

ІНСТИТУТ ФІЗИКИ НАЦІОНАЛЬНОЇ АКАДЕМІЇ НАУК УКРАЇНИ

Кваліфікаційна наукова
праця на правах рукопису

МИСТЕЦЬКИЙ ВІКТОР АНАТОЛІЙОВИЧ

УДК 535.012.21, 535.42, 53.043

ДИСЕРТАЦІЯ

**ОПТИЧНЕ КЕРУВАННЯ ПАРАМЕТРАМИ ЛАЗЕРНИХ ПУЧКІВ
МЕТОДОМ ДВОПРОМЕНЕВОЇ ВЗАЄМОДІЇ В НЕМАТИЧНИХ РІДКИХ
КРИСТАЛАХ ТА ЇХ КОМПОЗИТАХ З ЗОЛОТИМИ
НАНОЧАСТИНКАМИ**

104 «Фізика та астрономія»

10 «Природничі науки»

Подається на здобуття наукового ступеня – доктора філософії
Дисертація містить результати власних досліджень. Використання ідей,
результатів і текстів інших авторів мають посилання на відповідне джерело.

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док. фіз.-мат. наук
Бугайчук Світлана Анатолійовна

Київ – 2026

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SUMMARY

Mystetskyi V.A. Optical control of laser beam parameters by two-wave mixing technique in nematic liquid crystals and their composites with gold nanoparticles. – Qualified scientific work on the rights of manuscript.

Dissertation for the scientific degree of Doctor of Philosophy in Field of Science 10 “Natural Sciences” in Specialty 104 “Physics and Astronomy”, – Institute of Physics of the National Academy of Sciences of Ukraine. – Kyiv, 2026.

The dissertation work is devoted to **the study of photorefractive and plasmonic mechanisms of refractive index change in the cells of nematic liquid crystals (LC) and their composites with gold nanoparticles (NPs)** under the action of laser beams and applied electric voltage.

The method of dynamic holography is used, namely two-wave mixing (TWM) of laser beams in reversible photosensitive materials. Therefore, the main subject of the study is the properties of phase dynamic grating recorded in pure nematic LCs and in LC-nanocomposites with gold NPs; identification of physical parameters of LCs and their composites, as well as characteristics of interacting laser beams that affect the value of the modulation depth of the dynamic grating and its recording and erasing time constants.

This dissertation presents a complex of theoretical studies on the TWM in various LC systems. This is due to the fact that quite a lot experimental results have been accumulated on the recording of dynamic grating in LC nanocomposites, but there is still no unified theory that outlines the prospects for obtaining advanced characteristics with such recording, as well as new areas of its applications.

In the course of the dissertation, theoretical models are developed to describe the processes of formation of a dynamic phase grating, and also self-diffraction and diffraction of laser beams on it; numerical experiments and calculations are performed; the results of theoretical calculations are compared with experimental data.

The following systems are investigated and new scientific results are obtained:

In the **second section**, the kinetics of director reorientation in a nematic LC cell and the corresponding change in the extraordinary refractive index of the transmitted light are calculated. The modeling is conducted to identify regularities in the reorientation time of LC director depending on the elastic and viscous properties of the LC medium, the electric field strength, and the spatial confinement effects. The Erickson-Leslie model is used to describe the reorientation of the LC director under the action of DC electric fields. The simulations is performed for a spatially homogeneous electric field as well as for a spatially modulated sinusoidal field. The obtained results show the formation of fast dynamic grating of the refractive index under the action of a DC spatially modulated sinusoidal electric field. For LC with a high viscosity value, the dynamic grating becomes quasi-stationary.

In the **third section**, an analysis of experimental studies of nominally pure nematic LCs (NLCs) is performed, in which one obtained the recording of dynamic holographic gratings not only in cells with homeotropic orientation but also with planar orientation. The explanation can be found on the basis of the photorefractive mechanism of grating recording, which is characterized by the formation of a nonequilibrium charge on the surface of the cell substrate under the influence of a spatially inhomogeneous light field. The emergence of an internal tangential electric field (along the cell substrates), together with an external electric field applied normally to the cell substrates, opens up additional possibilities for controlling the direction of the resulting electric field vector. In this section, we develop and analyze a model of laser beam intensity changes due

to self-diffraction and diffraction on a dynamic grating created in nominally pure NLCs. The dynamic phase grating is formed due to the mechanism of collective reorientation of LC molecules, which leads to a change in the characteristics of birefringence in the NLC cell. According to this model, a new result is obtained that the maximum diffraction efficiency is achieved for small angles for reorientation of LC director (up to 0.5 radians ($\sim 28^\circ$) in thin cells) relative to the initial state. The results of the calculations for the output intensities of laser beams in the first orders of self-diffraction and diffraction are in good agreement with experimental measurements. In particular, they explain the dependence of the diffraction efficiency on the value of the external applied voltage, which has a well-defined maximum.

In the **fourth section** it is presented a theoretical analysis of the complex dielectric permittivity of nematic LC-nanocomposites with Au NPs embedded in the cell volume. The mechanism of refractive index change is associated with the excitation of localized surface plasmon resonance (LSPR) in Au NPs in the visible spectral region, which is accompanied by an increase in the local field factor. This mechanism leads to a significant decrease of time constants for dynamic grating recording and erasure compared to the mechanism of collective reorientation of the LC molecules. Our results show that the dynamic grating of the refractive index can be recorded at a very small volume fraction of NPs(Au) less than 0.01 due to the strong absorption at the LSPR at visible wavelengths. At the same time, if the grating is recorded with a He-Ne laser, whose wavelength is far from the maximum of the LSPR, the efficiency of the phase grating can be significant: 35-45% in the self-diffraction regime. The theoretical results obtained are in good agreement with the experimental data, according to which only thermal gratings are recorded in the LC-nanocomposites with NPs(Au), since the volume fraction of NPs(Au) in them is significant and uncontrollable.

In the **fifth section**, a theoretical analysis is conducted of the experimental results on the study of self-diffraction and diffraction in hybrid LC cells (HLCs) containing a gold nano-island film on one of the cell substrates. HLCs are

characterized by a faster response time. The recording of dynamic grating occurs due to the surface-induced photorefractive mechanism. The technique of two-wave mixing is used in the recording mode under the influence of periodic rectangular pulses generated either by a laser beam or by an applied electric voltage. Modifications to the shape of laser pulses were experimentally obtained in TWM using HLC. We have developed a theoretical model of the TWM and performed numerical experiments. By comparing experimental data obtained from the analysis of changes in the shape of laser pulses with the results of numerical simulations using the dynamic model developed by us, we can estimate the time constants for recording and relaxation of the dynamic grating in a particular LC material. In this case, the minimum relaxation time of the grating determines the speed of optical signal switching.

Results obtained in the dissertation work will contribute to: 1) creation of new effective materials based on LCs for photonics, incorporating nano-(micro-) structures and exhibiting significantly improved performance characteristics; 2) creation of a theoretical model of the surface-induced photorefractive effect arising from the simultaneous action of light beams and electric fields at the inorganic-organic interface; 3) development of effective technologies for the manufacture of modern multifunctional hybrid LC materials with high performance for optoelectronics, multifunctionality and pixel-free integration in which is achieved through the use of spatially inhomogeneous light beams or interference light structures; 4) studying new effects for controlling optical beams in LC cells to develop new applications for sensors and devices designed to control optical beams and images.

Keywords: Liquid crystals, organic molecules, nematic phase, laser radiation, diffraction, diffraction gratings, holographic gratings, high-order diffraction, Bragg reflection, spectroscopy, nanoparticles, plasmonics, surface plasmon resonance, efficiency, two-beam interference.

(Q1—Q3) SCImago

Journal and Country Rank *Journal Citation Reports:*

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<https://doi.org/10.15407/ujpe68.7.474>.

(Q4) SCImago Journal

and Country Rank *Journal Citation Reports:*

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2 (Q2): S. Bugaychuk, V. Mystetskyi, Yu. Kurioz, A. Taki, **Optical dielectric spectroscopy related to plasmon resonance in LC-nanocomposites with embedded low-sized Au nanoparticles**, *Journal of Molecular Structure*, **1349**(1), Article 143532, 5 January 2026, Q2, <https://doi.org/10.1016/j.molstruc.2025.143532>;

: IX International research and practice Conference "Nanotechnology and nanomaterials" (NANO2021) (27-29 August, 2021) Lviv, Ukraine; XXV Galyna Puchkovska International School-Seminar "Spectroscopy of Molecules and Crystals" (21-24 September 2021), Kyiv, Ukraine; XXIII INTERNATIONAL YOUNG SCIENTISTS CONFERENCE ON APPLIED PHYSICS ICAP 2023 May, 16-20, 2023, Kyiv, Ukraine; XI International research and practice Conference "Nanotechnology and nanomaterials" (NANO2023) (16-19 August, 2023), Bukovel, Ukraine; XX Optics of Liquid Crystal Conferences, (OLC 2023), 17-22 September 2023, Szczecin, Poland; IEEE UKRAINE SECTION IGOR SIKORSKY KYIV POLYTECHNIC INSTITUTE, 2024 IEEE 42nd INTERNATIONAL CONFERENCE ON ELECTRONICS AND NANOTECHNOLOGY (ELNANO) (13-16 May, 2024), Kyiv, Ukraine; XII

International research and practice Conference "Nanotechnology and nanomaterials" (NANO2024) (21-24 August, 2024), Uzhhorod, Ukraine (2024);
XXVI Galyna Puchkovska International School-Seminar "Spectroscopy of Molecules and Crystals" (September 22-25, 2024), Wojanow, Poland.

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[33, 34].

S_0 ,

$$\vec{n} \equiv -\vec{n}$$

$$S_0 = \frac{1}{2} \langle 3\hat{c}_i^2 - 2\varphi - 1 \rangle \quad (1.1)$$

[25, 26].

(,).

$$S_0 = 1,$$

$$S_0 = 0.$$

$$0 < S_0 < 1$$

$$S_{app} = 0$$

n

[26, 33].

$$\epsilon_{||} = \dots,$$

$\epsilon_{||}$

ϵ_{\perp}

p_E

$> 0,$

[26, 35].

\vec{n} .

$$\epsilon_{\parallel} > \epsilon_{\perp},$$

$$\epsilon_{\parallel} < \epsilon_{\perp}$$

$$\epsilon(\theta) = (\epsilon_{\parallel}^{-1} \sin^2 \theta + \epsilon_{\perp}^{-1} \cos^2 \theta)^{-1} \quad (1.2)$$

[26].

$$n_e \approx n,$$

$n,$

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$n_{\text{E}}.$

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[25, 26].

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[33]

$$Q = Q(\vec{d}) (d^2 - 1/3) \quad (1.3)$$

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\vec{d}

\vec{r} ,

[41]

[42].

[43],

[44].

[45].

$$F = \frac{1}{2} K_1 (\vec{d})^2 + \frac{1}{2} K_2 (\vec{d} \cdot \vec{r})^2 + \frac{1}{2} K_3 (\vec{d} \times \vec{r})^2 \quad (1.4)$$

\vec{d} .

:

$$F = \frac{1}{2} K_1 (\vec{d})^2 + \frac{1}{2} K_2 (\vec{d} \cdot \vec{r})^2 + \frac{1}{2} K_3 (\vec{d} \times \vec{r})^2 \quad (1.4)$$

K_1, K_2, K_3 –

[46].

K_1 –

(splay) $\vec{d} \cdot \vec{r} = 0$; K_2 –

(twist)

$\vec{d} \cdot \vec{r} = 0$; K_3 –

(bend), $\vec{d} \times \vec{r} = 0$. F –

$1 \text{ } ^3, \vec{d}$.
 (1.4), K_1
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 $U/a, U -$, $a -$
 $U \approx 2$
 / (0.1) $a \approx 14 \text{ \AA}$, $K_1 \approx$
 $1.4 \cdot 10^{-1} \text{ эрг} / 1.4 \cdot 10^{-7} \text{ см} = 10^{-6} \text{ дин}$.
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$$(P \dots 1.1). \dots E_z$$

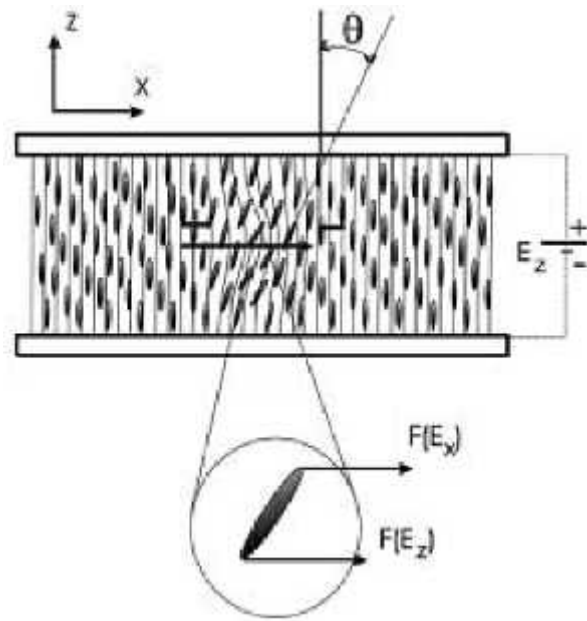
[28, 51]:

$$E_{X,\sigma} = \frac{(\sigma_{||} - \sigma_{\perp})c}{\sigma_{||}c^2 \theta + \sigma_{\perp}S^2 \theta} E_z, \quad (1.5)$$

$$E_{X,\varepsilon} = \frac{(\varepsilon_{||} - \varepsilon_{\perp})c}{\varepsilon_{||}c^2 \theta + \varepsilon_{\perp}S^2 \theta} E_z, \quad (1.6)$$

\dots (\dots); E_z \dots
 $\dots, E_{X,\sigma}, E_{X,\varepsilon}$

[51].



