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ANALYTIC THEORY OF LOW THRESHOLD LASING IN PHOTONIC SPIRAL MEDIA

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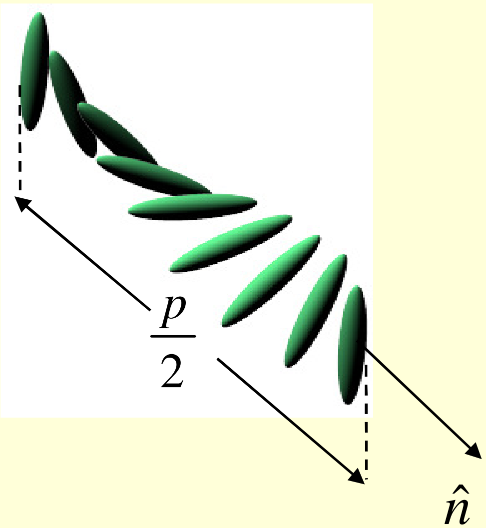
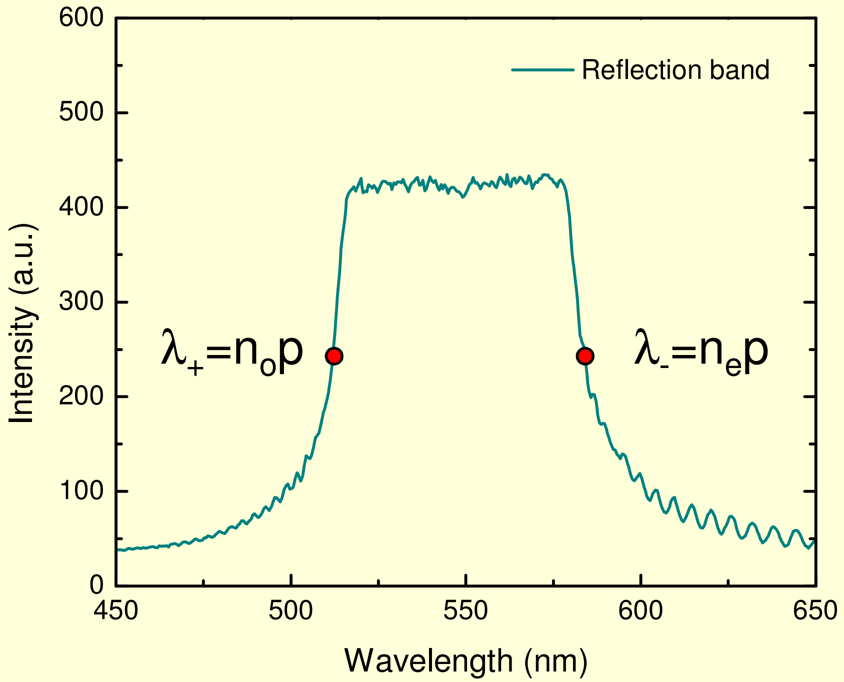
LOCALIZED OPTICAL MODES IN CLC: APPLICATION TO LASING AND OTHER OPTICAL PHENOMENA

1. INTRODUCTION
2. EIGEN WAVES IN CHIRAL LC
3. BOUNDARY PROBLEM (EDGE MODE)
4. ABSORBING LC
5. AMPLIFYING LC
6. OPTIMIZATION OF PUMPING
7. DEFECT MODES
8. ACTIVE DEFECT LAYER (BIREFRINGENT, AMPLIFYING, ABSORBING and so on)
9. CONCLUSION

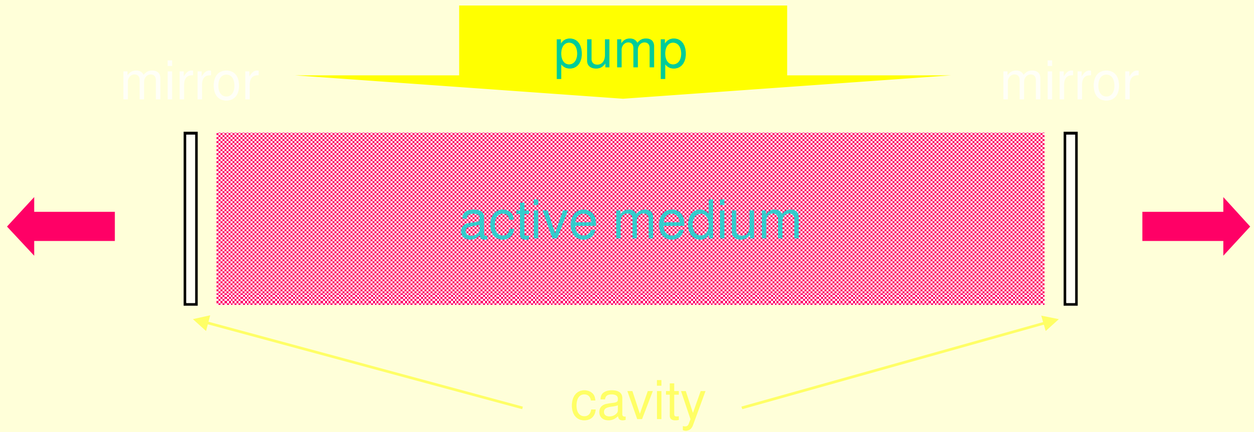
Cholesteric Liquid Crystal



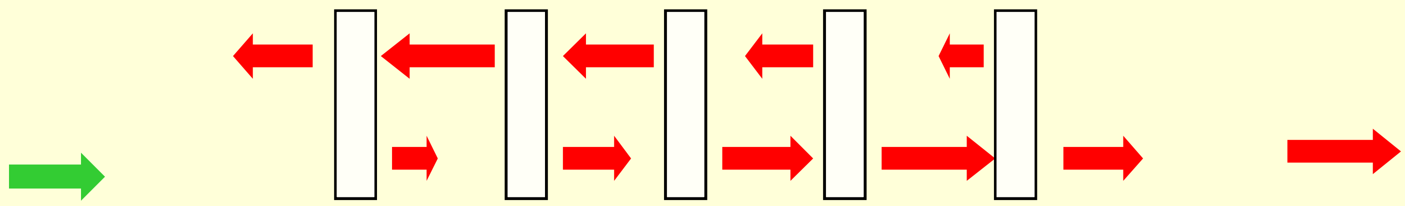
$$\lambda = n(T)\,p(T)$$

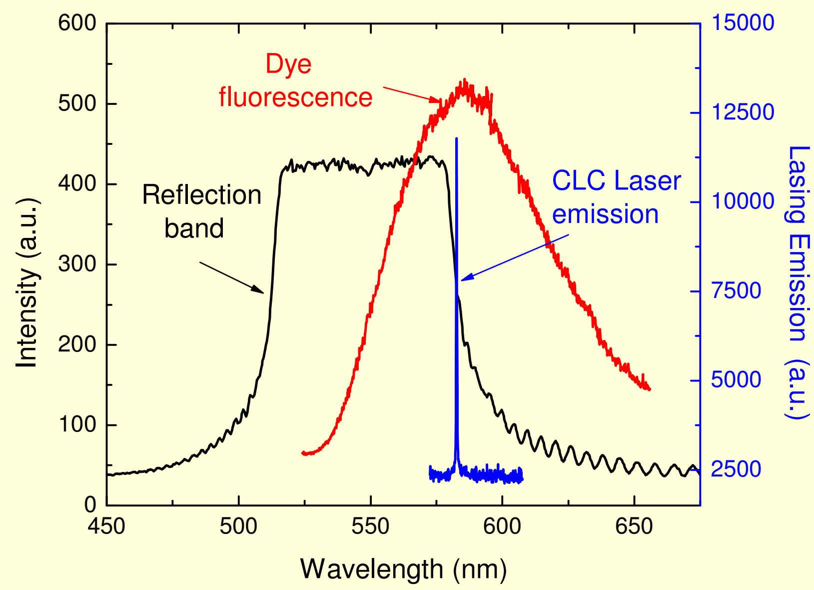


Lasing



Cholesteric Liquid Crystal Laser





Mirrorless laser

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FITTING THEORY AND EXPERIMENT

Edited by I.M. Khalatnikov
Director, L.D. Landau Institute of Theoretical Physics,
USSR Academy of Sciences, Moscow

Optics of Chiral Liquid Crystals

V.A. Belyakov & V.E. Dmitrienko

VOLUME 13, PART 1 (1989)

Soviet Scientific Reviews are published by harwood academic publishers

V.A. Belyakov

Diffraction Optics of Complex-Structured Periodic Media

With 86 Illustrations

Springer-Verlag , 1992.
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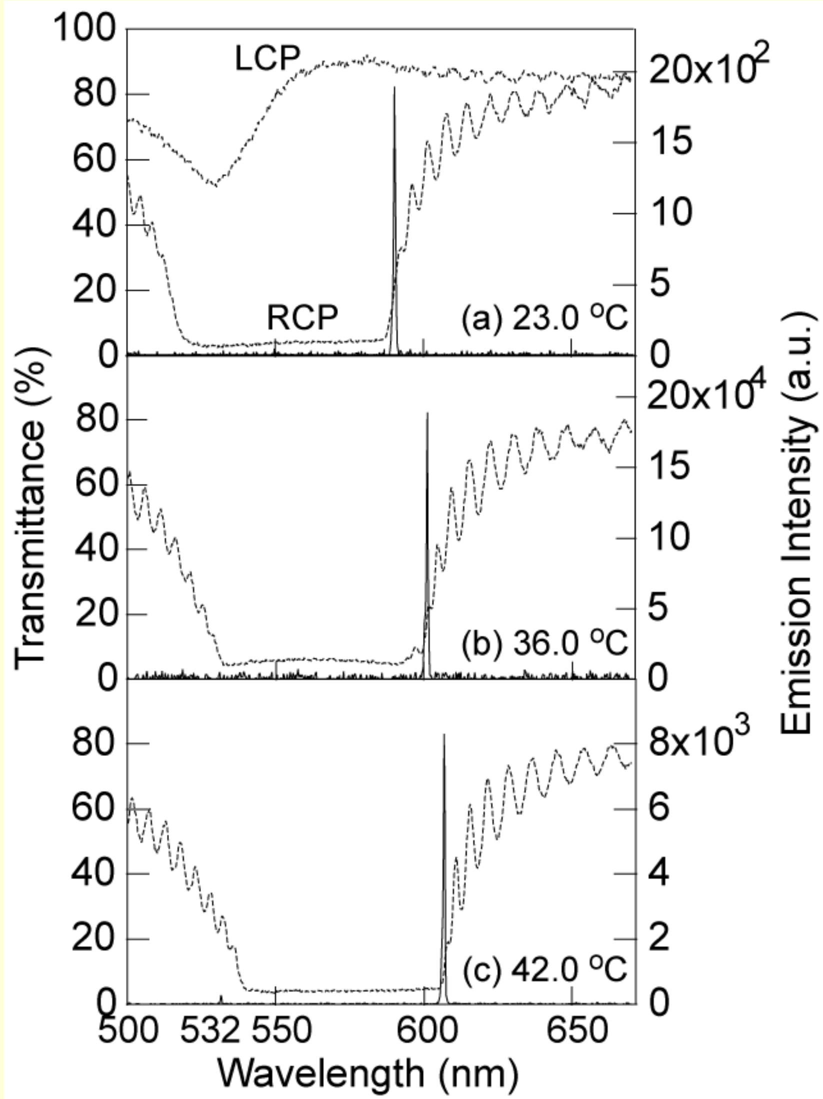


Fig. 1, Matsuhisa et al, Appl. Phys. Lett. 90, 091114 (2007)

EIGEN WAVES IN CHIRAL LC

As it is known [7,8,9] the eigenwaves corresponding to propagation of light in chiral LC along a spiral axes, i.e. the solution of the Maxwell equation

$$\partial^2\mathbf{E}/\partial z^2 = c^{-2}\, \boldsymbol{\varepsilon}(z)\, \partial^2\mathbf{E}/\partial t^2 \qquad (28)$$

are presented by a superposition of two plane waves of the form

$$\mathbf{E}(z,t) = e^{-i\omega t}\,[\mathbf{E}^{+}\mathbf{n}_{+}\exp(i\mathbf{K}^{+}\mathbf{z}) + \mathbf{E}^{-}\mathbf{n}_{-}\exp(i\mathbf{K}^{-}\mathbf{z})] \qquad (29)$$

where ω is the light frequency, $\mathbf{n}_{\pm}$ are the two vectors of circular polarizations, $\varepsilon(z)$ is the dielectric tensor of the chiral liquid crystal [7 - 10], c is the light velocity and the wave vectors $\mathbf{K}^{\pm}$ satisfy to the condition

$$\mathbf{K}^{+} - \mathbf{K}^{-} = \tau, \qquad (30)$$

where τ is the reciprocal lattice vector of the LC spiral ($\tau=4\pi/p$, where p is the cholesteric pitch).

