d R_u]\}|^2, \quad (9)$$

where $\Delta\varphi$ is the phase difference of two beam component with different linear eigen polarization at propagation in the defect layer of thickness d. At small $\Delta\varphi$ the spectral shape of transmission and reflection are the same as for an isotropic defect layer (see fig. 7). However, for larger $\Delta\varphi$ the spectral shape of transmission and reflection changes significantly (see fig. 8, fig. 9 for $\Delta\varphi = \pi/16$, $\pi/8$, respectively).

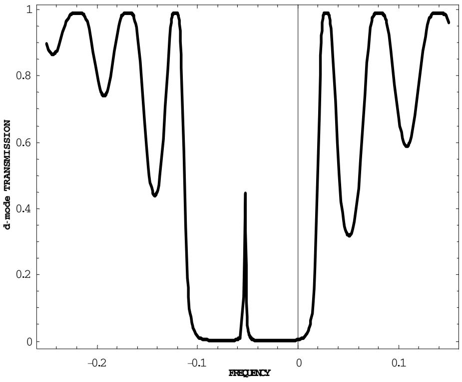

Fig. 8.

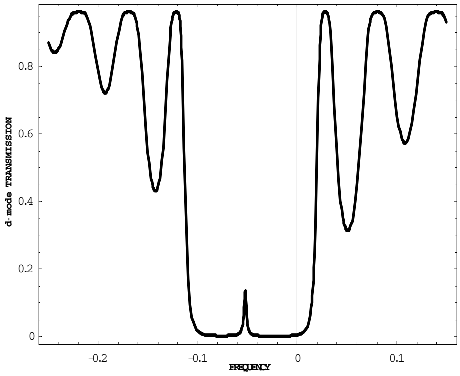

Fig. 9.

Correspondingly, the effect of anomalously strong light absorption (and amplification) at the defect mode frequency and, consequently, the lowering of the lasing threshold are not so pronounced for a birefringent defect layer as in the case of the LMS with an isotropic defect layer. The effect of anomalously strong light absorption at the DM frequency for absorbing defect layer is discussed. It is shown that in DFB lasing at LMS with an amplifying defect layer an adjusting of the pumping frequency to the DM or EM frequency results in a significant lowering of the lasing threshold and the threshold gain is lowering with increase of defect layer thickness. The options of effectively influence at the DM properties by varying the defect layer parameters are discussed. Examples of the localized mode influence on some other optical phenomena in CLC (e. g. nonlinear frequency conversion, Cherenkov radiation etc.) are briefly discussed.

The work is supported by the RFBR grants № 11-02-90419-Ucr-f-a and № 12-02-01016-a.

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Поступила в редакцию 19.09.2012 г.