. 1.1 – [51].

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20 . He-Cd (= 0,44)

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[51].

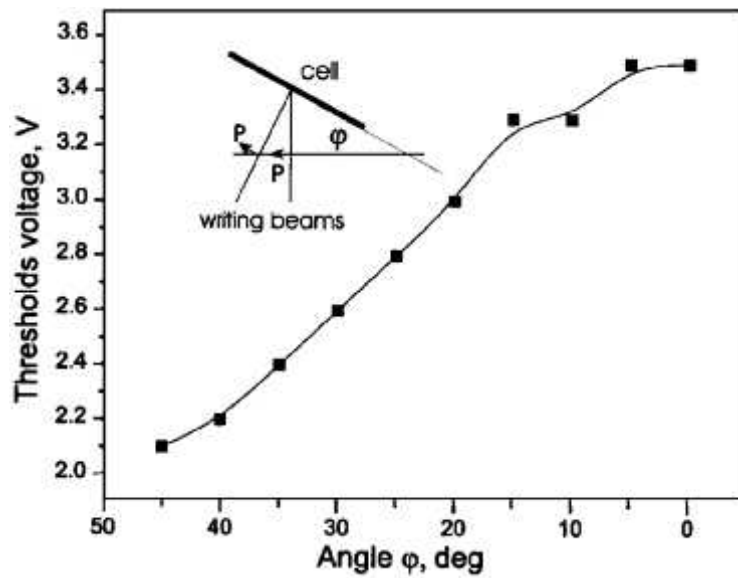
I_d

. 1.3.

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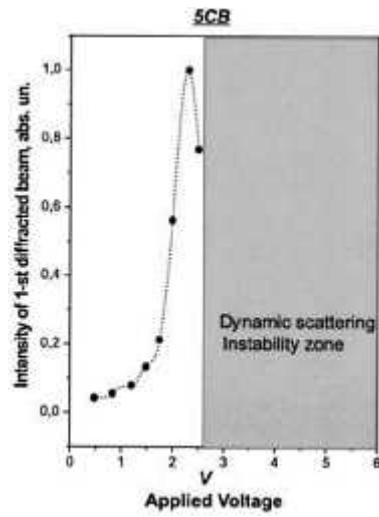
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$$\theta \approx \frac{\epsilon |E| L}{3 \pi} \frac{2\alpha}{\lambda}, \quad (1.7)$$

(1.7),

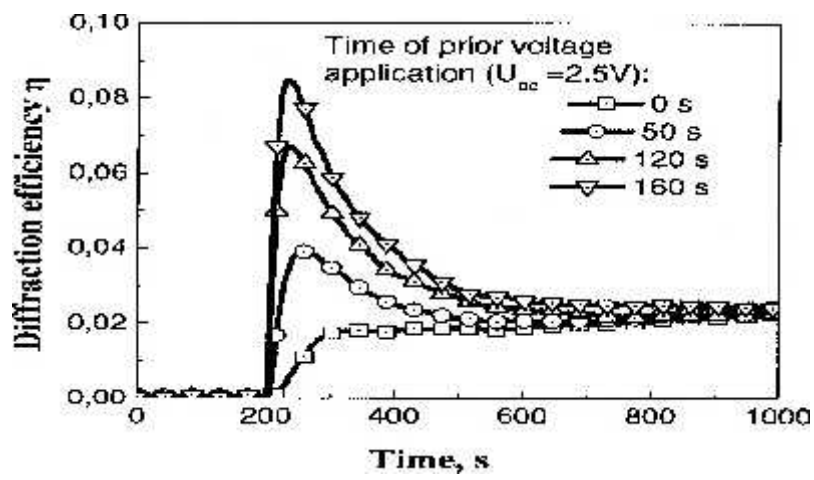
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$n(\)$

I_{100} , A_{100}^{\pm} (0.51, 0.49, 0.46), η_{100} (0.6328, 0.44), η_{100}^{\pm} (0.51, 0.49, 0.46) He-Ne (0.6328), He-Cd (0.44) [51].

[54].

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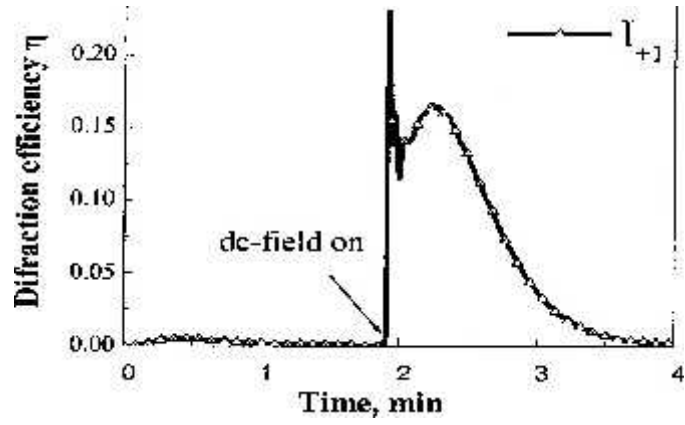


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$I_{100} \propto U_{dc}^{-2}$, $U_{dc} = 2.5$ [54].

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(P . 1.5) [54].

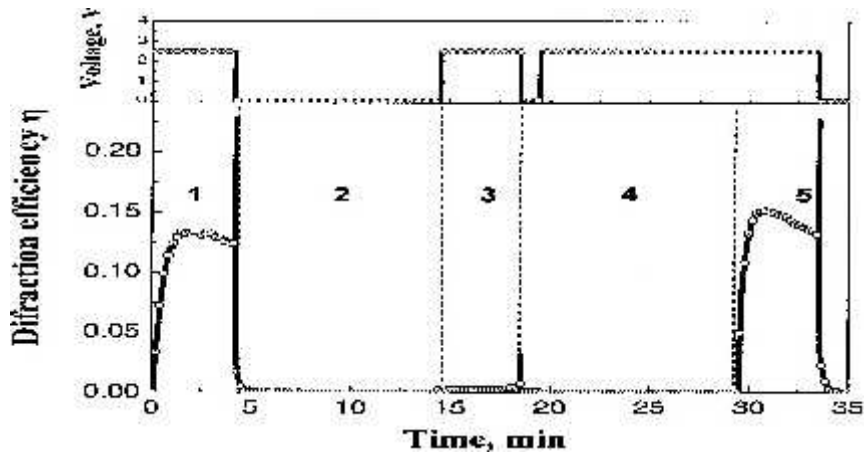


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(I_{pi} =0÷50 $\frac{\text{Bar}}{\text{cm}^2}$) λ_{ti} =532 ,

$$\begin{aligned}
 & \frac{\partial}{\partial T} (n - \dots) \\
 & , T - \dots) \\
 & + (Au) \dots e- o- \dots [55]. \\
 & oo- \dots , oe-
 \end{aligned}$$

E7

$$\begin{aligned}
 & , \eta_{ee} , \dots I_{0,p1} \dots ee- \dots q \perp E_{0,p1} \\
 & = 50 \dots \\
 & \eta_{ee} \propto I_{0,p1}^2 \dots \eta_{ee} \approx \left(\frac{A}{A_T}\right)^2 [55],
 \end{aligned}$$

$$\begin{aligned}
 n^{ee}(I_{0,p1}) &= \eta_{ee}^e I_{0,p1} , \\
 \eta_{ee}^e &= 1.08 \times 10^{-2} \frac{\text{cm}^2}{\text{KBT}} = 50 \mu \dots \eta_{ee} (I_{0,p1}) \\
 & \dots (ee- \\
 & q \perp E_{0,p1} ; oe- \dots q \perp E_{0,p1} \dots q \perp E_{0,p1}).
 \end{aligned}$$

$$n^{oe}/n^{ee} = 0.9.$$

$$\eta \sim \Lambda^2,$$

$$n \propto \frac{1}{q^2}.$$

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$$(\tau_f^0 = 0.7)$$

$$(\tau_s^0 = 1, =$$

50 μ)

Λ^2 .

τ_s^0

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$\mathbf{q} \perp \mathbf{d}$

1.5,

$\mathbf{q} \parallel \mathbf{d}$ [55].

(. 1.7),

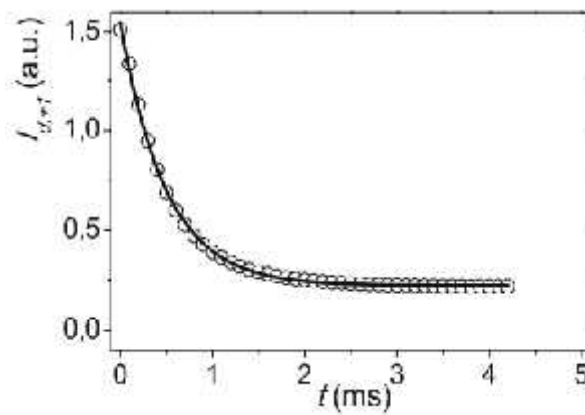
τ^0

τ_f^0 ,

Λ^2

q

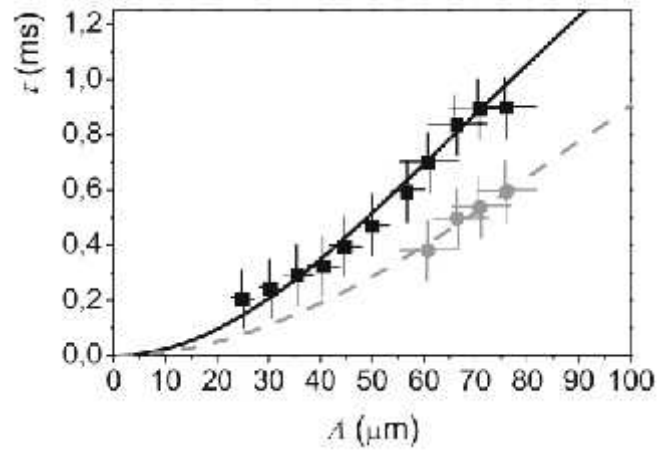
d (. 1.8) [55].



. 1.7.

$$\left(\frac{I_{d, \text{test}}(t)}{I_{d, \text{test}}(0)} \right) = 0.5 \quad [55].$$

= 45 μm



1.8.
()

$$(11) \quad \tau_{\perp}^0 () () \quad \tau_{\parallel}^0 ()$$

$$k_x^{\perp} = 0,2 \frac{\text{Br}}{\text{m}\cdot\text{K}} \quad k_x^{\parallel} = 0,4 \frac{\text{Br}}{\text{m}\cdot\text{K}} [55].$$

1.5.

(),

3D-

[7, 8, 22].

() .

57], [16, 31, 32, 58].

[9, 59-62].

[18, 63, 64].

[24, 61, 65-67]. [68, 69]

Au - , ,
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, (Au) - .

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/ .

1.5.1.

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Au -

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[18, 23, 70].

Nd:YAG (, =532 , 29
) , .

(-)

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U.

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He-Ne

. 1.9

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-

[70].

. 1.10

/

Au

$$U=2\div 4$$

Au

+U

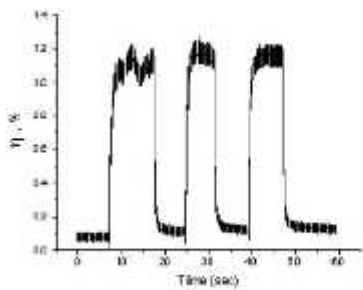
. 1.10

Au

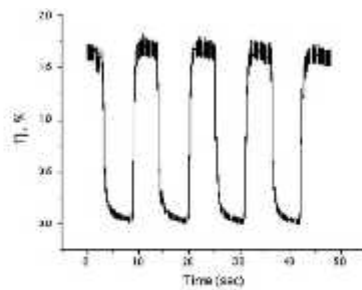


. 1.9.

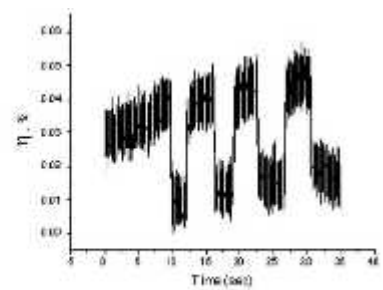
[70].



(1)



(3)



(8)

. 1.10.

$U=3$

[70].

[61].

$$n = n_2 I_0, \quad n_2 =$$

$$\chi^3[\epsilon] = n_2 I_0 \left[\frac{c}{W} \right] \cdot \frac{3 \cdot 10^4}{4\pi} c \cdot \epsilon_e \cdot n_0^2 \approx 19,015 \cdot n_0^2 \cdot n_2 \left[\frac{c}{W} \right], \quad (1.8)$$

$$c =, \quad \epsilon_e =, \quad n_0 =$$

$$n_0 = n_1 = 1.5268,$$

E7

[61].

$$\eta = \frac{I_{(+1)}}{I_0} = T \cdot [J_1^2(\zeta) + J_2^2(\zeta)], \quad \zeta = \frac{2\pi}{\lambda} \cdot \frac{1-T}{\alpha} \cdot n_2 I_0 \quad (1.9)$$

$$I_{\{+1\}} = \{+1\}, \quad T = 10^{-L} =$$

$$, \quad D =, \quad = [D \ln(10)]/d =$$

$$, \quad d =, \quad h_1 = h_2 =$$

$$, \quad I_0 =$$

$$14.5, \quad 1, \quad I_0 = 1.85$$

$$/ 2, \quad 2$$

$$h_1 = h_2 = 0: \quad 1.9$$

n_2 :

$$n_2 = \frac{\lambda}{\pi} \cdot \frac{\alpha}{1-T} \cdot \frac{\sqrt{I_0}}{I_0} \quad (1.10)$$

1.1.