The wave vectors **K**$^{\pm}$ in the four eigen solutions (29) are determined by the eq.(30) and the following formulas

$$K_j^{+} = \tau/2 \pm \kappa\{1+(\tau/2\kappa)^2 \pm [(\tau/\kappa)^2 + \delta^2]^{1/2}\}^{1/2}, \qquad (31)$$

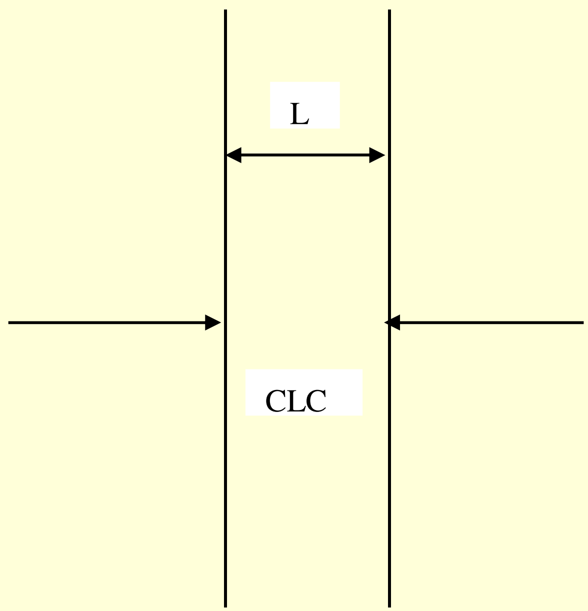
Where j numerates the eigen solutions with the ratio of amplitudes (E^-/E^+) given by the expression

$$\xi_j=(E^-/E^+)_j = \delta/[(K_j^{+} - \tau)^2/\kappa^2-1], \qquad (32)$$

where $\kappa = \omega\varepsilon_0^{1/2}/c$, $\varepsilon_0 = (\varepsilon_{\parallel}+ \varepsilon_{\perp})/2$, $\delta = (\varepsilon_{\parallel} - \varepsilon_{\perp}) / (\varepsilon_{\parallel}+ \varepsilon_{\perp})$ is the dielectric anisotropy, and $\varepsilon_{\parallel}$, $\varepsilon_{\perp}$ are the principal values of the LC dielectric tensor [8 - 10]. Define the ratio of the dielectric constant imaginary part to the real part as γ, i.e.

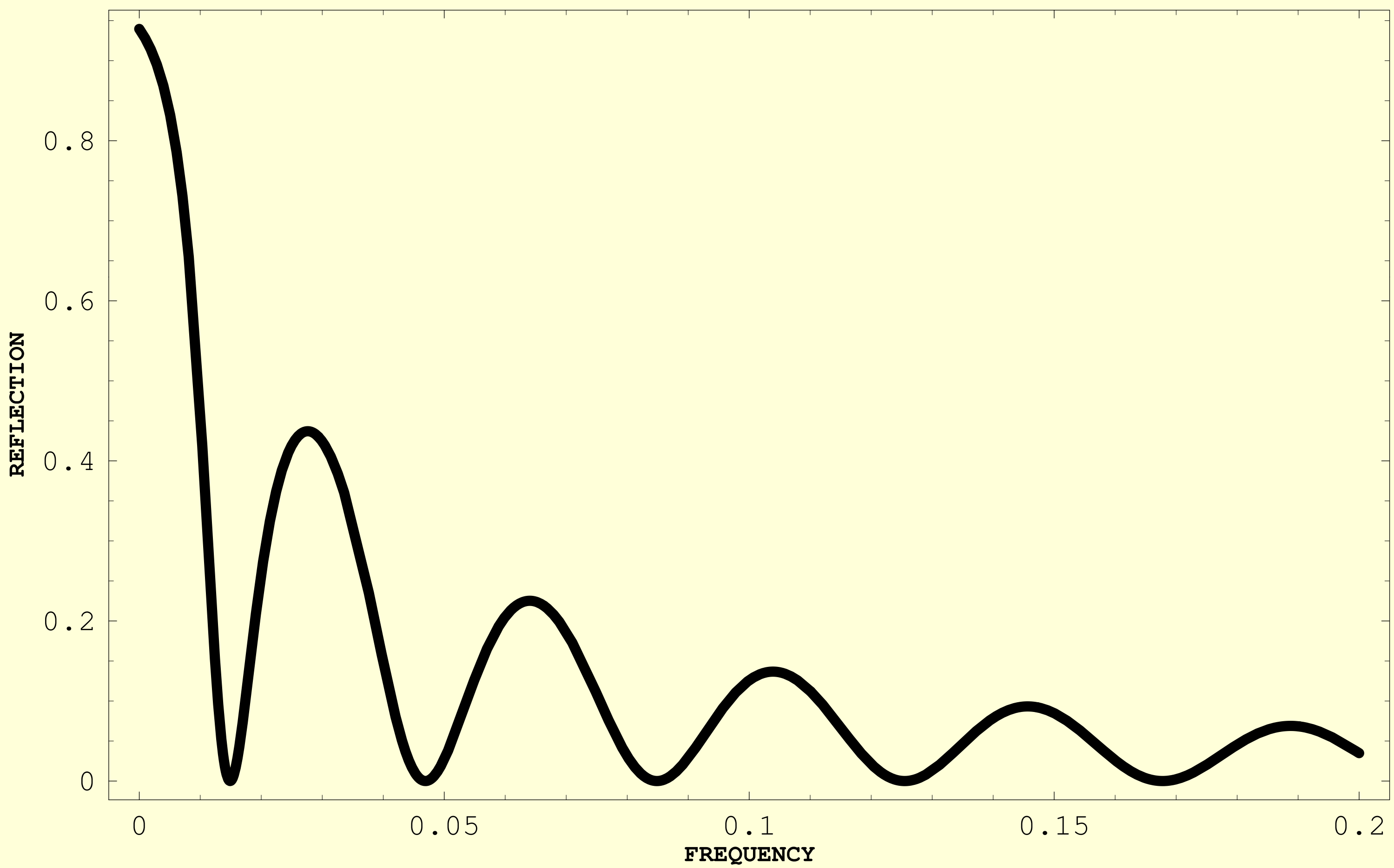
$$\varepsilon=\varepsilon_0(1+i\gamma).$$

Schematic of the boundary problem for edge modes



UNABSORBING LC LAYER

γ=0 ($\delta(\nu$-1) is plotted at the abscissa, see below)



EM frequencies

It occurs that for nonabsorbing LC layers the real parts of EM frequencies are coinciding with the positions of the beats minima of the reflection coefficient R.

The frequency positions of the beats minima of the reflection coefficient R correspond to

$$qL=\pi n, \ \ \pm\nu=1+(\pi n/a)^2/2, \ \ \ n= 1, \ 2, \ 3 \ \ldots..,$$

$$\nu=2(\omega-\omega_B)/\delta\omega_B, \ \omega_B = c\tau/2e_0^{1/2}, \qquad\qquad a= \delta L\tau/4.$$

The complex frequencies are determined by the dispersion equation (the solvability condition of the homogeneous Eqs.(8)) :

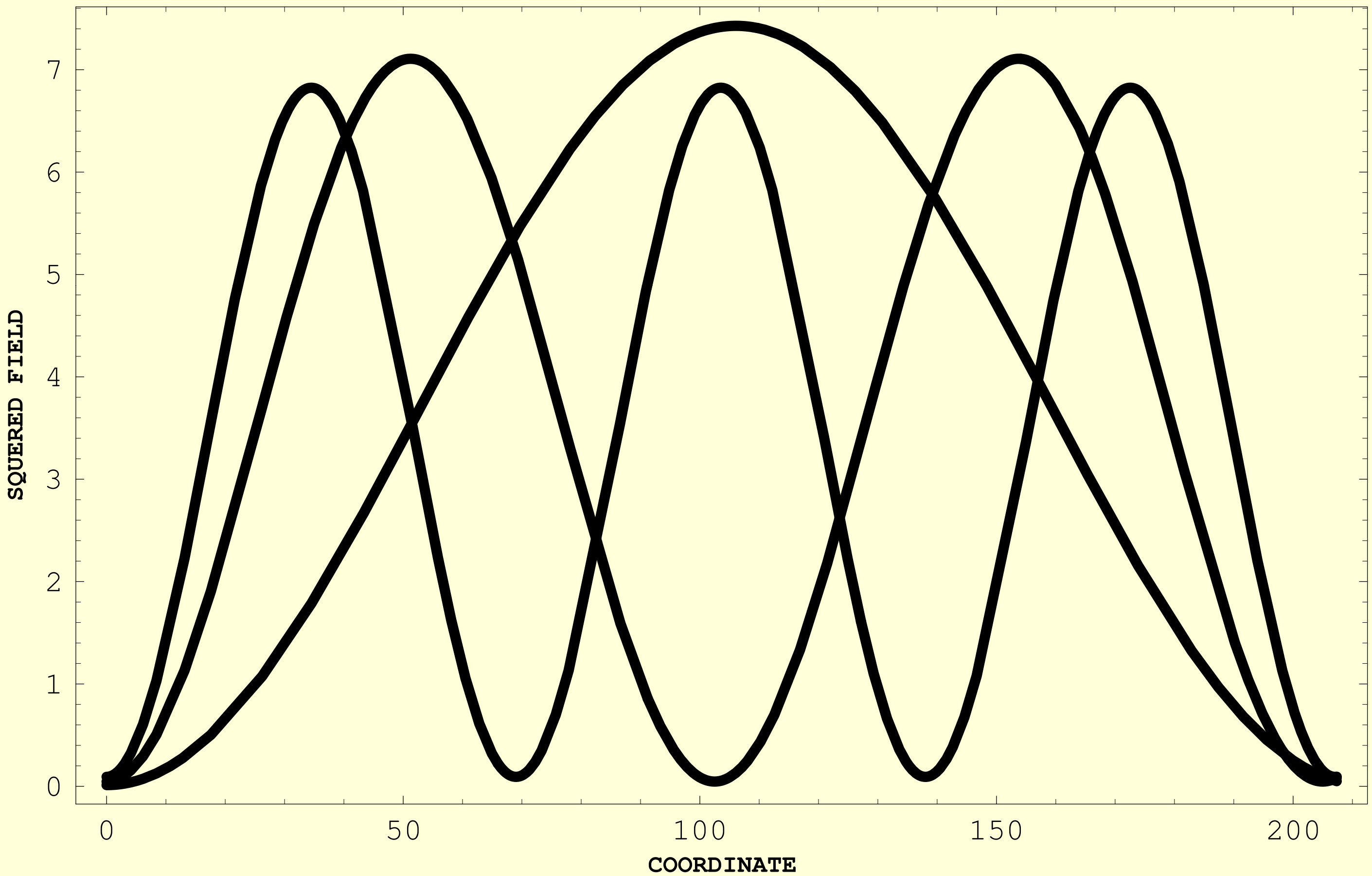
$$\mathbf{tgqL= i(q\tau/\kappa^2)/[(\tau/2\kappa)^2+ (q/\kappa)^2-1]} \qquad\qquad \mathbf{(12)}$$

In a general case the solution of Eq.(12) determining the EM frequencies $\omega_{EM} =\omega^0{}_{EM}(1+i\Delta)$ may be found only numerically. For a sufficiently small Δ ensuring the condition LImq<<1 an analytic solution exists:

$$\Delta=-\tfrac{1}{2}\,\delta(n\pi)^2/(\delta L\tau/4)^3.$$

The corresponding EM life-time is ♦=(L/c)(δL/pn)^2

Calculated EM coordinate (in the dimensionless units $z\tau$) energy distribution inside the CLC layer for the three first edge modes (δ=0.05, N=33, n=1,2,3).