1.1.

[70]

Au

	(Au) ([/],)	$\eta_{\{+1\}}$, %	d, μ	D	T	α , μ^{-1}	n_2 , c^{-2}/W
1	50–180	1.17	13.5	1.135	0.073	0.1935	0.009
2	20–230	5.49	13.5	1.25	0.056	0.2132	0.024
3	20–250	1.53	13.5	1.42	0.038	0.2421	0.017
4	20–250, [400/160]	0.45	13.5	1.27	0.054	0.2166	0.007
5	20–260, [470/170]	0.63	12.6	1.215	0.061	0.2220	0.008
6	20–420	1.5	12.6	1.53	0.029	0.2786	0.022
7	20–380	0.53	12.6	1.42	0.038	0.2594	0.011
8	50–330, [100/170]	0.045	12.6	1.78	0.017	0.3252	0.006
9	50–360, [560/170]	1.25	12.6	1.34	0.046	0.2448	0.014
10	50–500, [600/560]	0.6	12.6	1.58	0.026	0.2887	0.015
11	50–600, [660/430]	0.01	12.6	2.62	0.002	0.4787	0.010
12	–	0.045	12.6	4.55	–	–	–

1.5.2.

.1.11.

: (=532); /2 –

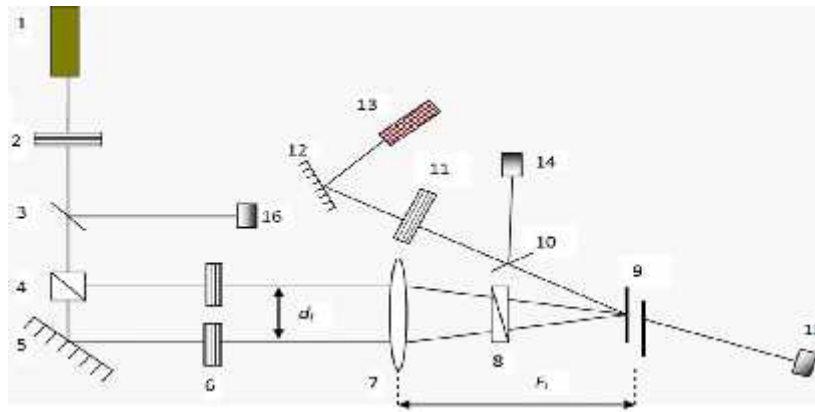
; ; ; ; ;

- ; He-Ne (=632.8); . -

,

45°

[52, 68, 71, 72].



. 1.11. : 1 –
 ($\lambda = 532$); 2 – $\lambda/2$ – ; 3, 10 –
 ; 4 – - ; 5, 12 – ; 6, 8, 11 –
 ; 7 – ; 9 – ; 13 – He-Ne ($\lambda = 632.8$); 14, 15, 16 –
 [72].

-
 : - ~ 300
 (), As_2S_3 1 (b), ITO 50 () (. 1.12).
 : ITO-
 Au; $-As_2S_3$; - . - 12-13 μ ,
 7 $n=0.2$. -

.
 ($\lambda = 532$). $I_{(+1)}$
 15 He-Ne .
 0 10 .

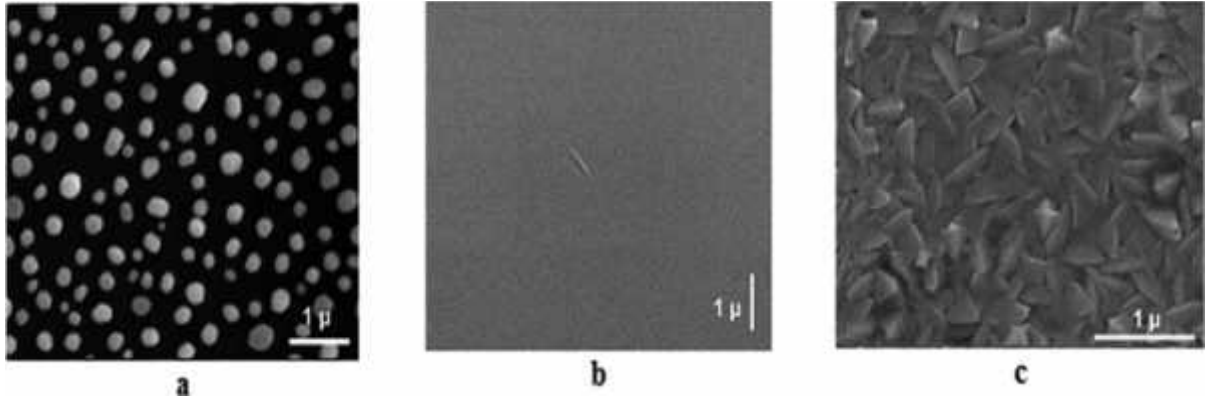
. 1.13. $\eta = \frac{I_{+1}}{I_0} 100\%$:

. 1.13

η

[72]. 1.13

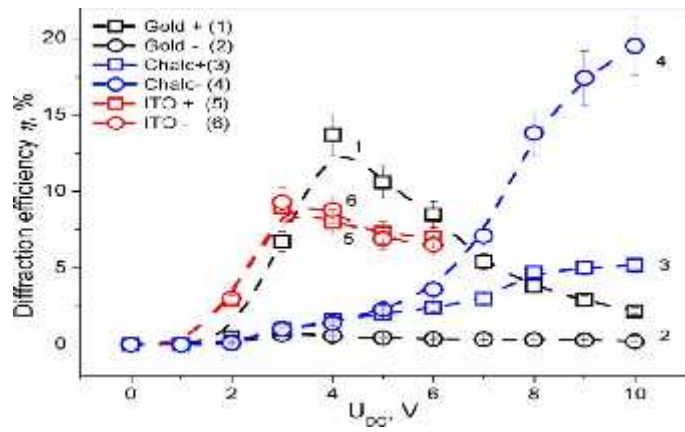
, : 1)
; 2)



. 1.12

(a), As_2S_3 (b) (): ITO (c). 60

[72].



. 1.13.

[72].

[18, 53, 72].

q_s E_s

q_s ()
 [65, 66, 73-76].

q_{sc} E_s ,
 (1 . 1.13).

2 . 1.13).

(. 3 4 . 1.13).

[75, 76].

()

p-

()

n-

[67, 75, 76].

As_2S_3

p-

(. 3

. 1.13).

(. 4 . 1.13).

ITO,

(. 5 6 . 1.13).

. 1.13.

1.5.3.

. 1.14.

YAG: Nd

= 532 ,

52

1 2

S

F

1 2.

1 2

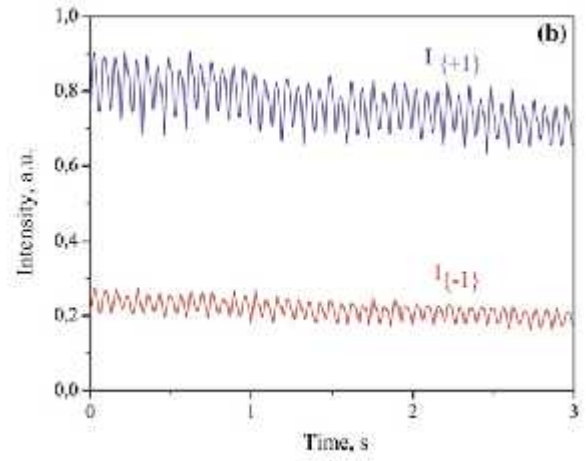
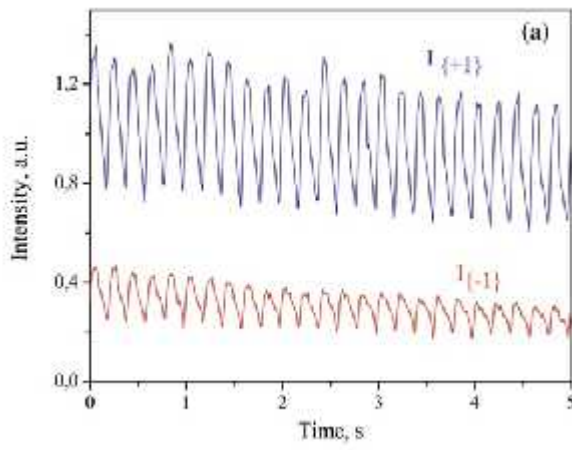
$\Lambda \approx 26$

= 45°

1 ,

$I_0 = 6.62 / \text{ }^2$.

S,



. 1.15.

). a)

$f = 5 \text{ Hz}$; b) $f = 15 \text{ Hz}$ [69].

$$\begin{pmatrix} I_{\{+1\}} & I_{\{-1\}} \\ U=0 & U=+5 \end{pmatrix}$$

1.6.

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[1, 3, 5, 7].

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[8, 23, 77];

[12, 49, 71];

(O),

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[23];

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[78, 79].

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[18, 63].

[54].

[29, 30],

[61, 69, 70, 72].

5CB LC1264,

LC1264

().

2.1

.2.1.

L

$x y$

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$z,$

,6-

$z.$

$z.$

d

$C: C \parallel d$.

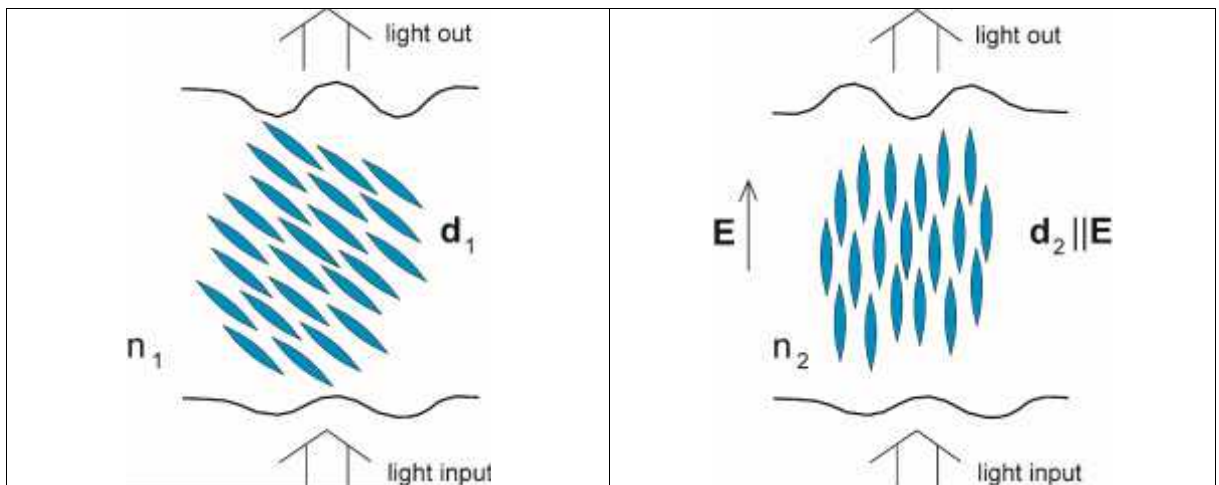
E

P .

[26, 28, 80].

γ_1

γ_1 .



2.1.

$K_3 = K_1 = K$ [26, 34, 81, 82]:

$$\frac{d}{dt} = \frac{K_3}{\gamma_1} \cdot \frac{d^2 \theta}{dz^2} + \frac{\epsilon_0 \Delta \epsilon}{\gamma_1} \cdot \sin(\theta) \cos(\theta) \cdot E^2 \quad (2.1)$$

K_3 — (B), K_1 — (S), γ_1 —

, $\Delta \epsilon$ — , E —

, ϵ_{ij} —

z

[26, 59].

1)

E_c

2)

3)

4)

$$: \Delta n = n_{||} - n_{\perp}, \quad n_{||} \quad n_{\perp} -$$

[26].

C

d [26, 34, 56, 83].

$$a_{i,j} = 1/\epsilon_{i,j},$$

k

, $k \parallel z$ (z

z), C, (x, z),
 $n_{\parallel} \parallel y$
 n_{\perp} , (x, z).

(t, z) n_{\parallel} n_{\perp} C. (x, z), $n_{\perp}(t)$
 3):

$$n_{\perp}(t) = \frac{n_{\parallel} n_{\perp}}{\sqrt{n_{\parallel}^2 \cos^2 \theta(t, z) + n_{\perp}^2 \sin^2 \theta(t, z)}} \quad (2.2)$$

2.2

(1)–(2) [84, 85].
 5CB
 LC1264, 2.1.
 $\theta = \pi/2$.
 $\theta = 0$. (2)
 $n_{\perp}(\theta)$
 $n_{\perp} = n_{\parallel}$ $n_{\perp} = n_{\perp}$ [26].
 n_{\perp}

2.1.

	5CB [86, 87]	LC1264 [88]
K33	10,4 pN	10 pN
γ_1	0,112	0,45
Δ	21,6	11,5
Δ	0,1832 (24 C, $\lambda=632,8$)	0,18 (25 C)
$n_{ }$	1,7103 (24 C, $\lambda=632,8$)	1,71 (25 C)
n_{\perp}	1,5271 (24 C, $\lambda=632,8$)	1,53 (25 C)

: $L=30 \mu$

$L=10 \mu$

125 μ

1

1000 μ

20%.

. 2.2,

n_e

5CB.

$L=30 \mu$

$L=10 \mu$

E

E

$$E=U/L, \quad U -$$

$sat -$

n_e .

5CB

$sat < 100$

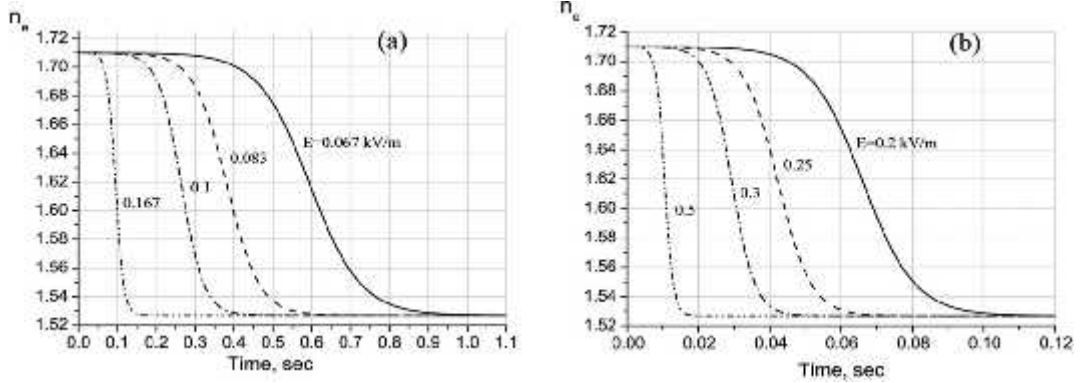
sat

, $sat=10$

$L=10 \mu$

$$\tau \approx 10$$

$$E > 0,5 \quad / \quad .$$



. 2.2.

5CB . ()

$L=30 \mu$; b) $L=10 \mu$.
 $E=0,067$ / ($U=2$), $E=0,083$ / ($U=2,5$), $E=0,1$ / ($U=3$), $E=0,167$ / ($U=5$) $L=30$; $E=0,02$ / ($U=2$), $E=0,025$ / ($U=2,5$), $E=0,3$ / ($U=3$), $E=0,5$ / ($U=5$) $L=10$, $U -$

$$n_e(t, x),$$

$$: E = E_0 \sin(x \cdot 2\pi/\Lambda), \quad \Lambda -$$

$$x, \quad E_0 -$$

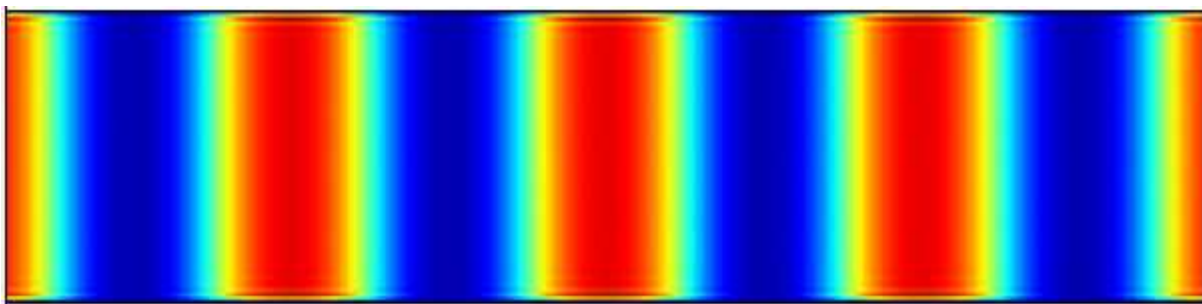
$$E_0 = U/L$$

(1)–(2),

. 2.3.

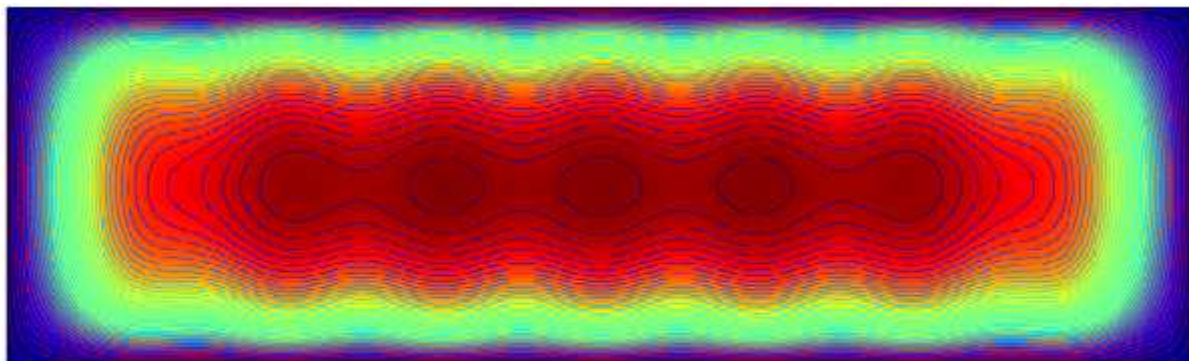
N_g

$$N_g = n_e(E_m) - n_e(E_m) \quad (2.3)$$



. 2.3.

$t=0.15$, $E_0=0.167$ / (U=5 B) $=50 \mu$
 $L=30 \mu$, $-5CB.$



. 2.4. « »

(,),
 $E_0=0.167$ / (U=5 B), $=30 \mu$,
 $t=10.1$, $L=30 \mu$, $-5CB.$

. 2.4

$=30 \mu$,

$t=10.1$.

γ_1

[26, 80].

. 2.5 (a) 5CB

. 2.5 (b)

LC1264,

γ_1 (.

2.1).

: $=50 \mu$

$=20 \mu$.

E.

. 2.5 (a),

N_g

5CB,

:

LC1264

(. 2.5 (b),

$E_0=0.067$

/ $E_0=0.083$ /).

LC1264 [68, 89, 90].

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0.5 / .

3.

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[23].

3.

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[61, 68, 70, 72].

3.1

[91].

$$\pm d (d -$$

).

[26].

. 3.1.

L

$x \ y.$

$z,$

$$C : C \parallel d .$$

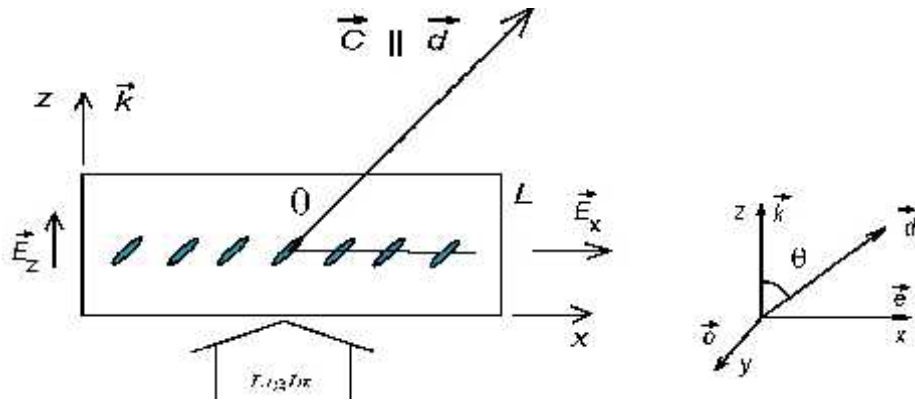
d

d

$$\vec{E}_z = \vec{E}_0$$

z.

z.



. 3.1. 2D

z,

\vec{d} -

L -

\vec{c}

\vec{E}_z \vec{E}_x

\vec{k} -

\vec{d} \vec{e} ,

y x.

\vec{E}_s ,

[18, 63].

$$x - \vec{E}_x = \vec{E}_s$$

. 3.1.

\vec{E}

\vec{P} .

<0 , >0 , ()

[26].

(splay) $d \cdot \ddot{r} = 0$; $K_2 -$ (twist) $d \cdot \ddot{r} = 0$; $K_3 -$
 (bend), $d \times \ddot{r} = 0$.

(, . [26, 80]).

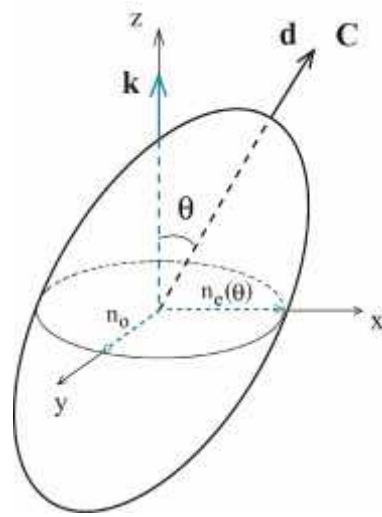
$\theta_{\text{li}} = \pi/2$ [91].

$$E_x = E_y,$$

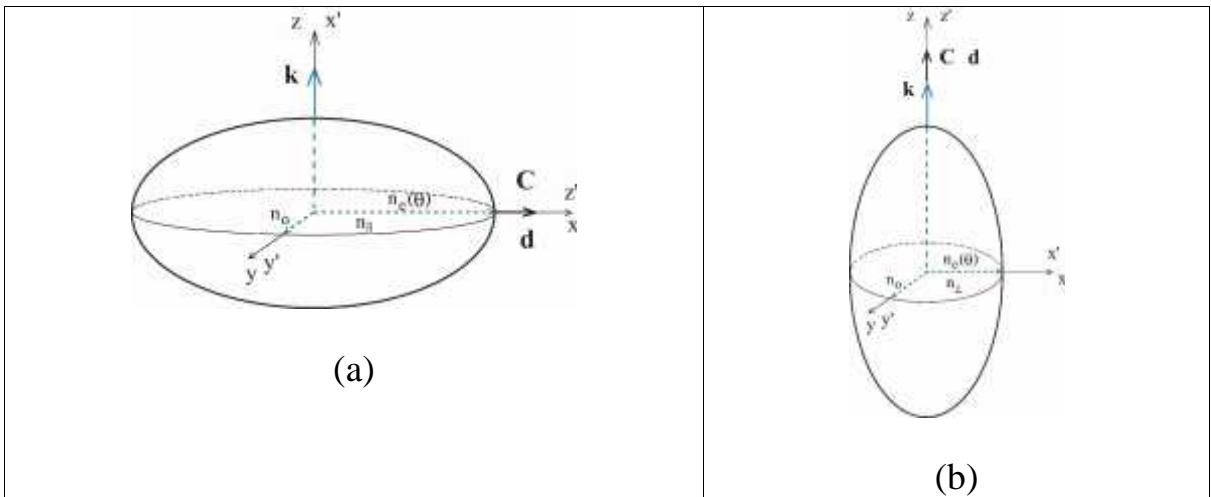
$$: E = E_x + E_y .$$

$E_x,$

[91].



3.2. , θ , C z
 k .



3.3. S-
 n_{\perp} n_{\parallel} . (a)
 $C \parallel x$. (b)
 $C \parallel$

z . $z: k \parallel z$.
 k . (x, y, z)
 (x', y', z') ,

Δ

0,5.

[26, 33].

$>0,$

5

LC1264

7.

$x.$

$z: E_x.$

(

)

$z,$

, $d \parallel z.$

$x(E_x)$

$K_1,$

((1.4)).

S-

),

z

(x, z) (3.2).

$z,$

– (3.4). n_E

(3.4) :

$$Z = n_E \bar{s} ; \quad X = n_E \bar{c} ; \quad Y = 0 \quad (3.3)$$

(3.2),

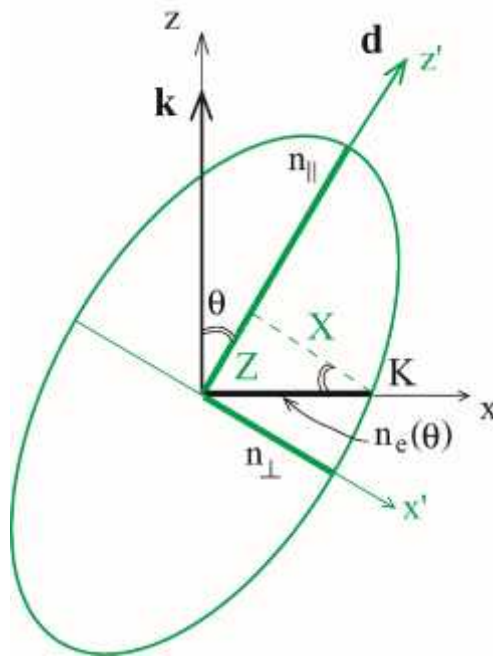
$$\frac{n_E^2 \bar{c}^2 \theta}{n_{\perp}^2} + \frac{n_E^2 \bar{s}^2 \theta}{n_{\parallel}^2} = 1 \quad (3.4)$$

$n_E(\theta)$:

$$n_E(\theta) = \frac{n_{\parallel} n_{\perp}}{\sqrt{n_{\parallel}^2 \bar{c}^2 \theta + n_{\perp}^2 \bar{s}^2 \theta}} \quad (3.5)$$

$$\theta = 0 \quad n_E(\theta) = n_{\perp},$$

$$\theta = \pi/2 \quad n_E(\theta) = n_{\parallel} \quad (3.3) \quad (),$$



. 3.4.

$n_e(\theta)$.

K

(x, z) .

3.1.2

2D

(. 3.1)

S-

z

[92, 93].

(

),

. 3.5.

E

(x, y) ,

z :

$$E_e = a = E(\psi); E_o = b = E(\psi) \tag{3.6}$$

$$, 2\pi n_o L/\lambda \quad 2\pi n_e L/\lambda ,$$

:

$$\delta = (2\pi/\lambda)(n_e - n_o)L \quad (3.7)$$

S-

(x, z),

- . ,

$$, n_{\perp} = n_{\perp}.$$

θ ,

$$n_e(\theta = 0) = n_{\perp}$$

$$, n_e(\theta = \pi/2) =$$

n_{\parallel}

, , n_{\perp} n_{\parallel}

.

:

$$\Delta n = n_e(\theta) - n_o [26].$$

E θ z ,

,

$$: d \parallel E .$$

-

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d ,

θ .

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,

$$(3.7) \quad n_e = n_e(\theta)$$

$$(3.5), \quad n_e = n_{\perp}$$

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,

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[92, 93].