anomalously strong absorption (1-R-T)

(at the edge mode frequencies (a) γ=0.001, (b) γ=0.005)

Fig.1a

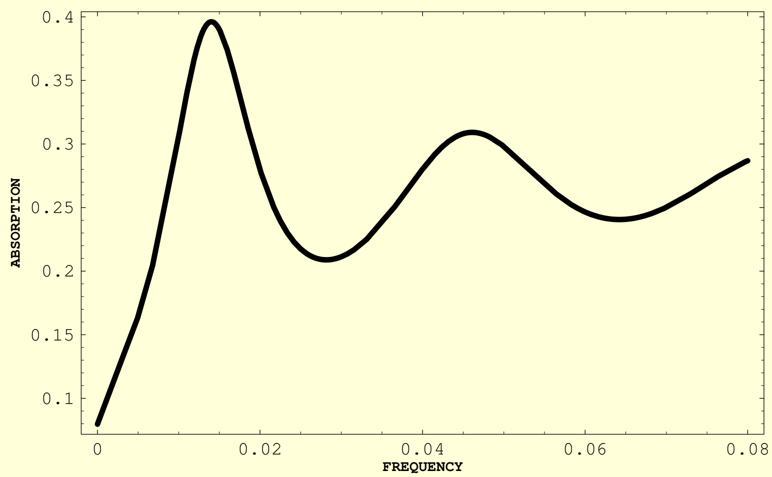
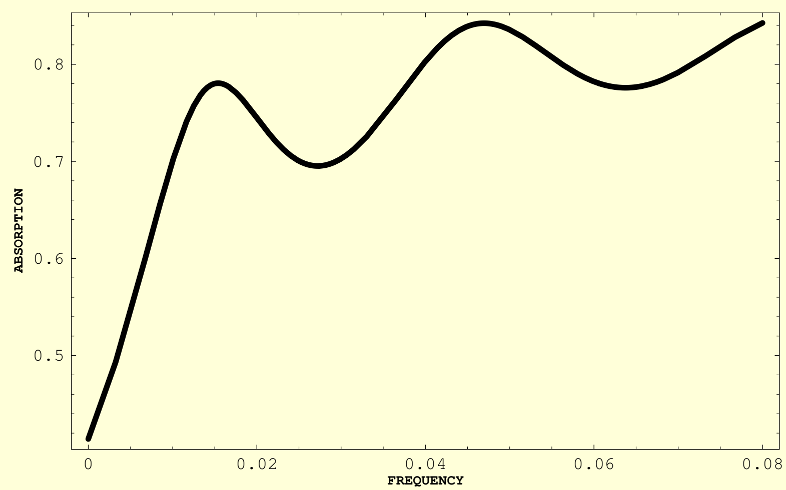
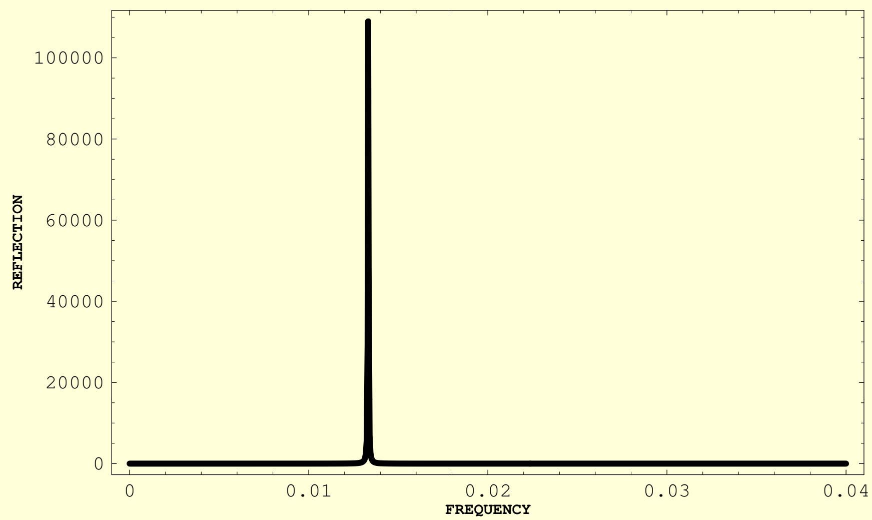


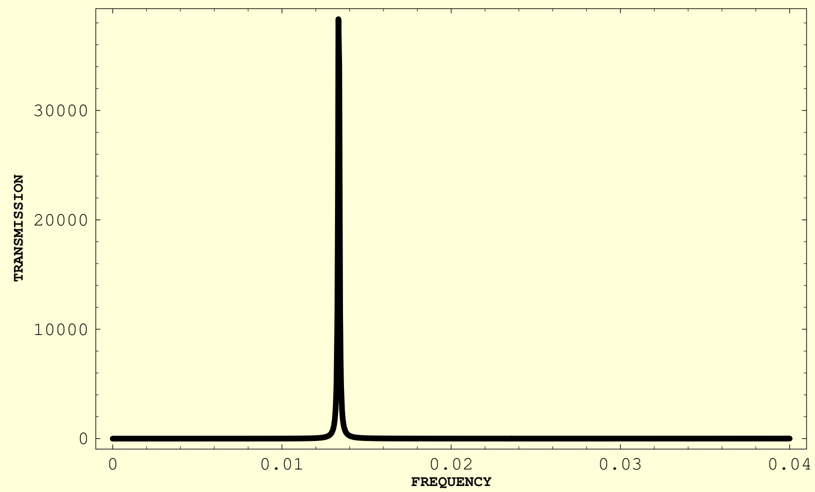
Fig.1b



REFLECTION AND TRANSMISSION CLOSE TO FIRST EDGE LASING MODE

γ=- 0.00565 (δ=0.05, $4\pi L/p$=300)





Edge lasing modes

The equation determining the edge lasing modes (at $\gamma<0$) is given by the following expression:

$$tgqL= i(q\tau/\kappa^2)/[\tau/2\kappa)^2+ (q/\kappa)^2-1] \qquad \textbf{(37)}$$

In general case, this equation has to be solved numerically. However for a very small negative γ the frequency values of the edge lasing modes are pinned to the frequencies of zero value of reflection coefficient in its frequency beats outside of the stop band edge for the same layer with zero imaginary part of the dielectric tensor [10,13]. It is why for this limiting case for a small $|\gamma|$ and L|Imq|©1 the threshold values of the gain (γ) for the edge lasing modes may be found analytically:

$$\gamma =-\delta(n\pi)^2/a^3 = -\delta(n\pi)^2/(\delta L\tau/4)^3 \qquad \textbf{(38)}$$

The threshold values of $|\gamma|$ are inversely proportional to the third power of the layer thickness and a minimal value of $|\gamma|$ corresponds to n=1.

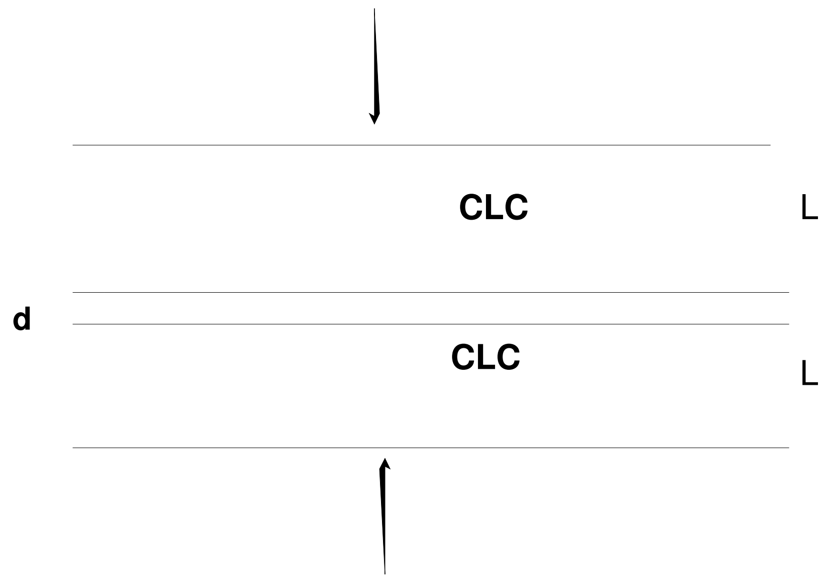
OPTIMIZATION OF PUMPING

The highest efficiency of the pumping and the lowest value of the lasing
threshold gain may be reached if the lasing occurs at the first EM frequency and the pumping wave is under conditions of the anomalously strong absorption effect. These may occur in a collinear geometry, however it demands a very special choice of the CLC parameters. A regular way to reach the optimization is to use a non collinear pumping [11,14]. The corresponding value of the angle between the
spiral axis and the pumping wave propagation direction is determined approximately as:

$$\theta=\arccos[\omega_l/\omega_p],$$

where ω_l and ω_p are the lasing and pumping frequency, respectively.

SCHEMATIC OF A DEFECT MODE STRUCTURE
Fig.1



T(d) versus the frequency for a nonabsorbing CLC, δ=0.05, N=33, d/p=0.1

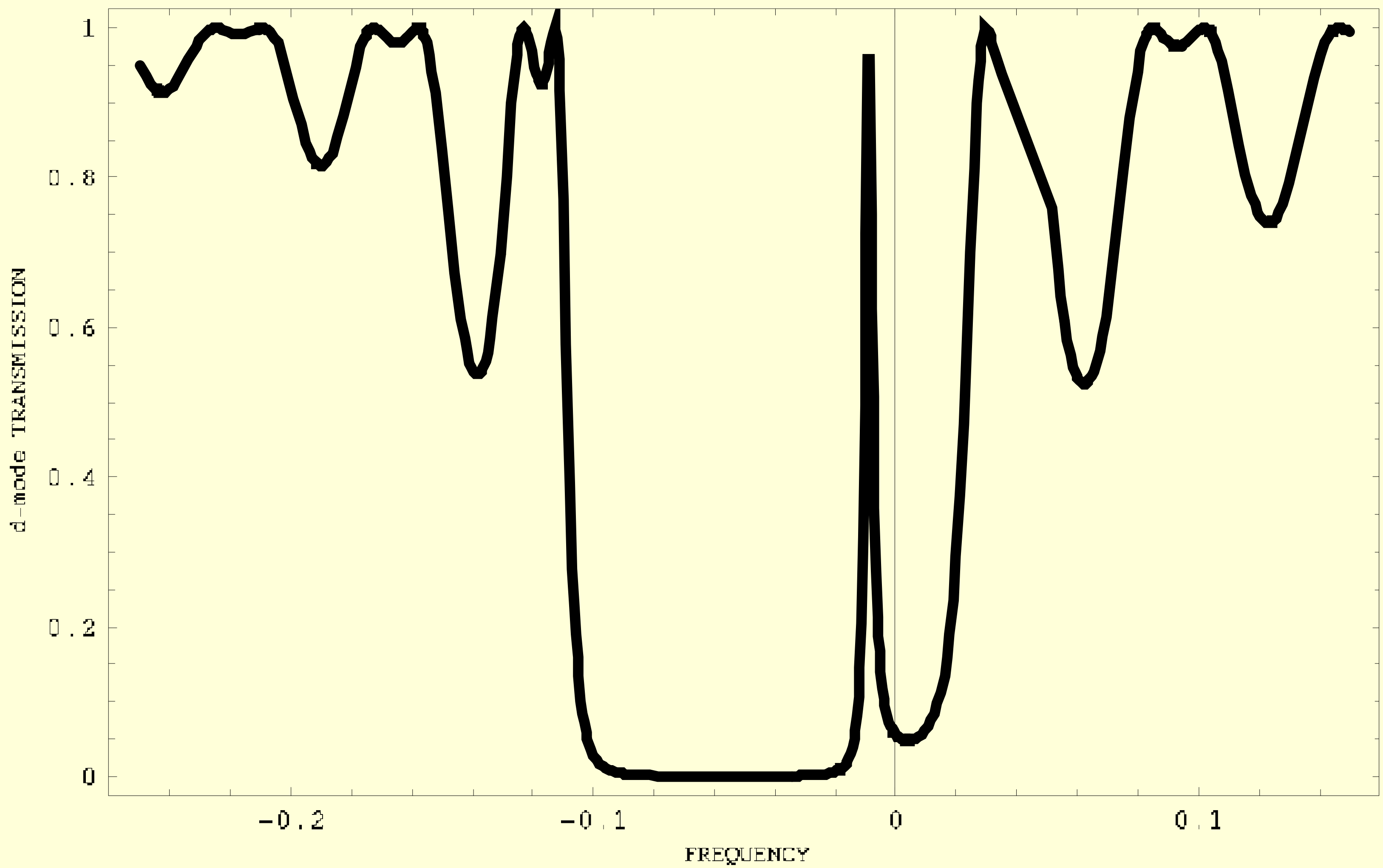
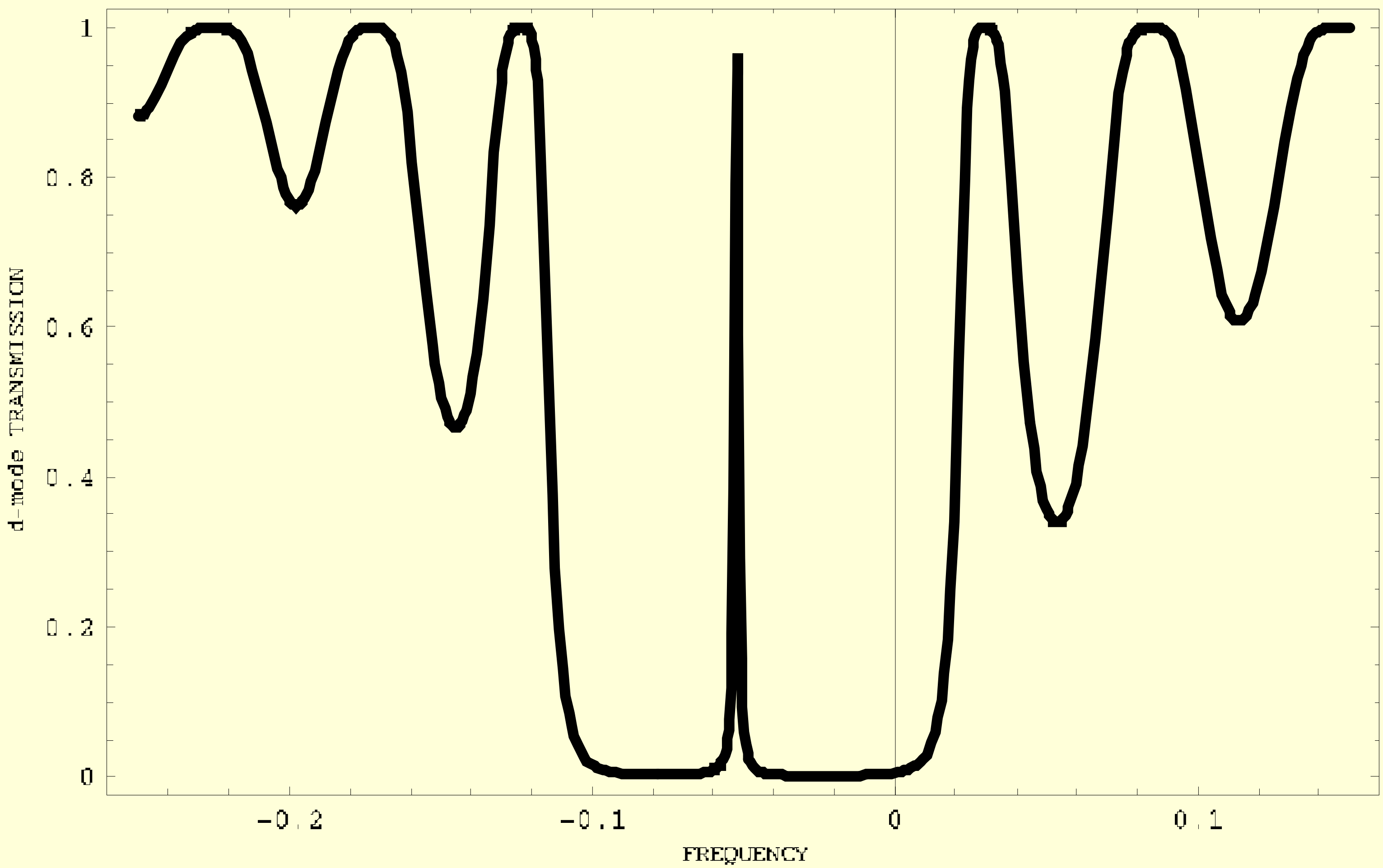


Fig.3a

T(d) versus the frequency for a nonabsorbing CLC, δ=0.05, N=33. d/p=0.25

Fig.3b



R(d) versus the frequency for a nonabsorbing CLC at d/p=200.1; δ=0.05, N=33.

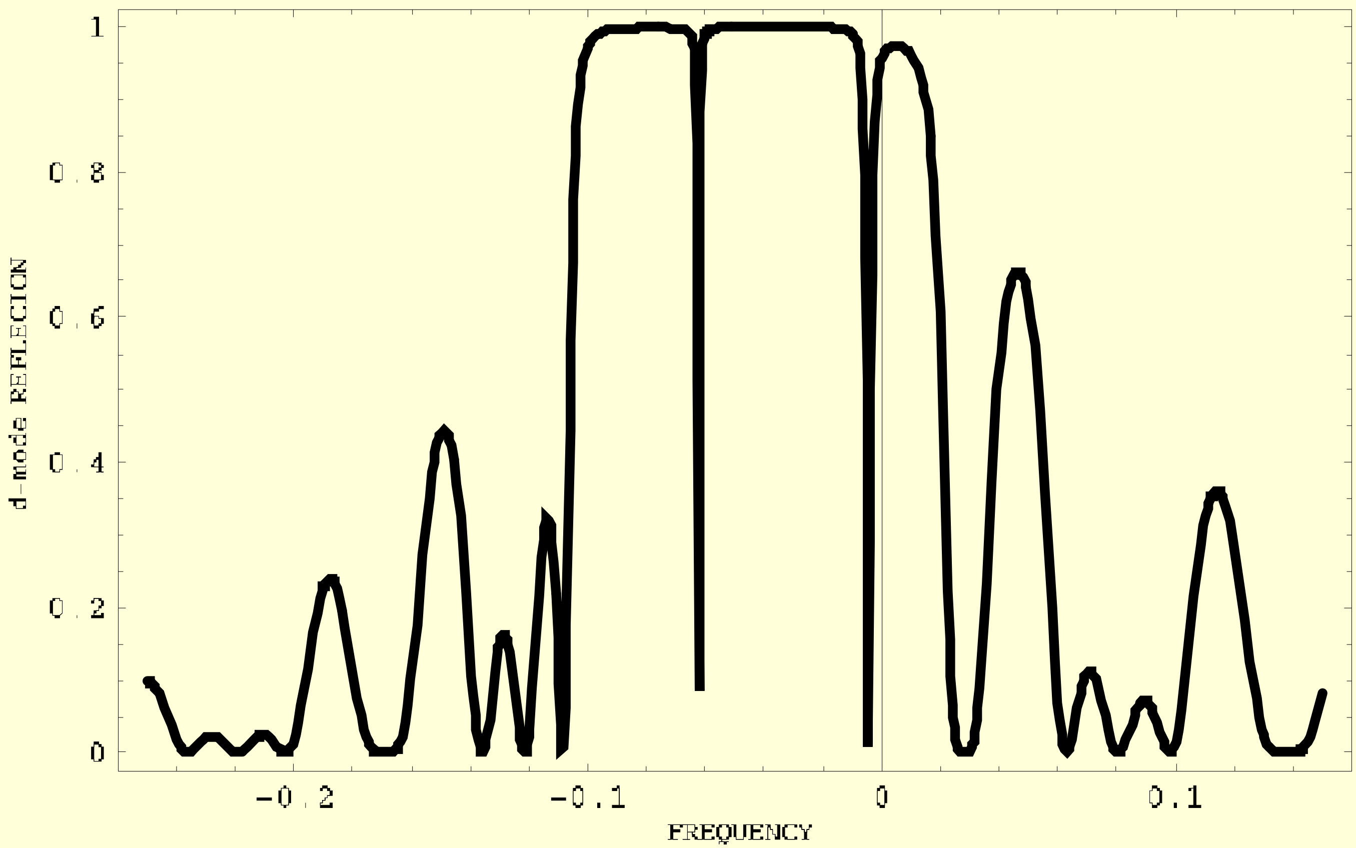
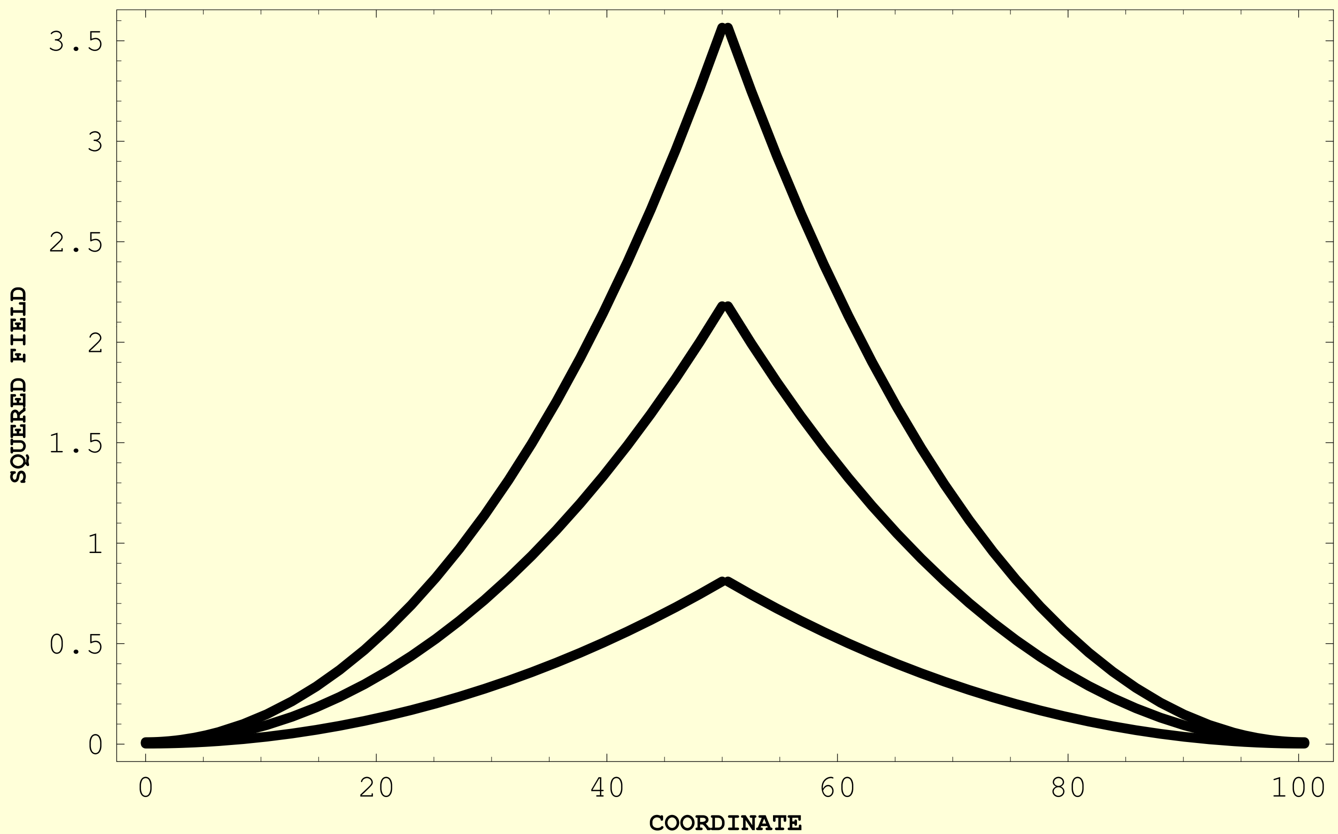


Fig.4a

Calculated distribution of the squared field modulus in the CLC layers versus the distance from the defect layer centre (x=z/p) (δ=0.05,0.04,0.025 from the top curve to the bottom, respectively); d/p=1/4, N=50 .