ψ x ,

-

x

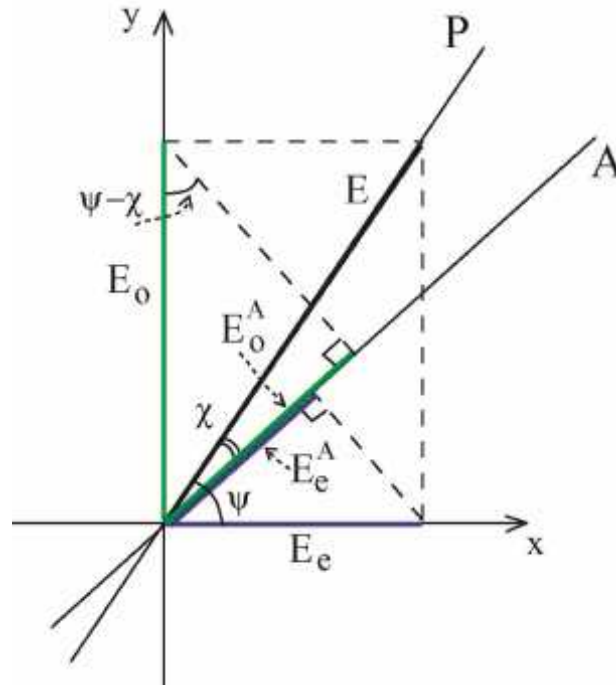
(P . 3.5). E

,

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A,

$$E_e = E_0 \cos(\psi - \chi); E_e^A = E_0 \sin(\psi - \chi) \quad (3.8)$$



3.5.

P A

(x, y)

E

E_e E_0

E_e^A E_0^A

I

$$I = |E_e^0 + E_0^0|^2$$

$$E_e^0 =$$

$$E_e e^{i(\omega - kn_e L)}, E_0^0 = E_0 e^{i(\omega - km_0 L)},$$

$$I = I_e^A + I_0^A + 2(I_e^A I_0^A)^{1/2} \cos(\delta) \quad (3.9)$$

(3.8) (3.9):

$$I = E^2$$

$$\frac{1}{2} \sin(2\psi) \sin(2(\psi - \chi)) \cos(\delta) \quad (3.10)$$

$$\tilde{c}_i(\delta) = 1 - 2s_i^2\left(\frac{\delta}{2}\right)$$

$$(2.10)$$

$$\frac{1}{2} \left\{ s_i^2(2\psi) s_i^2(2(\psi - \chi)) - s_i^2(2\psi) s_i^2(2(\psi - \chi)) s_i^2\left(\frac{\delta}{2}\right) \right\} \quad (3.11)$$

$$(3.11).$$

$$\tilde{c}_i^2(\psi - \chi) = \frac{1}{2} [1 + \tilde{c}_i(2(\psi - \chi))]; \quad s_i^2(\psi - \chi) = \frac{1}{2} [1 - \tilde{c}_i(2(\psi - \chi))]$$

$$\tilde{c}_i^2\psi - s_i^2\psi = \tilde{c}_i(2\psi); \quad \tilde{c}_i^2 + s_i^2 = \tilde{c}_i(A - B)$$

$$\frac{1}{2} [1 + \tilde{c}_i(-2\chi)] = \tilde{c}_i^2(\chi)$$

$$I = E^2 \left[\tilde{c}_i^2(\chi) - s_i^2(2\psi) s_i^2(2(\psi - \chi)) s_i^2\left(\frac{\delta}{2}\right) \right] \quad (3.12)$$

$$, \quad A \perp P . \quad \chi = \pi/2$$

$$I = E^2 s_i^2(2\psi) s_i^2\left(\frac{\delta}{2}\right) \quad (3.13)$$

$$x, \quad y \left(\psi = 0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}, \dots \right),$$

$$\psi = \frac{\pi}{4}, \frac{3\pi}{4}, \frac{5\pi}{4}, \dots$$

$$\psi = \pi/4$$

$$x \left(\dots \right), \quad (x, z),$$

$$I_m = E^2 s_i^2\left(\frac{\delta}{2}\right) = I_0 s_i^2 \frac{\pi(n_e(\theta) - n_o)L}{\lambda} \quad (3.14)$$

$$I_U \quad (3.14)$$

L,

$$\Delta = n_e - n_o \quad \lambda .$$

3.1.3

2D

2D ,

: 5 , LC1264 7.

3.1

3.1.

	$n_{ }$	n_{\perp}	Δ_m	δ_m , L=10 μm , =0.532 μm =0.632.8. μm	δ_m , L=20 μm , =0.532 μm =0.632.8. μm
5 (24 ⁰ C, =632.8 nm)	1.7103	1.5271	0.1832	21.63 18.18	43.25 36.36
LC1264 (25 ⁰ C)	1.71	1.53	0.18	21.25 17.86	42.5 35.73
E7 (25 ⁰ C)	1.7366	1.5258	0.2108	24.88 20.92	49.77 41.84
E7 (61 ⁰ C)	1.7462	1.5216	0.2246	26.51 22.29	53.03 44.58

3.1

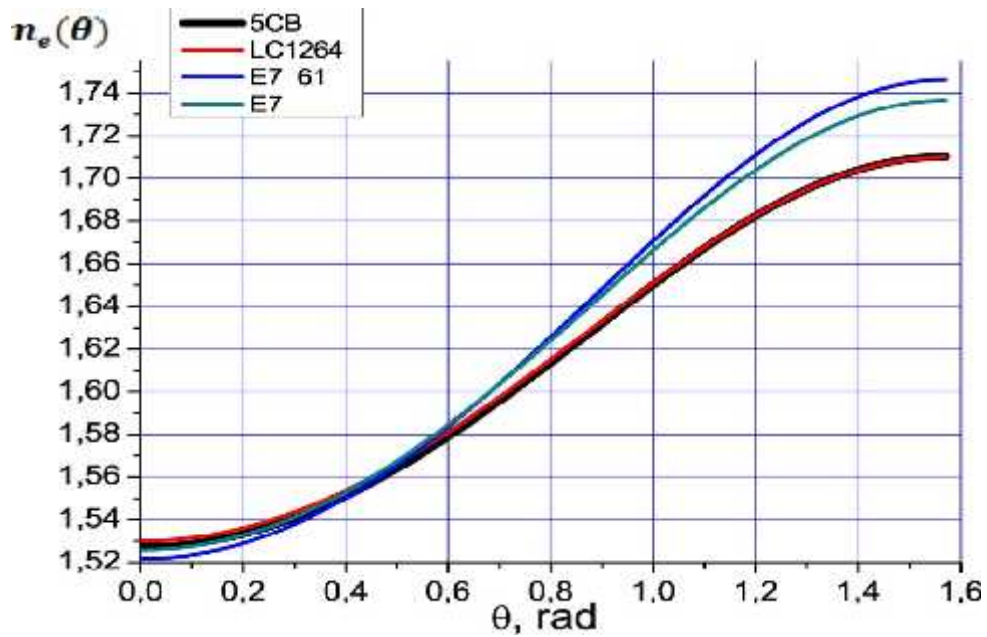
$$\delta \quad (3.7), \quad \Delta_m$$

$$, \quad n_e(\theta) = n_{||},$$

P .3.6

$n_e(\theta)$,

(3.5)



. 3.6.

θ $n_e(\theta)$.

/2.

$\delta(L, \theta)$

$\theta = 0 \dots \pi/2$

(3.7)

P . 3.7 [91,

94].

(3.14)

. 3.8 3.9.

θ 0 $\pi/2$.

0 1: ,

$\theta \approx 0 \dots 0,6r_1$ (23^u)

$L = 10\mu$ $\theta \approx$

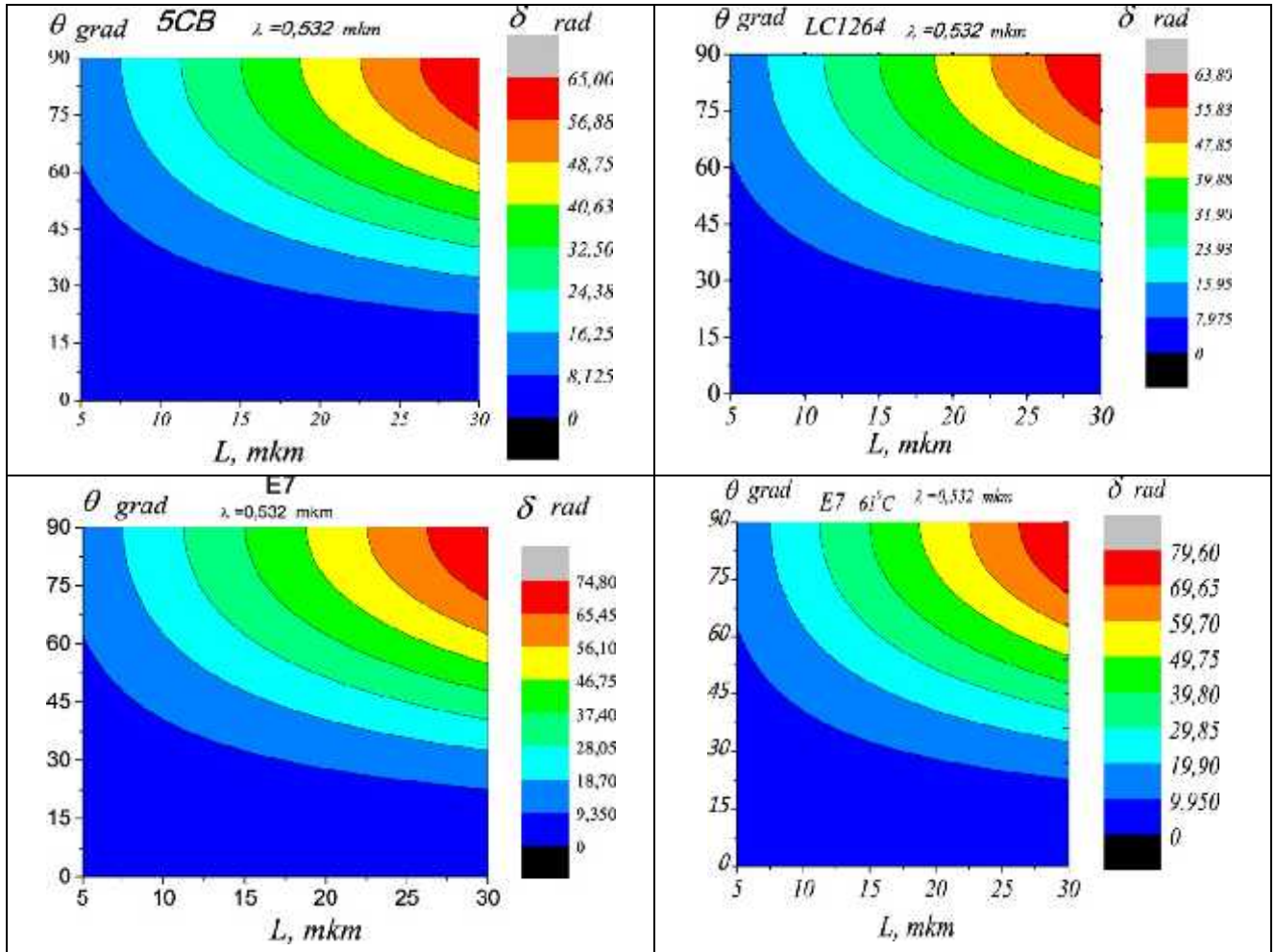
0 $\dots 0,3r_1$ (17^u)

$L = 20\mu$.

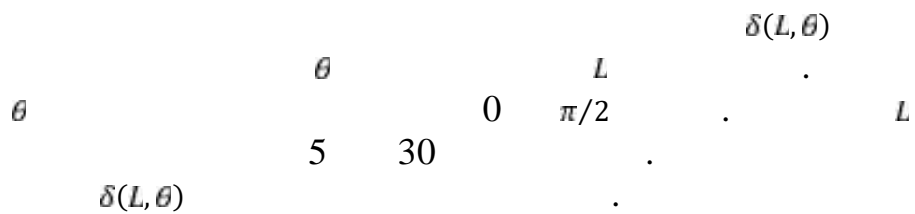
: $\theta \approx 0,32r_1 = (1,57 - 1,25)(18^u)$ (

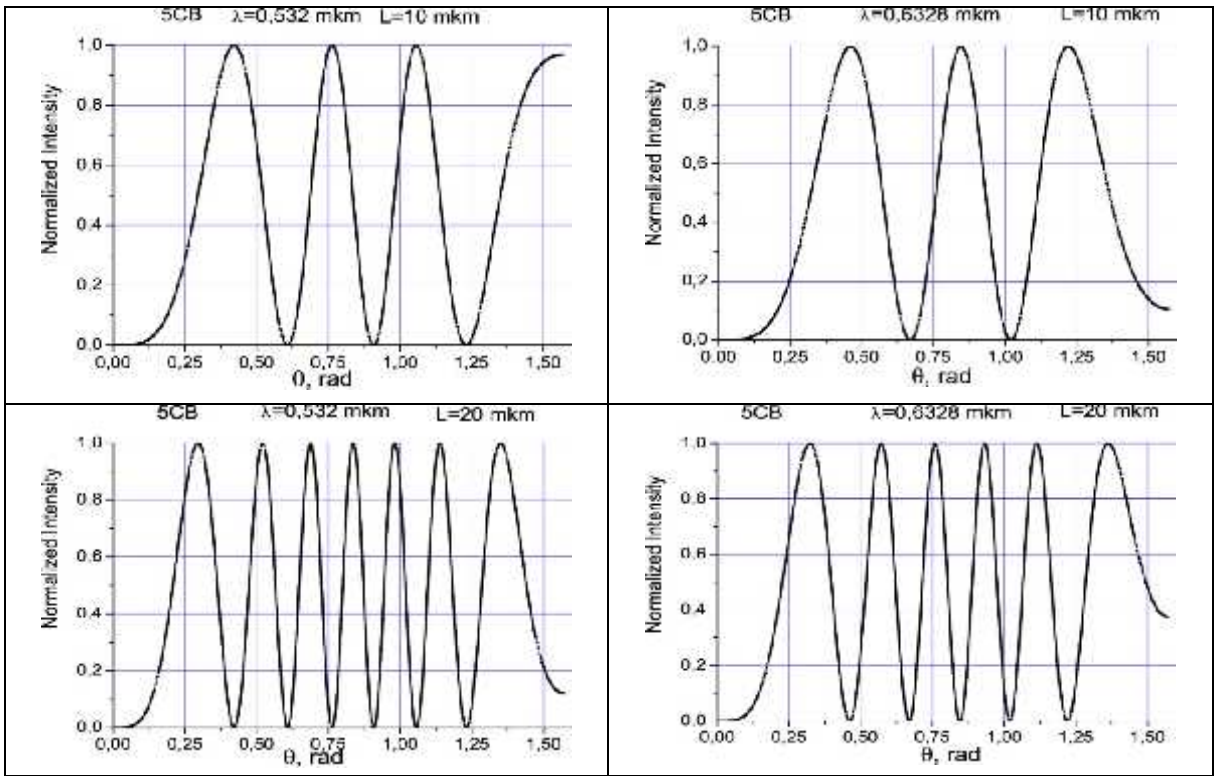
7, $L = 10\mu$,

$\lambda = 0,532\mu$) $\theta \approx 0,21r = (1,57 - 1,36)r$ (12^u) (7, $L = 20\mu$, $\lambda = 0,532\mu$). 3.3



. 3.7.

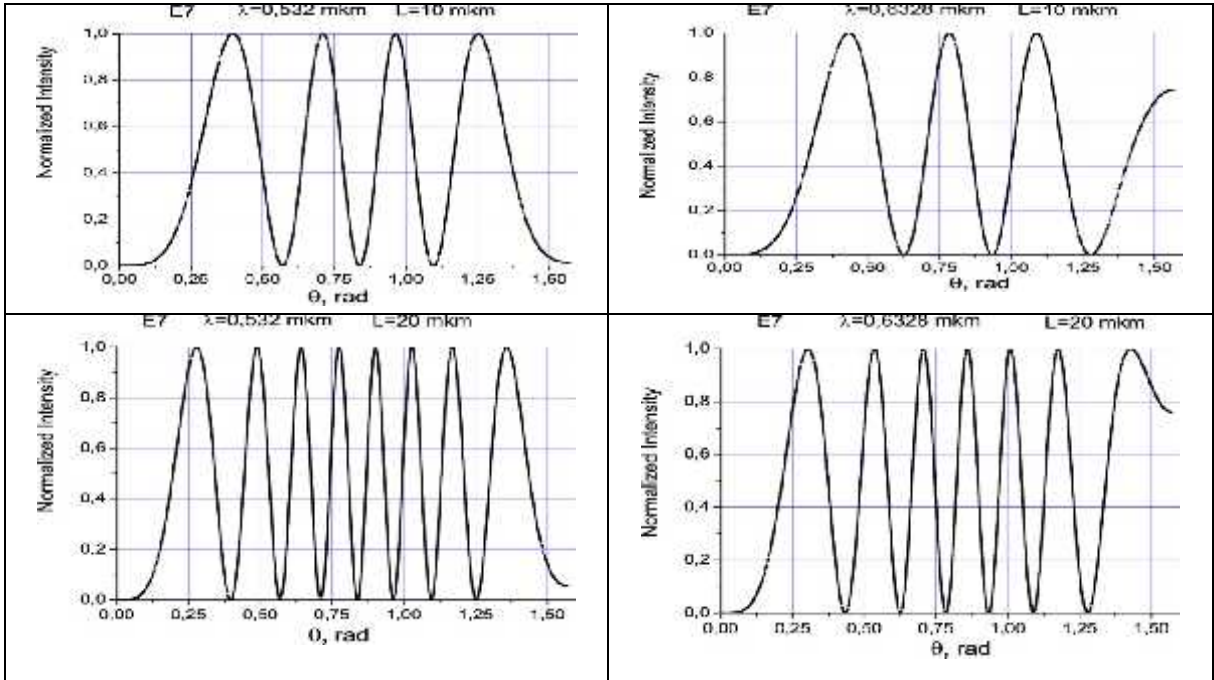




. 3.8.

5 . (- , -) .

θ , 2D-



. 3.9.

(- , -) .

θ , 2D- 7.

3.2

S-

) [95, 22].

3.3.

.3.10.

1

3

4 5,

6.

u 7,

(2,

(),

(8, 9, 10),

:

{{-1}

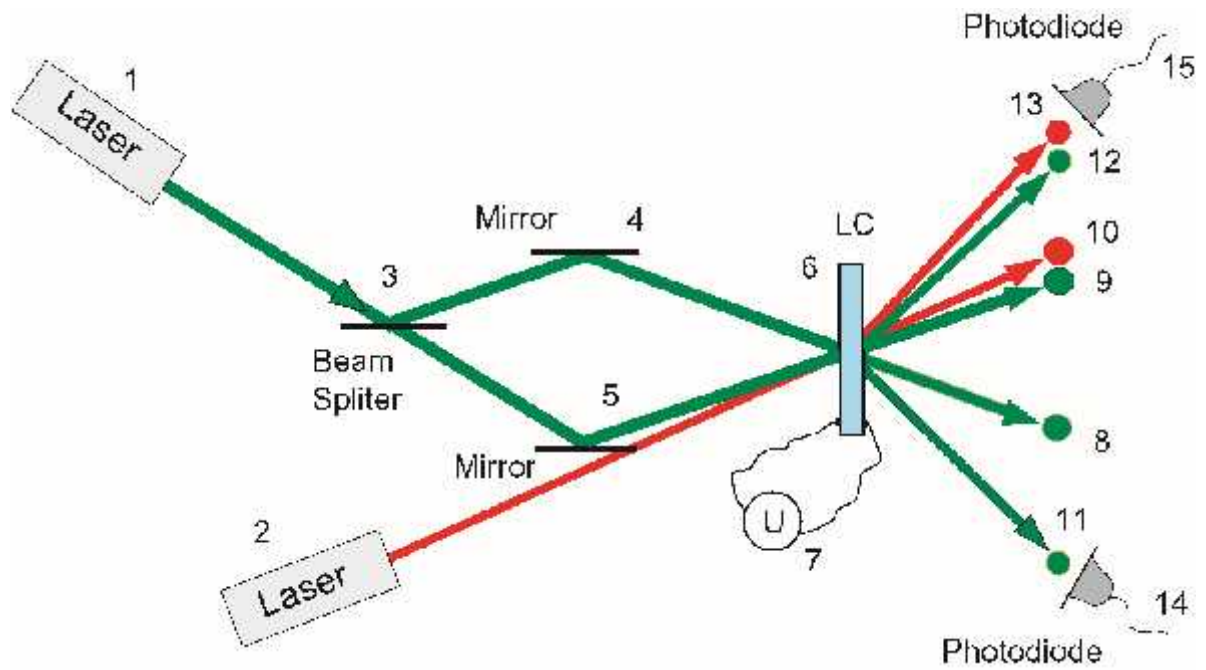
11; {+1} 12)

{{1} 13).

(14 -

15 -

),



3.10.

1 Nd:YAG

()

He-Ne

2 ()

6.

E_z

E_x

l ,

[13, 56, 77, 95]:

$$\Delta = n_2 l$$

(3.15)

$n_2 -$

[18, 47, 63].

« E_x » , E_z , « E_x »
 $E = E_z + E_x$.

3.2.1

S-

[61]:

$$I_{\{-1\}} = I_{\{+1\}} = T I_{\text{u}} [J_1^2(\zeta) + J_2^2(\zeta)] \quad (3.16)$$

$$\zeta : \quad \zeta = \frac{2\pi}{\lambda} L_{\text{e}} \Delta \quad (3.17)$$

(3.16), (3.17) : $I_{\{-1\}}, I_{\{+1\}}$
 $\{-1\} \quad \{+1\}$, ; T ; I_{u}
 ; J_1, J_2
 , ; L_{e}

$$\alpha : \quad L_{\text{e}} = \frac{1-T}{\alpha} \quad (3.18)$$

D , :
 $T = e^{-\alpha} , T = 10^{-D}, \alpha = \frac{D(1)}{L} \quad (3.19)$

$$I_{\{-1\}} = I_{\{+1\}} = T I_{\text{U}} J_{\text{I}}^2(\zeta) \quad (3.20)$$

$$(3.17). \quad \zeta \quad \delta(\theta, L)$$

$$: I_1 = I_2 = I_{\text{U}} .$$

$$3.1. \quad n_{\text{U}} = n_{\perp}, n_{\text{e}}(\theta)$$

$$(3.5).$$

$$L_{\text{e}} = L, \quad \zeta = \delta \quad (3.7). \quad \delta$$

$$\Delta \quad (3.2) -$$

θ

$$0 \quad \pi/2 (\theta = 0.. \pi/2), \quad \zeta = \delta \quad (3.7).$$

$$\delta(\theta, L) \quad . 3.7$$

$$0 (\theta = \pi/2..0).$$

, « »

δ :

$$\delta_m \left(L, \theta = \frac{\pi}{2} \right) = \frac{2\pi}{\lambda} (n_{\parallel} - n_{\perp}) L \quad (3.21)$$

$\delta(\theta)$

$$\delta_p = \delta_m(L, \pi/2) - \delta(L, \theta) \quad (3.22)$$

. 3.11

θ , . 3.7

, (L,) (3.7) (

), (3.22) ()

(3.5) (3.16).

($L_e = L$)

. 3.12 [91, 94].

.3.12 ,

() ,

E.

,

$\theta \approx 0.5$ ($\approx 28^\circ$) ($L = 5 \mu$), $\theta \approx$

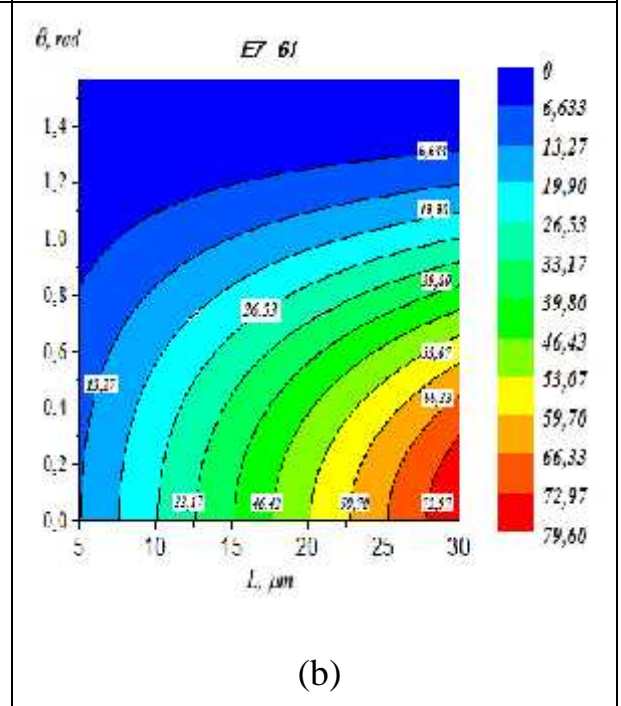
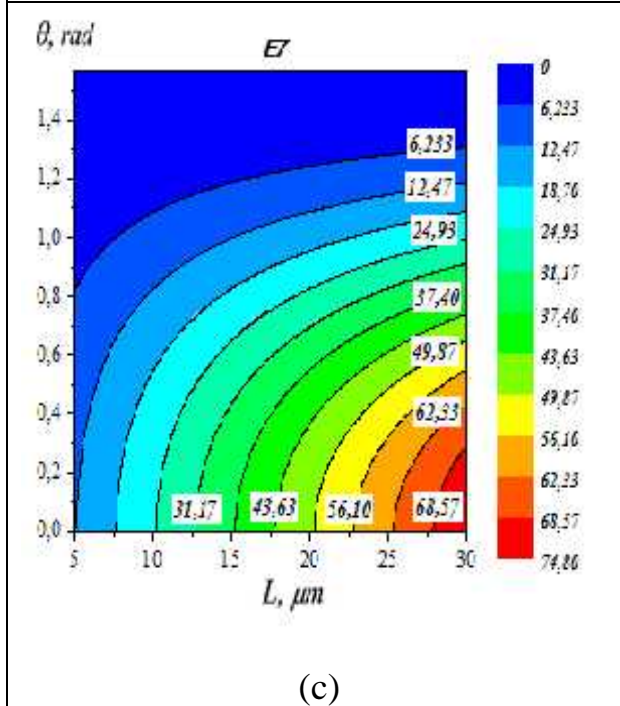
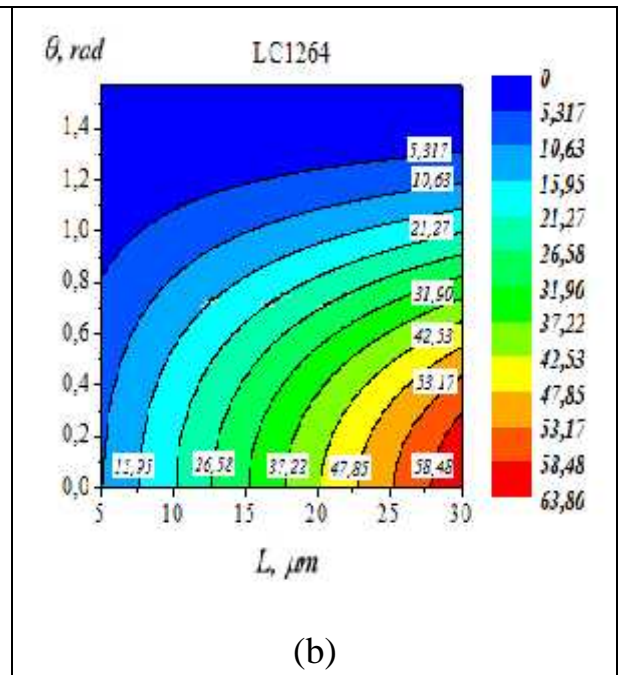
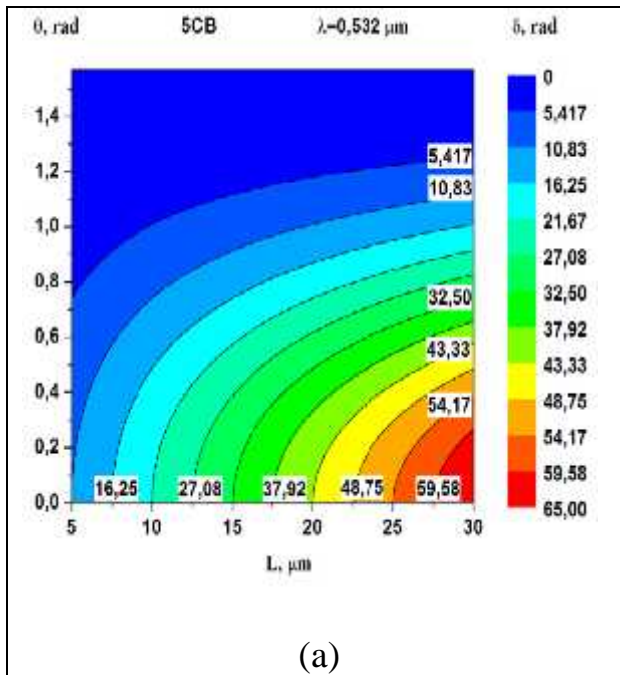
0.2 ($\approx 11,5^\circ$) ($L = 30 \mu$).