ABSORBING AND AMPLIFYING LC

(Thick CLC layers)

Assume for simplicity that the absorption in LC is isotropic, i.e. $\varepsilon = e_0(1+i\gamma)$. For thick CLC layers an analytic solution for γ ensuring maximal absorption may be found. For the position of ω_D just in the middle of the stop band the expression for γ reduces to

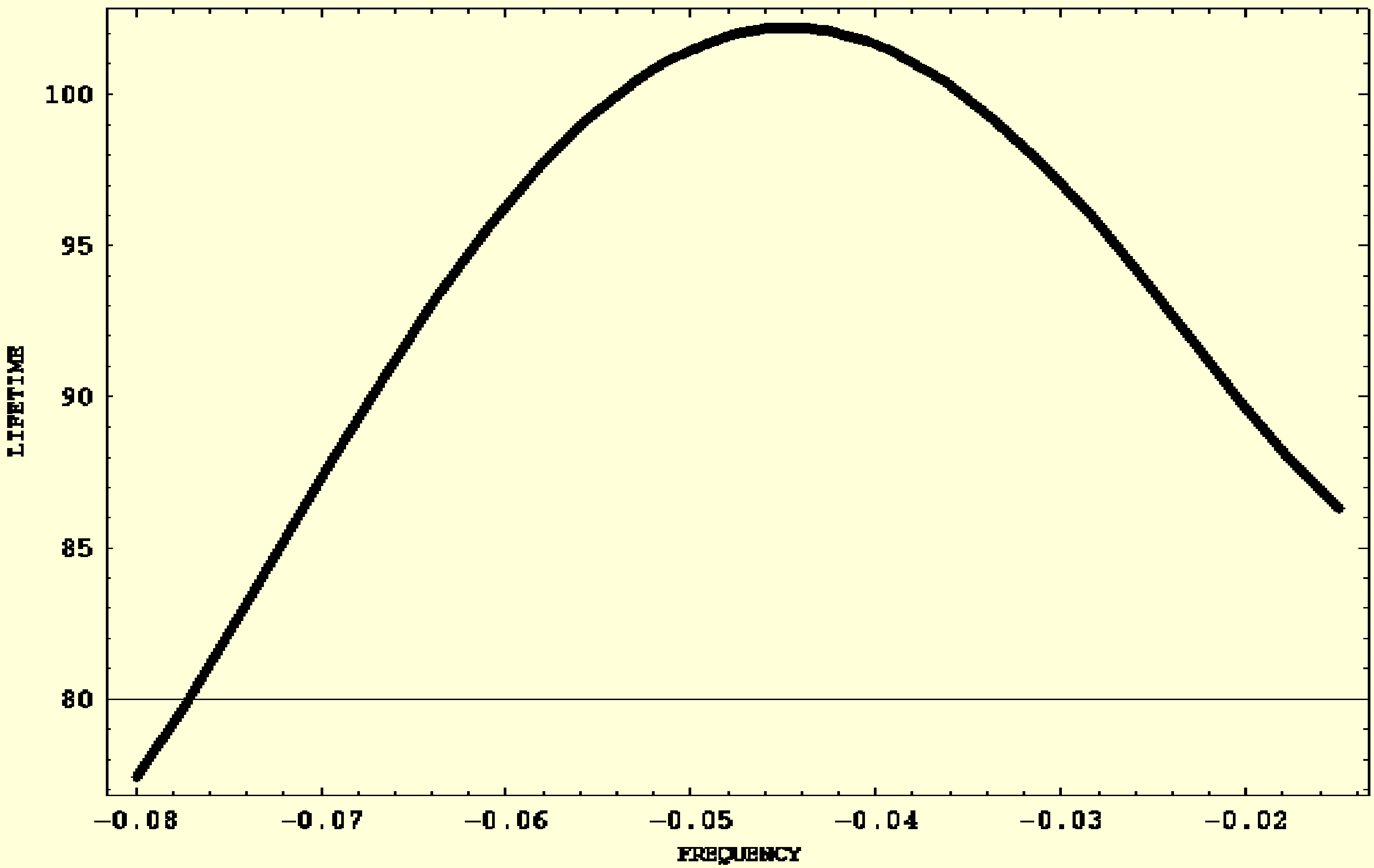
$$\gamma = (4/3\square)(p/L)\ \exp[-2\square\delta(L/p)]\ .$$

.

For thick CLC amplifying layers an analytic solution for γ (gain) corresponding to the lasing threshold may be found. For the position of ω_D just in the middle of the stop band the expression for γ is given by the formula

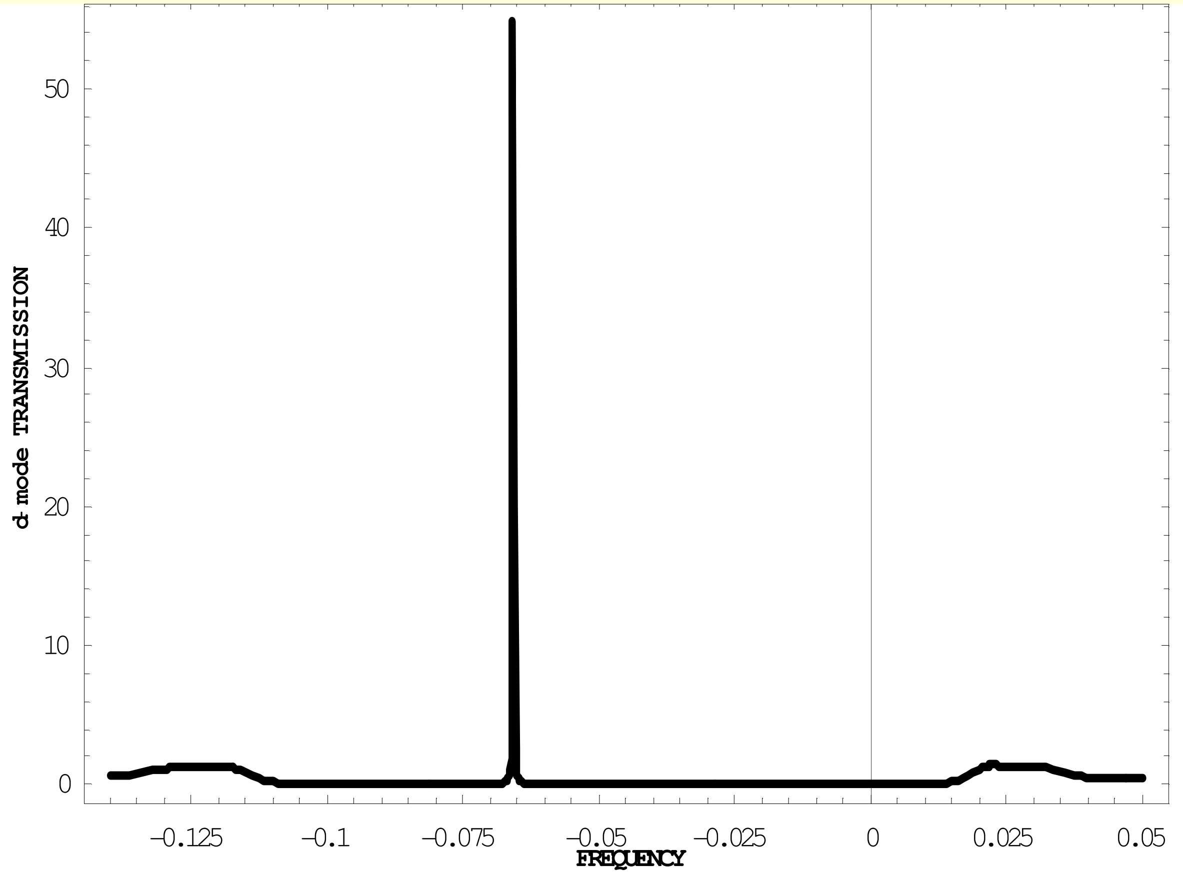
$$\gamma = -(4/3\square)(p/L)\exp[-2\square\delta(L/p)].$$

DM lifetime (normalized by the time of light flight throw DMS) dependence on the DM frequency location inside stop-band calculated for thick CLC layers (δ=0.05, N=40)



Transmission coefficient $|T(d,L)|^2$

for γ= -0.000675 (δ=0.05, N=33, d/p=2.25)

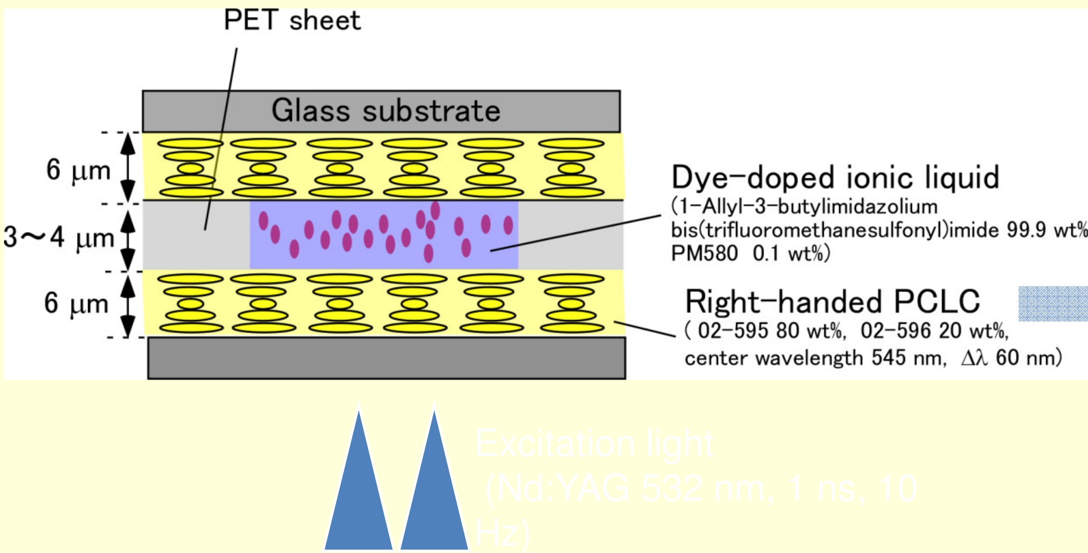


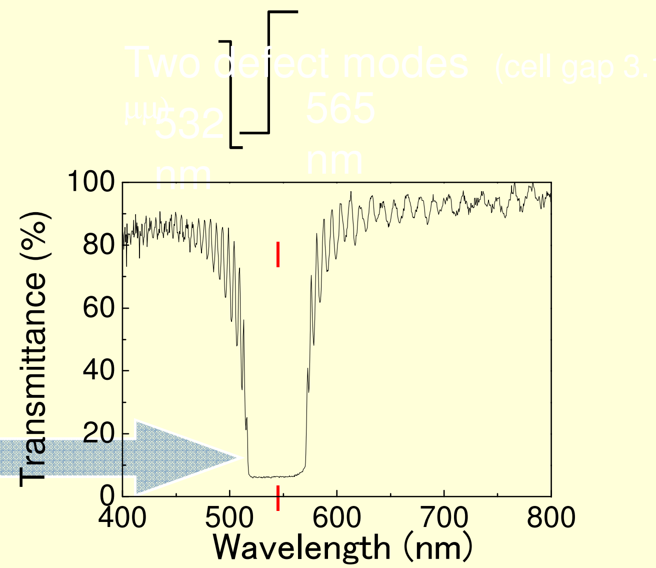
ACTIVE DEFECT LAYER (Device Configuration)

・The cell was sandwiched by two polymer cholesteric liquid crystal (PCLC) mirror (reflection bandwidth 60 nm, center 545 nm)

・The cell gap was 3~4 μm, where only two defect-modes (532 nm and 565 nm) exist in reflection band for defect-mode excitation and defect-mode lasing

・Pyrromethene 580 (laser dye, Exciton) was used to obtain laser action at the wavelength of 565 nm





Transmittance of right-handed PCLC irradiated with right-handed circularly polarized light

Fig.2a **Intensity transmission coefficient $|T(d,L)|^2$ for a low birefringent defect layer versus the frequency (Here and at all other figures " frequency" ■= $\delta[2(\omega-\omega_B)/(\delta\omega_B)$ -1)]) for diffracting incident and exiting polarizations at the birefringent phase shift at the defect layer thickness $\Delta\varphi = \pi/20$ at d/p=0.25; Lt=2pN, where here and at all other figures δ=0.05 and N= 33 is the director half-turn number at the CLC layer thickness L.**