,

$\theta = 0$.

δ

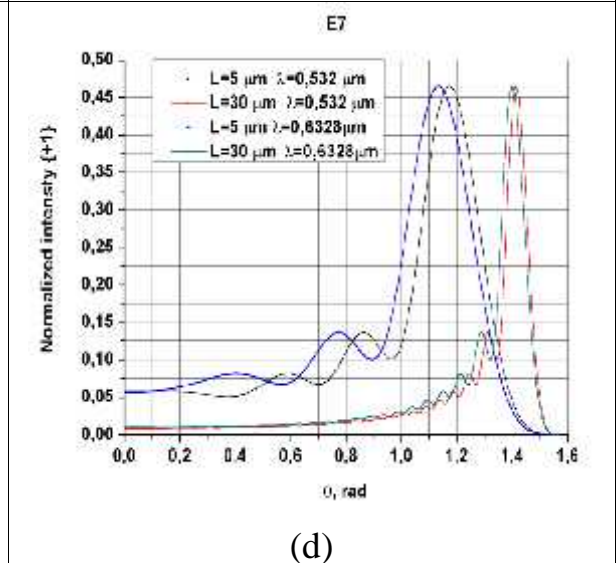
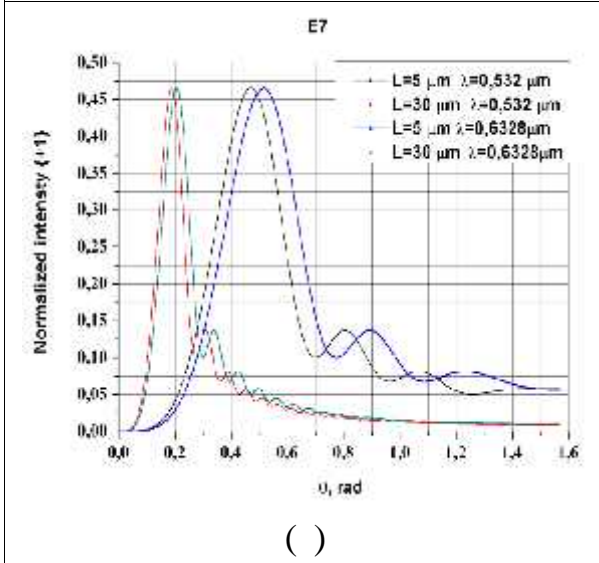
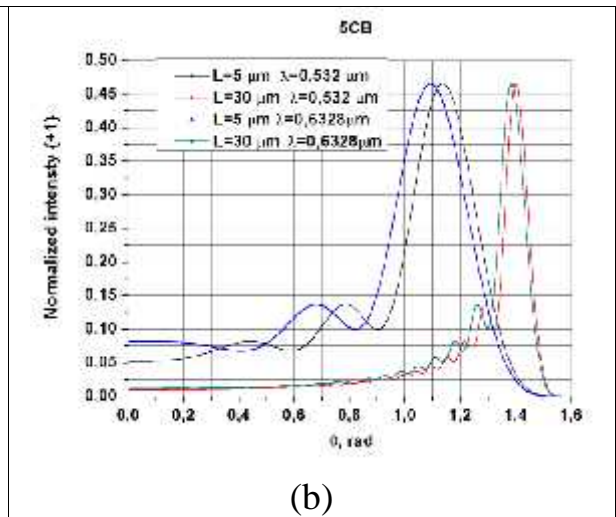
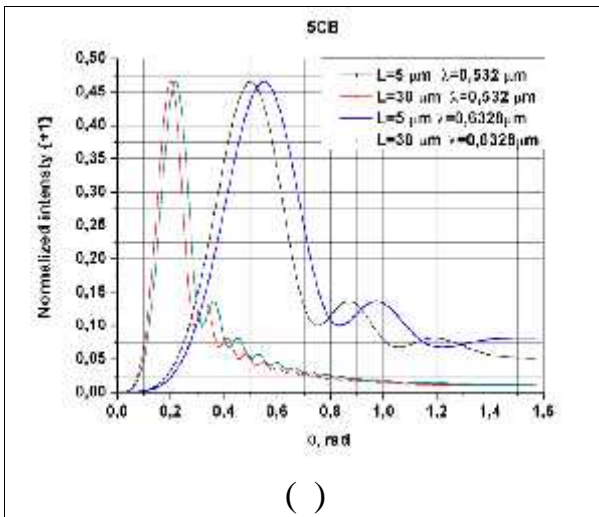
46%.



. 3.11.

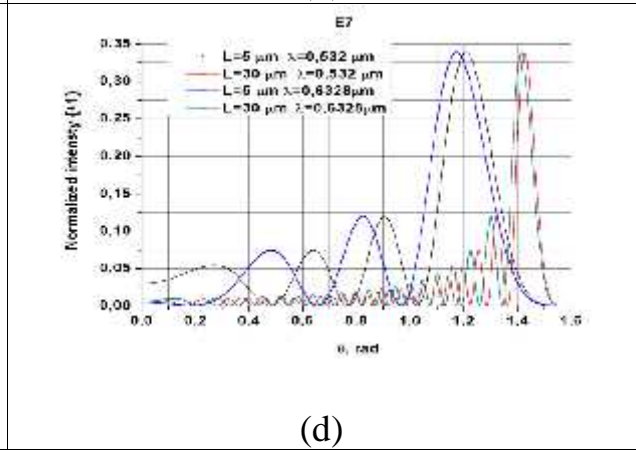
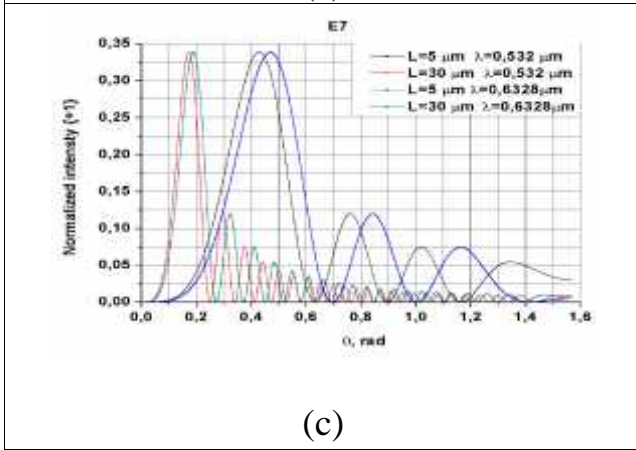
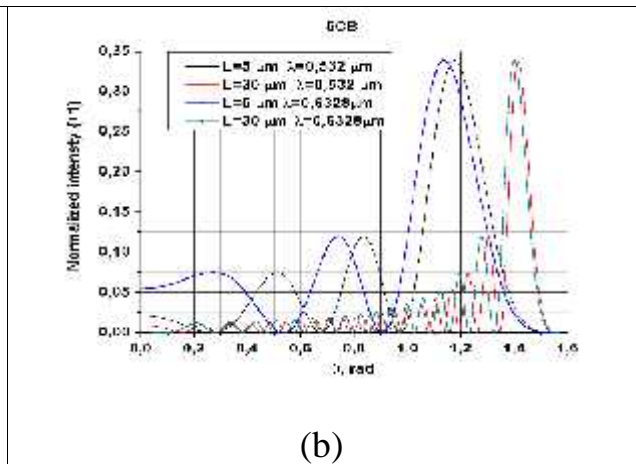
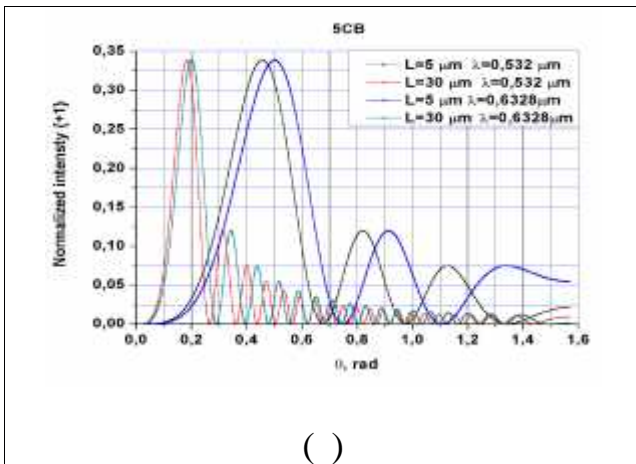
$$\delta_E(L, \theta) = \frac{z}{L} \cdot \frac{L}{5 \text{ to } 30 \mu}$$

$$\delta_P(L, \theta) = \frac{L}{0 \text{ to } L/2}$$



. 3.12. ()
: () 5 ; () 7
, (b) 5
, () 7
=0,532 micrometers =0,6328 micrometers
30 micrometers .
L_e = L.
(L,) (3.7) (
), (3.22) (
(3.5) (3.20)

. 3.13.



. 3.13.

()

, () 5
 , () 7
 =0,532 micrometers =0,6328 micrometers
 30 micrometers . L_g = L. 5

. 3.12,

theta,

37%,

θ :

θ

δ_p ,

$$: \Delta \approx 1.6 - 1.1 = 0.5 \quad (L = 5 \mu) \quad \Delta \approx 1.6 - 1.4 = 0.2 \quad (L = 30$$

μ).

3.2.2

3.2.1,

$T = 1$.

L .

(3.18).

α

T (., [61, 69, 70]).

T ,

α

D

(3.19).

(3.7), (3.22)

L

L_{eff} ,

T

(3.16) (3.20).

. 3.14 3.15

, $\alpha = 0.2 \mu^{-1}$, [91, 94], [70].

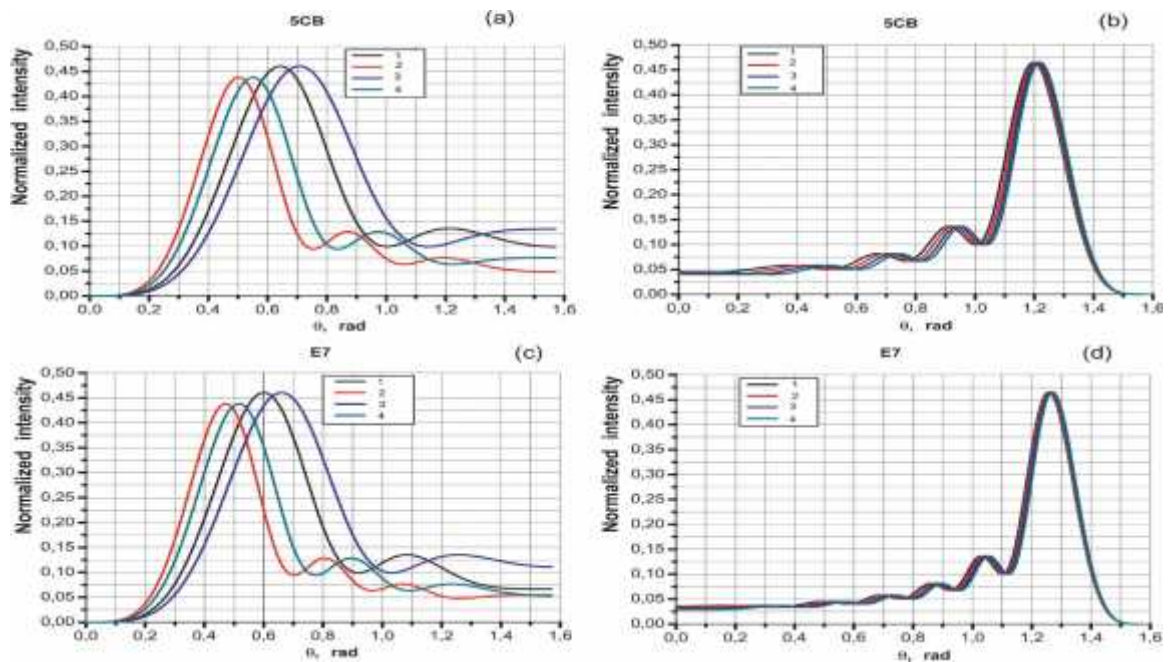
α

. 3.14-3.15,

L_{eff}

(. 3.14 (), (); . 3.15 (), ()).