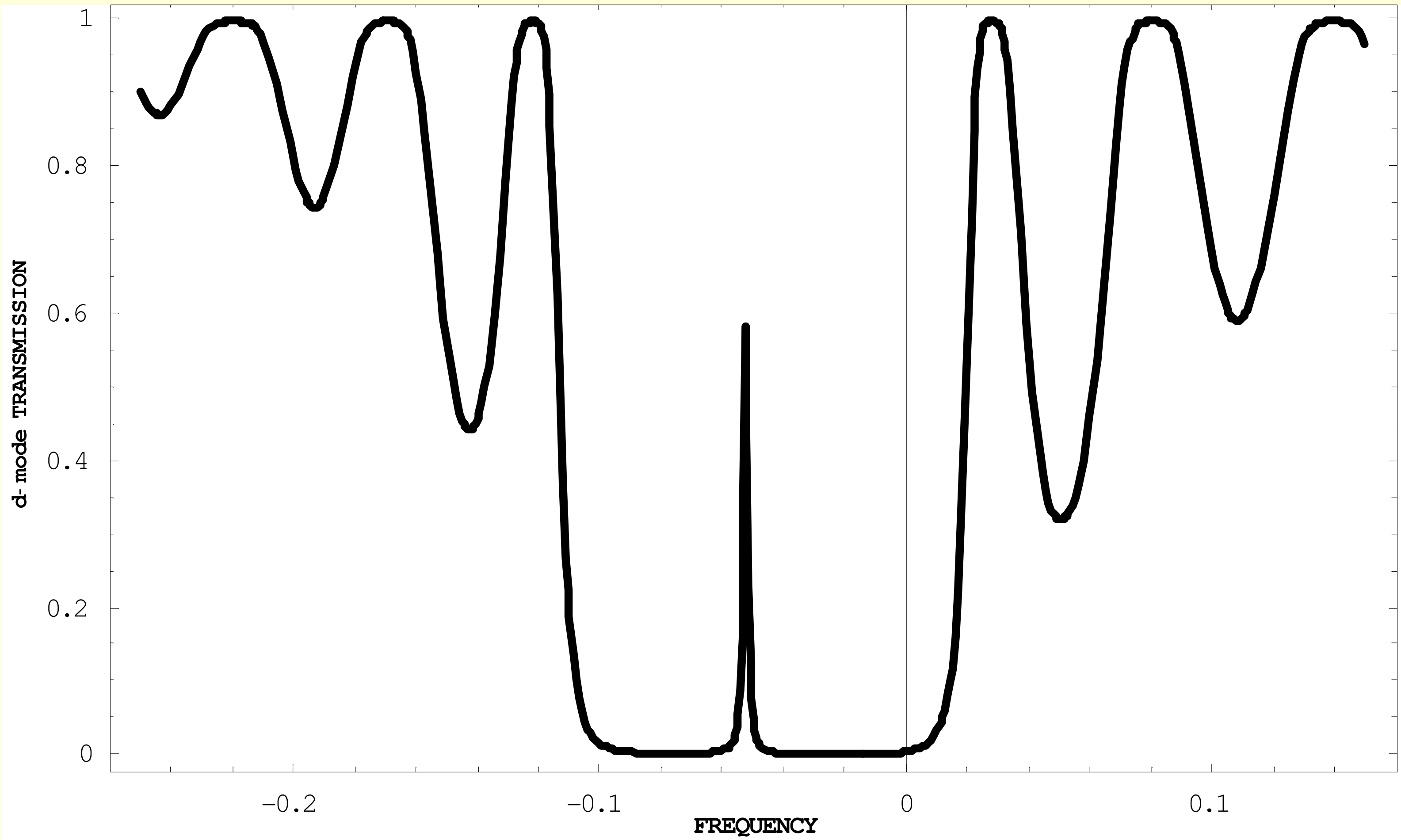


Fig.2b **Intensity transmission coefficient $|T(d,L)|^2$ for a low birefringent defect layer versus the frequency for diffracting incident and exiting polarizations at the birefringent phase shift at the defect layer thickness $\Delta\varphi = \pi/16$**

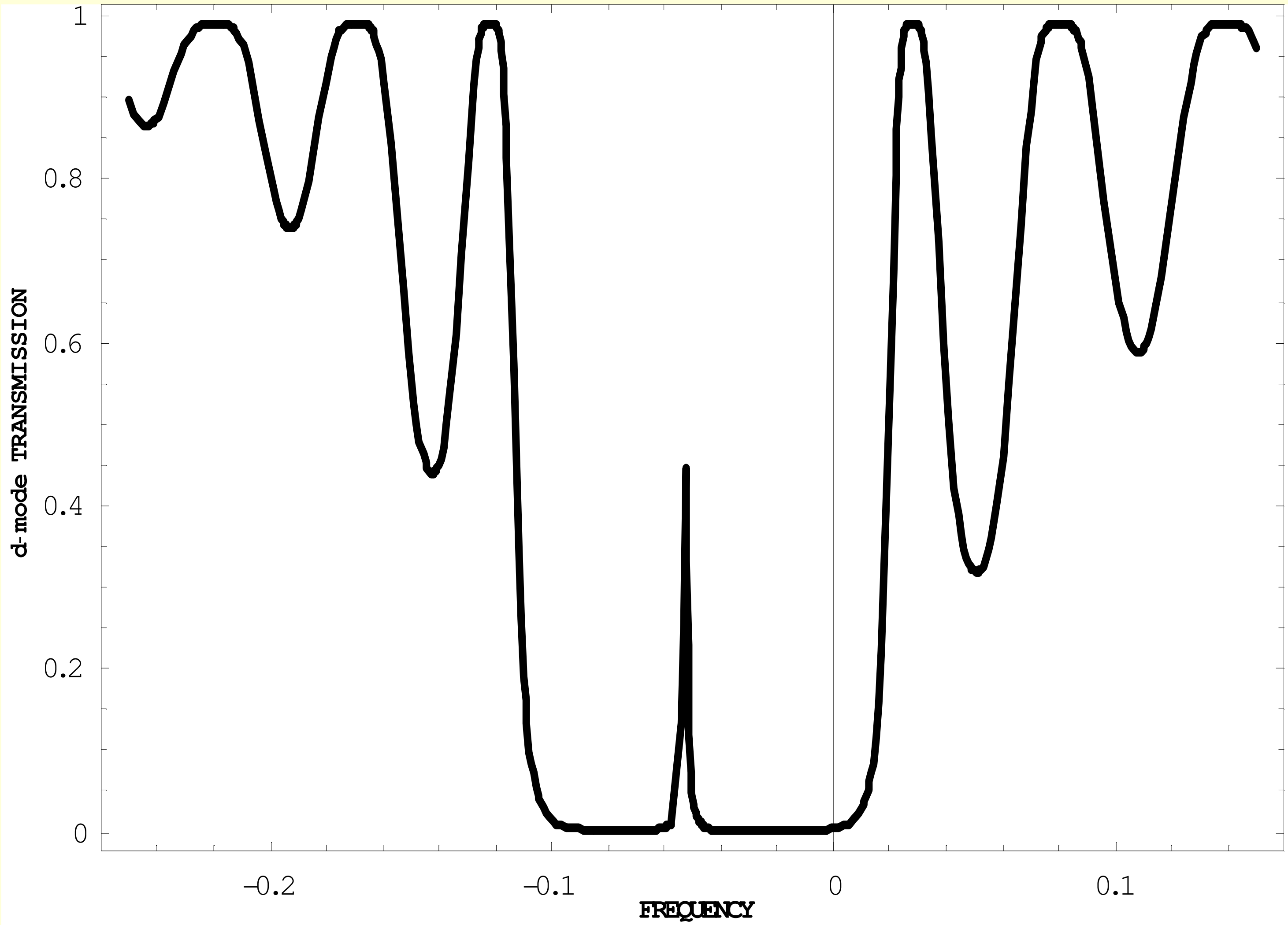


Fig.2c Transmission coefficient $|T(d,L)|^2$ for a low birefringent defect layer versus the frequency for diffracting incident and exiting polarizations at the birefringent phase shift at the defect layer thickness $\Delta\varphi = \pi/12$

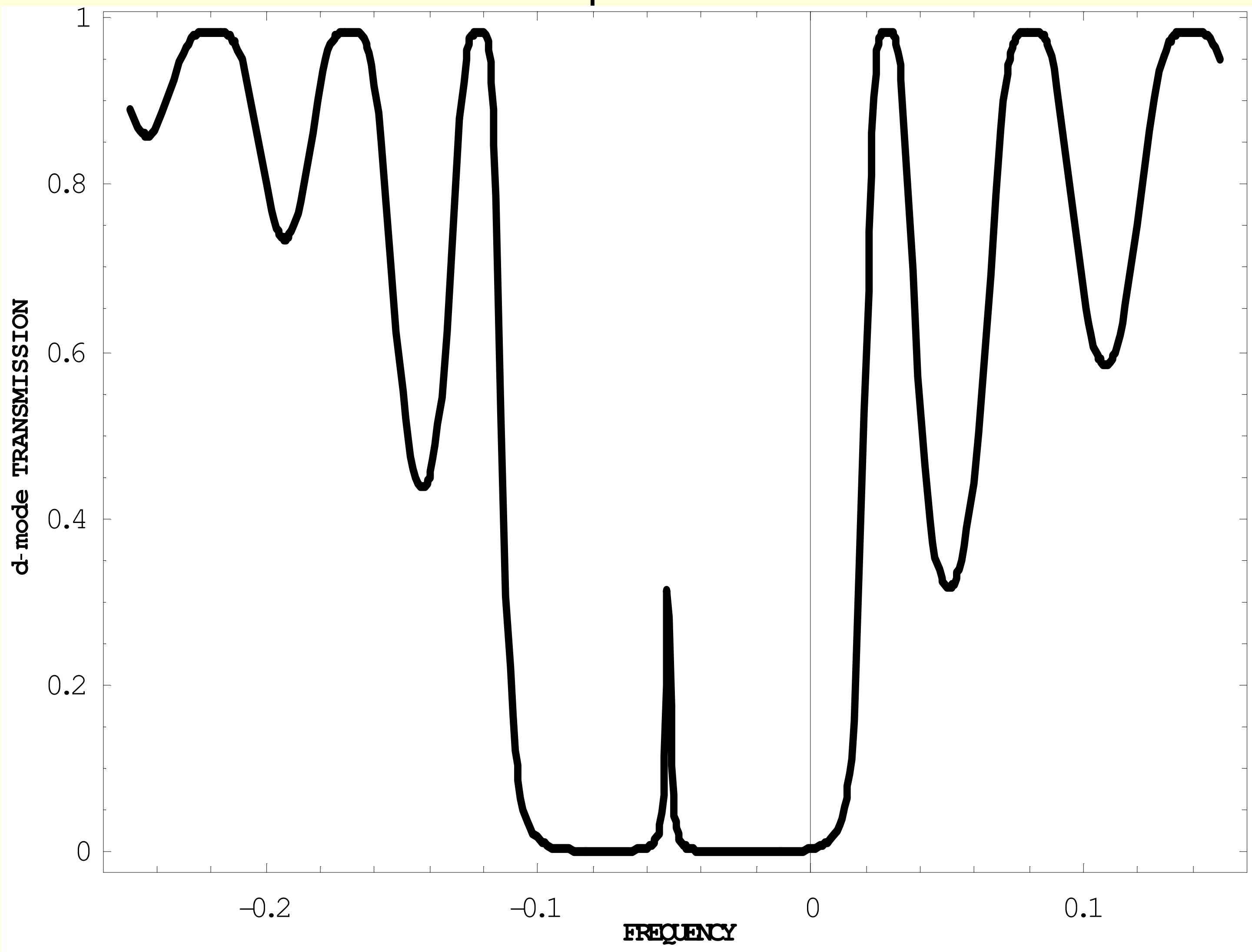


Fig.2d Transmission coefficient $|T(d,L)|^2$ for a low birefringent defect layer versus the frequency for diffracting incident and exiting polarizations at the birefringent phase shift at the defect layer thickness $\Delta\varphi = \pi/8$

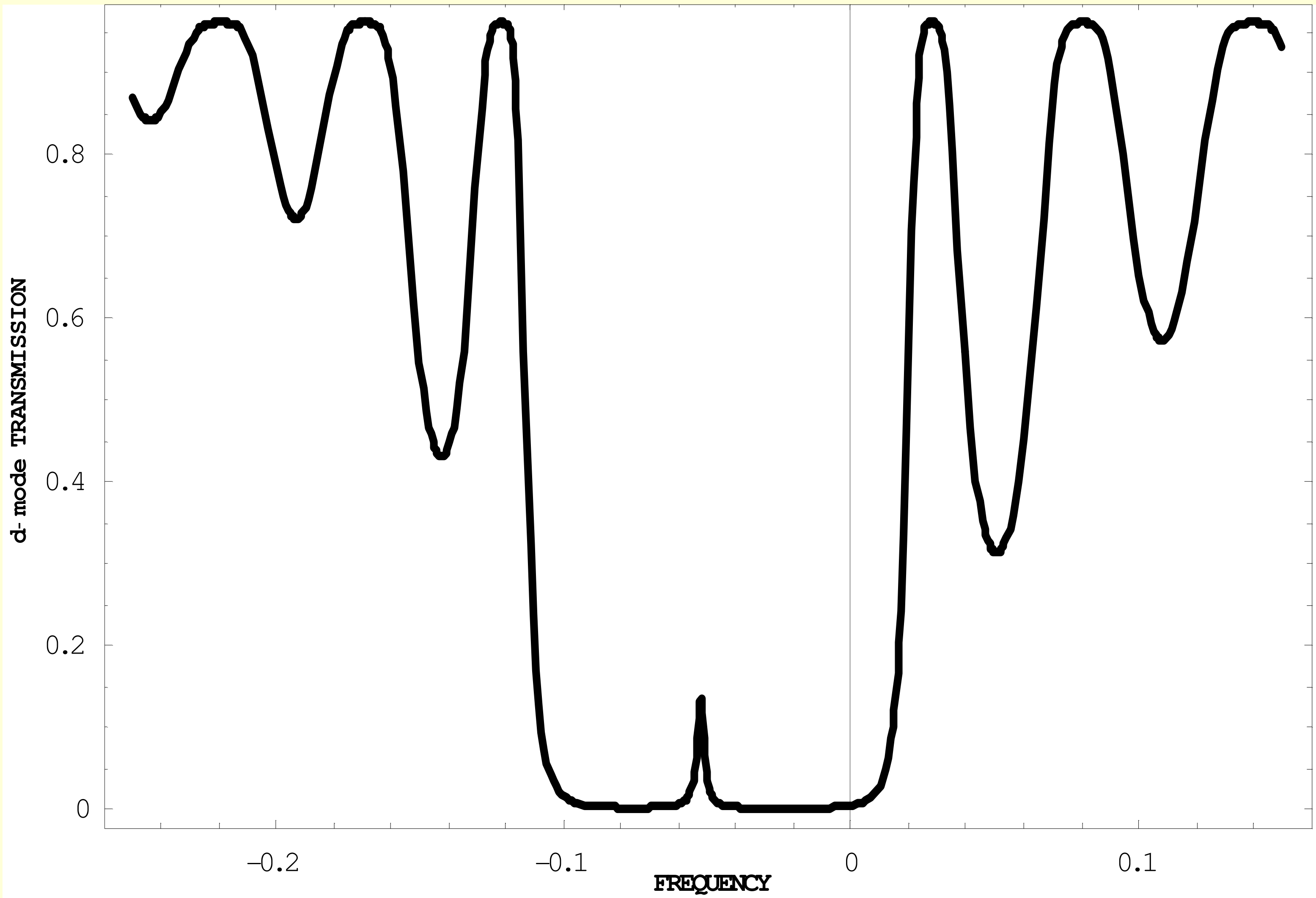


Fig.2e **Transmission coefficient $|T(d,L)|^2$ for a low birefringent defect layer versus the frequency for diffracting incident and exiting polarizations at the birefringent phase shift at the defect layer thickness $\Delta\varphi = \pi/6$**

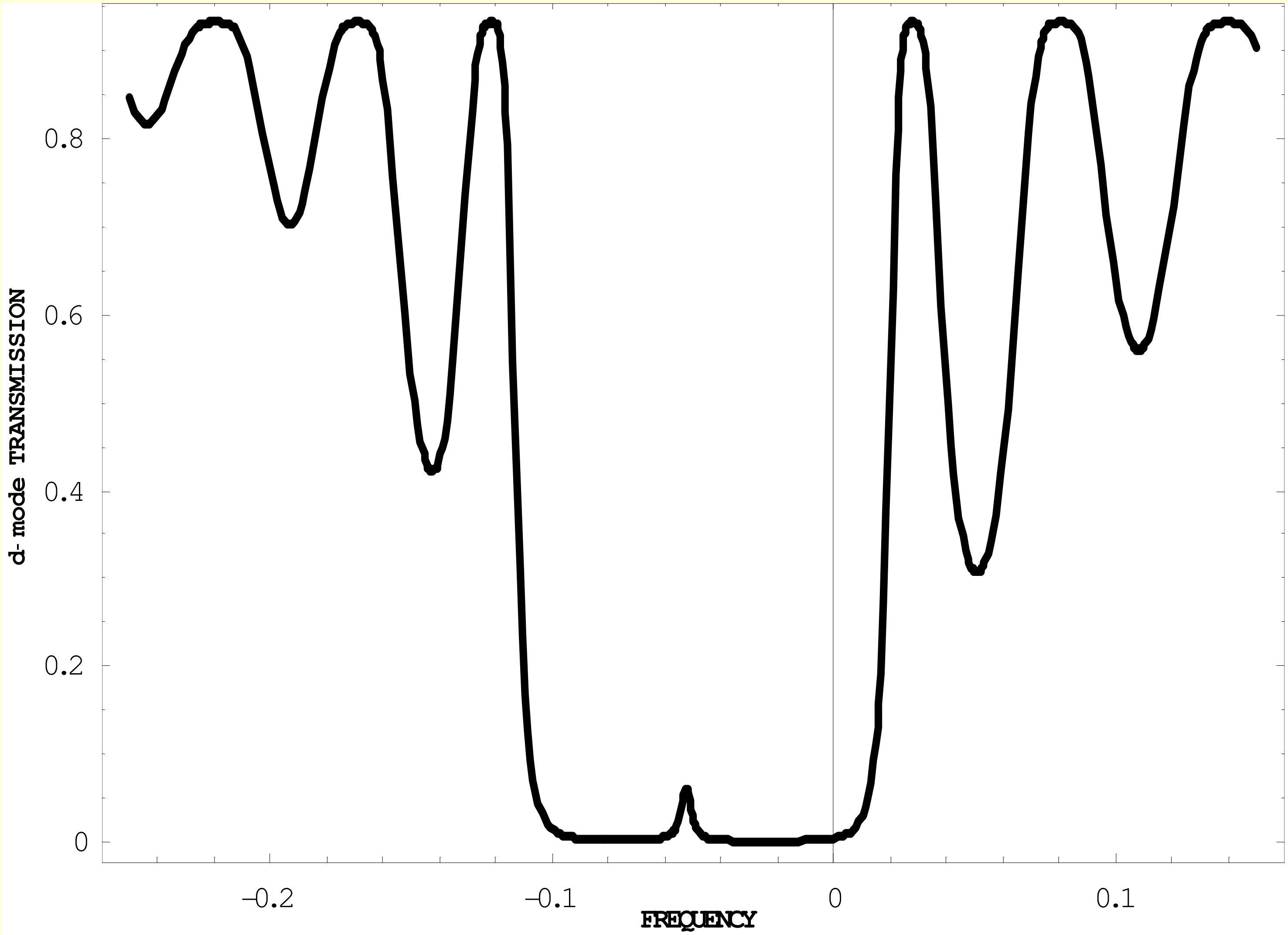


Fig.2f **Transmission coefficient |T(d,L)|2 for a low birefringent defect layer versus the frequency for diffracting incident and exiting polarizations at the birefringent phase shift at the defect layer thickness $\Delta\varphi = \pi/4$**

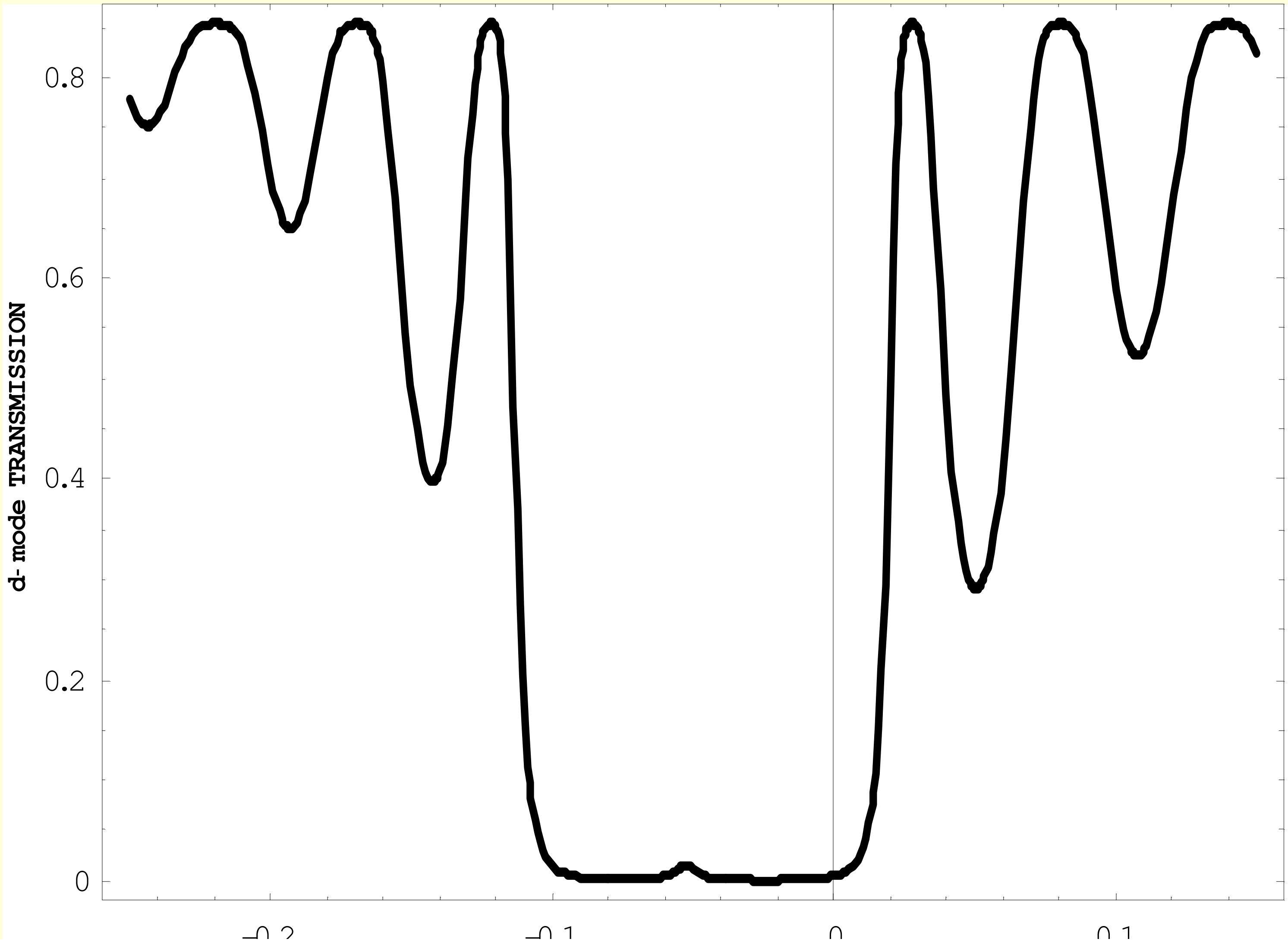


Fig.2g **Transmission coefficient $|T(d,L)|^2$ for a low birefringent defect layer versus the frequency for diffracting incident and exiting polarizations at the birefringent phase shift at the defect layer thickness $\Delta\varphi = \pi/2$**

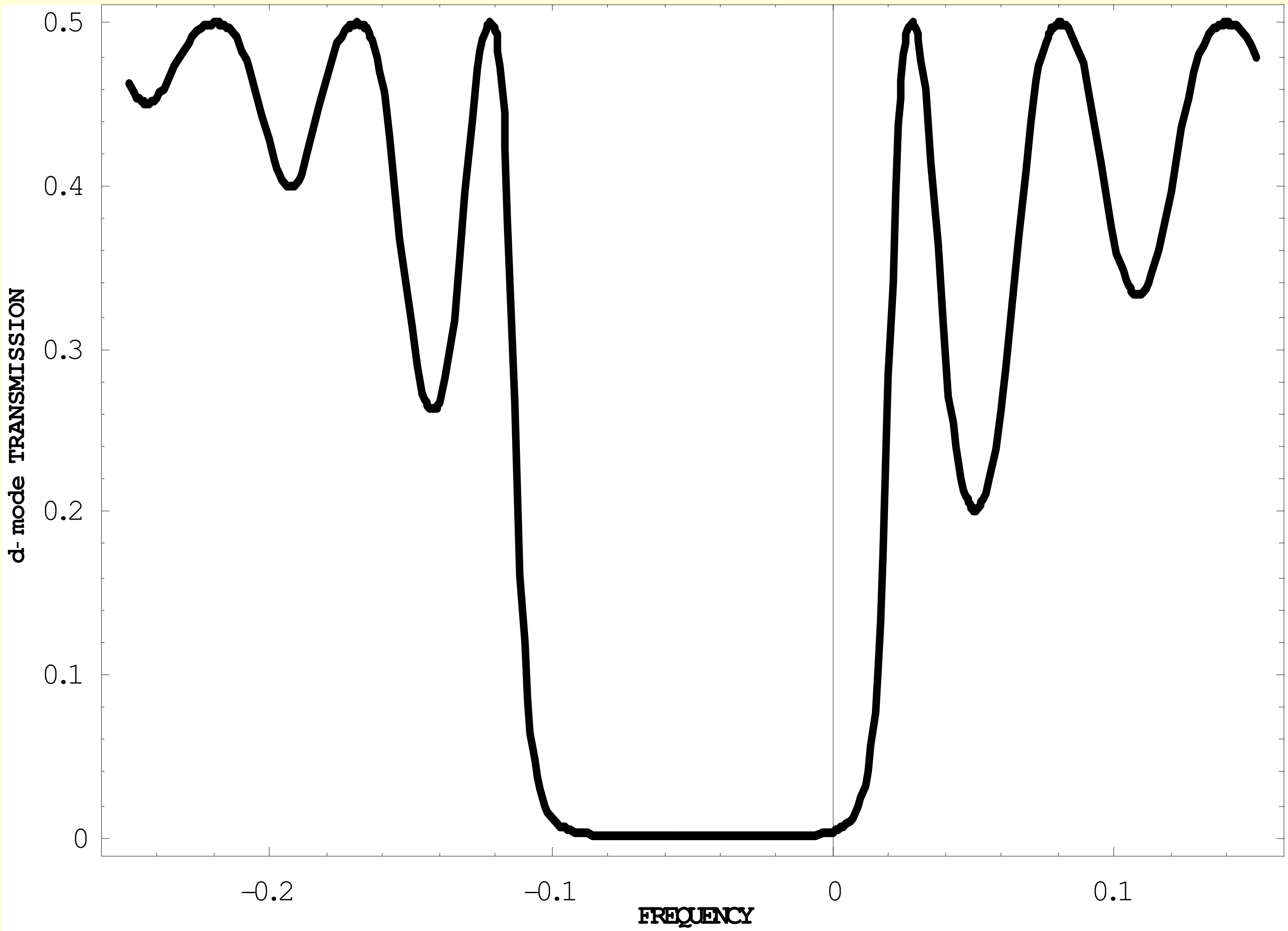
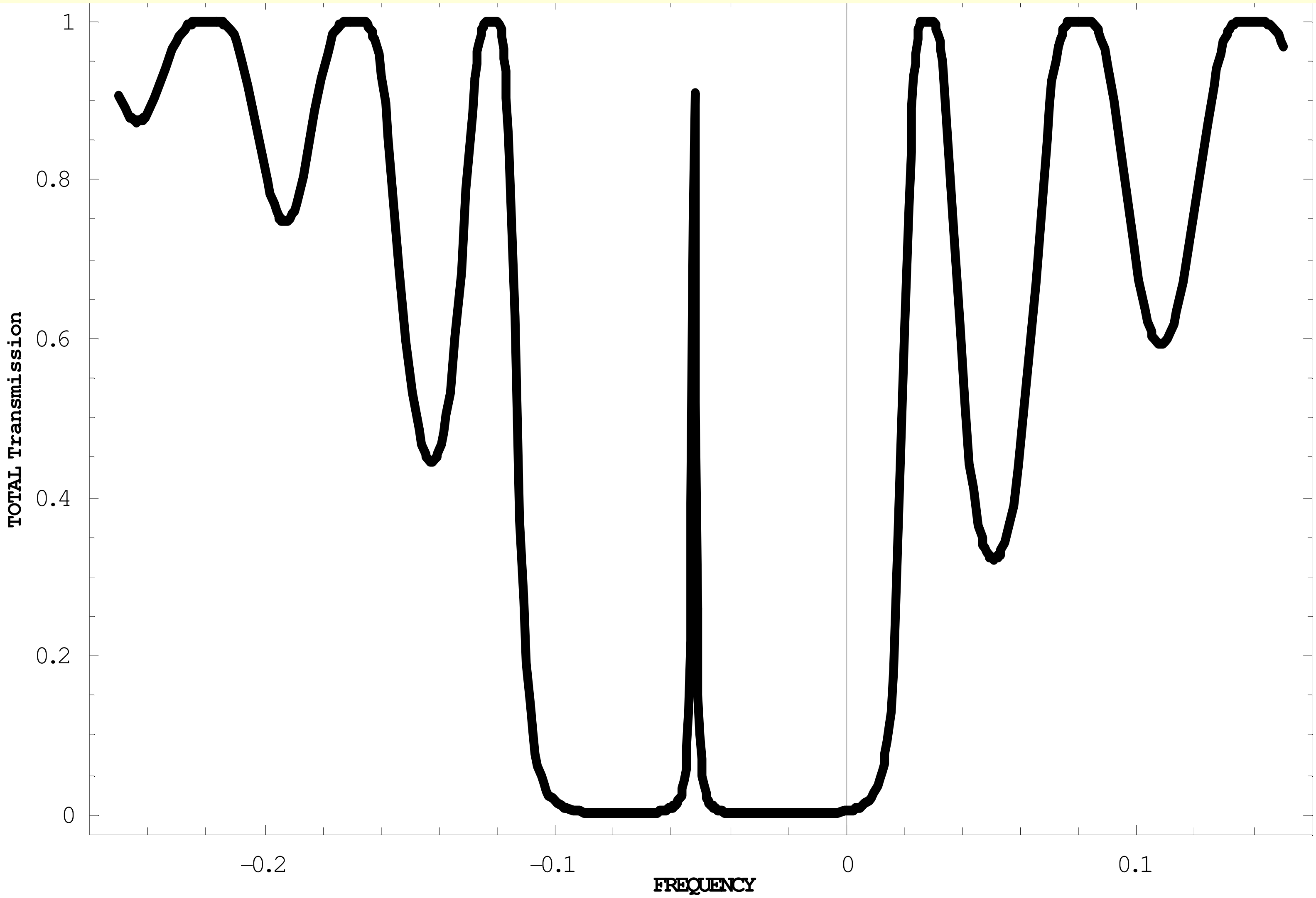
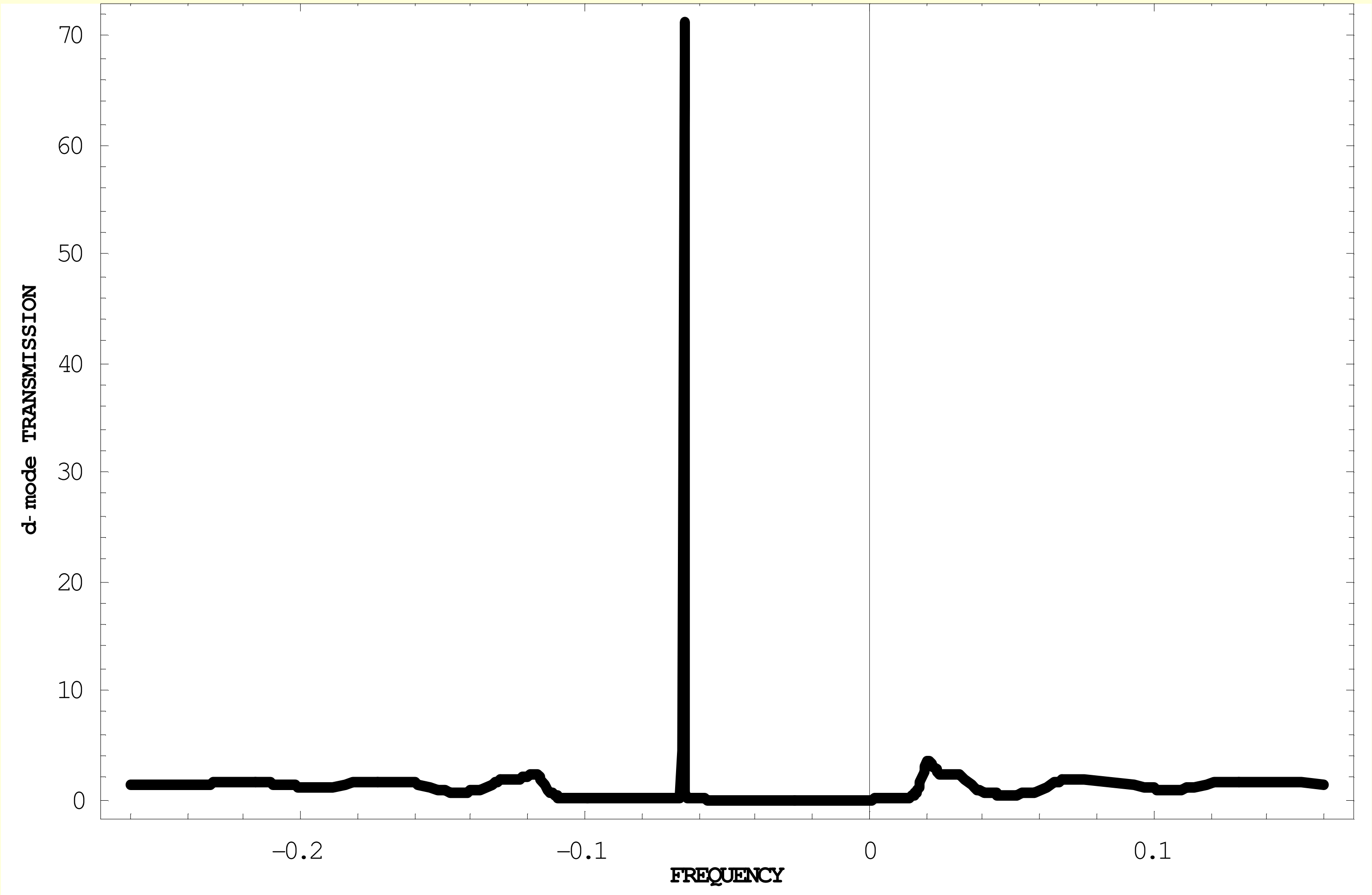


Fig.3a Calculated total intensity transmission coefficient versus the frequency for diffracting incident polarization at the birefringent phase shift at the defect layer thickness $\Delta\varphi = \pi/20$ for a nonabsorbing CLC at d/p=0.25.



Transmission coefficient $|T(d,L)|^2$ for a low birefringent defect layer versus the frequency for diffracting incident and exiting polarizations at the birefringent phase shift at the defect layer thickness $\Delta\varphi = \pi/6$, γ= - 0.002355 (δ=0.05, N=33, d/p=2.25)



CONCLUSION

1. Presented approach allows to reveal clear physical picture of the localized modes
2. Predicted low lasing threshold under the conditions of anomalously strong absorption effect
3. An interconnection between the gain and other LC and defect layers parameters at the threshold pumping energy for lasing at the defect (as well at the stop band edge) mode frequency is revealed
4. Much to be done in the theory and experiment

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