η .



. 3.14.

()

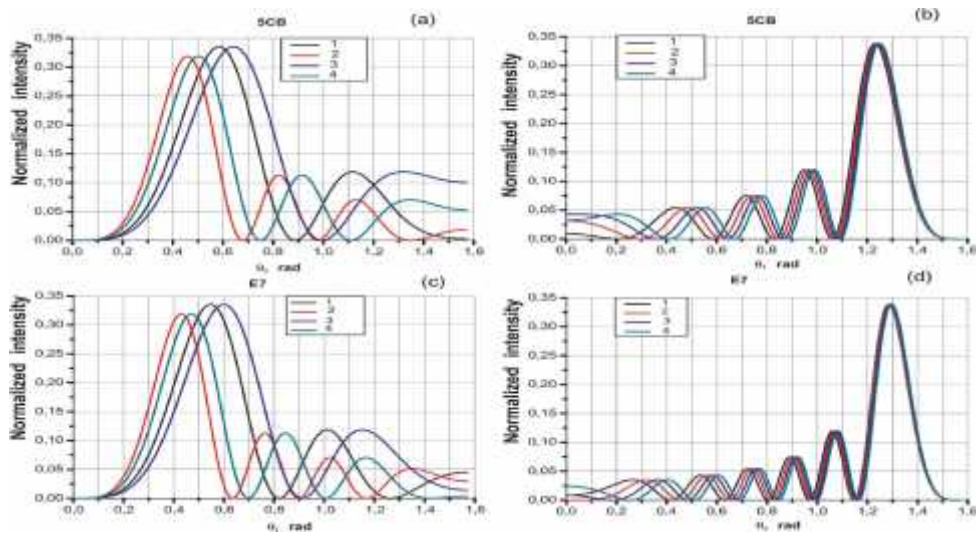
$= 0.2 \mu^{-1}$: () 5, (b) 5

; () 7, (d) 7

. $1 - L_e = 3.16 \mu$, $L = 5 \mu$, $\lambda = 0.532 \mu$; $2 - L_e$

$= 4.99 \mu$, $L = 30 \mu$, $\lambda = 0.532 \mu$; $3 - L_e = 3.16 \mu$, $L = 5 \mu$, $\lambda = 0.6328 \mu$;

$4 - L_e = 4.99 \mu$, $L = 30 \mu$, $\lambda = 0.6329 \mu$.



. 3.15.

()

(b) 5 $= 0.2 \mu^{-1} : () 5$ $i \quad i$,
 $i \quad i ; () 7$ $i \quad i$, (d)
 7 $i \quad i$. $1 - L_e = 3.16 \mu$, $L = 5 \mu$, $\lambda = 0.532 \mu$; $2 -$
 $L_e = 4.99 \mu$, $L = 30 \mu$, $\lambda = 0.532 \mu$; $3 - L_e = 3.16 \mu$, $L = 5 \mu$, $\lambda = 0.6328 \mu$;
 $4 - L_e = 4.99 \mu$, $L = 30 \mu$, $\lambda = 0.6329 \mu$.

3.3

S-

($\Delta E > 0$). . 3.1,

2D

E_z ,

, « »

E_x

$$, E = E_z + E_x,$$

U,

[61, 69, 70, 72].

$E_x,$

[91, 94]. . 3.16

$E.$

$$E_x = (E_x e_x, 0), E_z =$$

$$(0, E_z e_z), E_x, E_z -$$

, $e_x, e_z -$

$$E = (E_x e_x, E_z e_z).$$

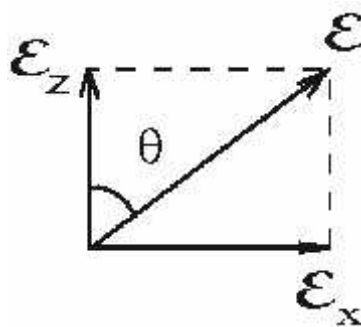
(. 3.16)

, θ :

$$\theta = \arctan \frac{E_x}{E_z} \quad (3.23)$$

$E_x,$

θ



. 3.16.

E_z

E_x

$E.$

$$\theta \quad E_z \quad (3.23).$$

$$\eta_{cl} = J_1^2(\delta); \quad \eta_{ls} = J_1^2(\delta) + J_2^2(\delta) \quad (3.24)$$

$$\delta = \frac{2\pi}{\lambda} [n_e(\theta) - n_{\perp}] L_e \quad (3.25)$$

$$\eta_{cl} \quad \eta_{ls} \quad (3.22)$$

$$\delta = \frac{2\pi}{\lambda} [n_{\parallel} - n_e(\theta)] L_e \quad (3.26)$$

$$n_e(\theta) \quad (3.5),$$

$$\theta \quad E_z \quad (3.23).$$

(3.24)–(3.26)

3.2.2 (3.18),

($\alpha = 0.2 \mu^{-1}$)

5 μ

30 μ : $L_e \ 4 \div 5 \mu$.

$L = 5 \mu$

η

U ,

E_x, E_z ,

θ^m . 3.16

$\theta = \alpha \quad (\epsilon_x/\epsilon_z)$, $\epsilon_x \quad \epsilon_z$

() ()

U

E_z ;

$E_x = \tilde{c}$.

$$\begin{cases} E_z(U) = \frac{U}{L} = E(U) \cdot \theta(U) \\ E_x = c = E_x^m = E^m \cdot s[\theta^m] \end{cases} \quad (3.27)$$

$E_z(U) -$

$U,$

$E(U)$

$\theta(U);$

E_x

$U.$

$\theta^m,$

θ^m

$$E^m(U_0) = E_z^m(U_0) + E_x^m$$

$U_0.$

(3.27)

$E_z^m(U_0)$

$E_x^m :$

$$E_x^m = \frac{U_0}{L} \cdot t(\theta^m) \quad (3.28)$$

(3.28)

(3.27)

:

$$\theta(U) = t \left[\frac{U_0}{U} \cdot t(\theta^m) \right]$$

(3.29)

U_0

θ^m

. 3.12 – 3.15.

5

. 3.12 – 3.13

$\theta^m,$

(.,

, [61, 69, 70, 72]),

U

15

U_0

3 .

$U_0 = 3$

. 3.16

(3.28)

$\theta^m =$

$$a \left(\frac{1}{E_x/E_x} \right).$$

3.2.

3.2. θ^m

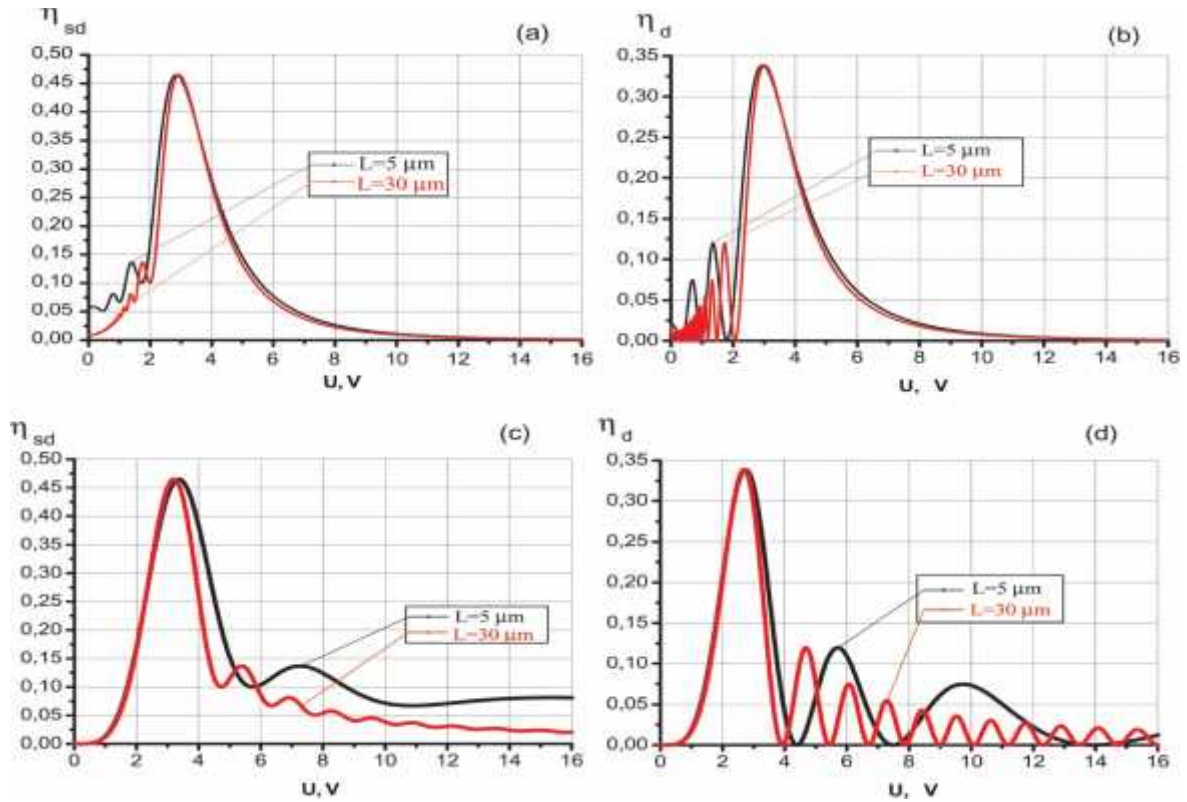
5 ,

3.12.

--	--	--	--

	$L = 5 \mu$	$L = 30 \mu$	$L = 5 \mu$	$L = 30 \mu$
E_z/E_x	2.0655	5.334	0.413	0.161
θ^m ()	0.451	0.185	1.179	1.411
t (θ^m)	0.484	0.187	2.421	6.211

. 3.17.



. 3.17.

$\eta_{sd}(U), \eta_d(U)$ vs U for $L = 5 \mu$ (black) and $L = 30 \mu$ (red).
 (a) η_{sd} vs U, V ; (b) η_d vs U, V ; (c) η_{sd} vs U, V ; (d) η_d vs U, V .
 « $T = 1, L_e = L$. »

$L = 30 \mu$

$U = 3$ -

U_{li} .

(. 3.17, , b)

$$U_0: U < U_0.$$

$$\eta; U; U > 6, \eta$$

(. 3.17, , d)

$$: U > U_0, \eta.$$

$$\eta$$

$$E_x$$

(3.28)

3.18 ()

$$L = 5 \mu .$$

$$E_z = U_0/L$$

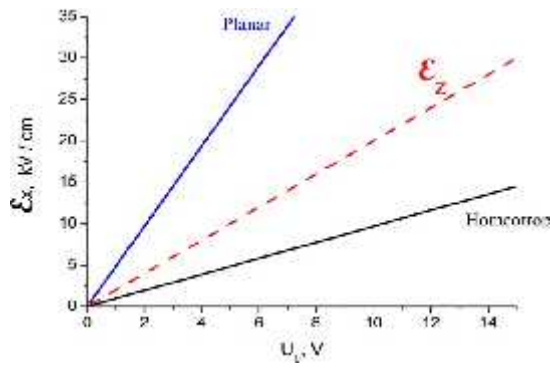
$$E_x$$

3.2 - . 3.18.

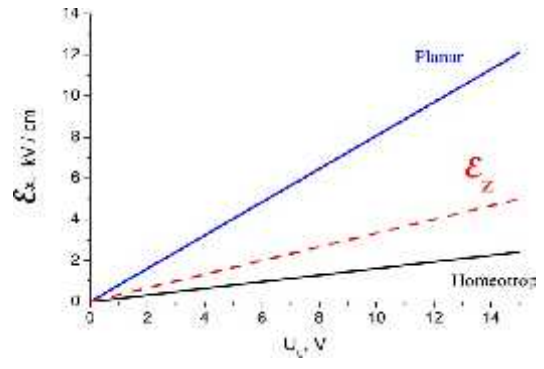
$$E_z.$$

$$E_x$$

$$E_z$$



()



()

. 3.18.
5 .

x

U_0 ,

E_x

U_0 . ()

$\alpha = 0.2 \mu^{-1}$.

$L = 5 \mu$. ()

$L = 30 \mu$

. 3.18 ()

:

$L = 30 \mu$

$\alpha = 0.2 \mu^{-1}$.

L_e

(3.18), $L_e = 4.9875 \approx 5 \mu$

θ^m $L = 5 \mu$

3.2.

6 .

E_x^m

U .

$\eta(U)$

U_0 ,

3.4

3.

1.

2.

3.

; ()

; ()

U_{I} ,

U

U ,

4.

U_{II}

5.

($\sim 5 \mu$),

($\sim 30 \mu$).

6.

4.

() , () ,
[96]. ,
/ -
 , , ,
 . ()
 .

[14, 31, 32, 97].

, - ,
 (- 3-10) , ,
 . ,
 - .
 -
 ,

[98-100].

, . -
 ,
 ,
 -

[61, 62, 72]. ,

- Au

[55, 101].

(Au),

<0,02 [102-104].

4.1

(Au)

()

[98-100].

S.

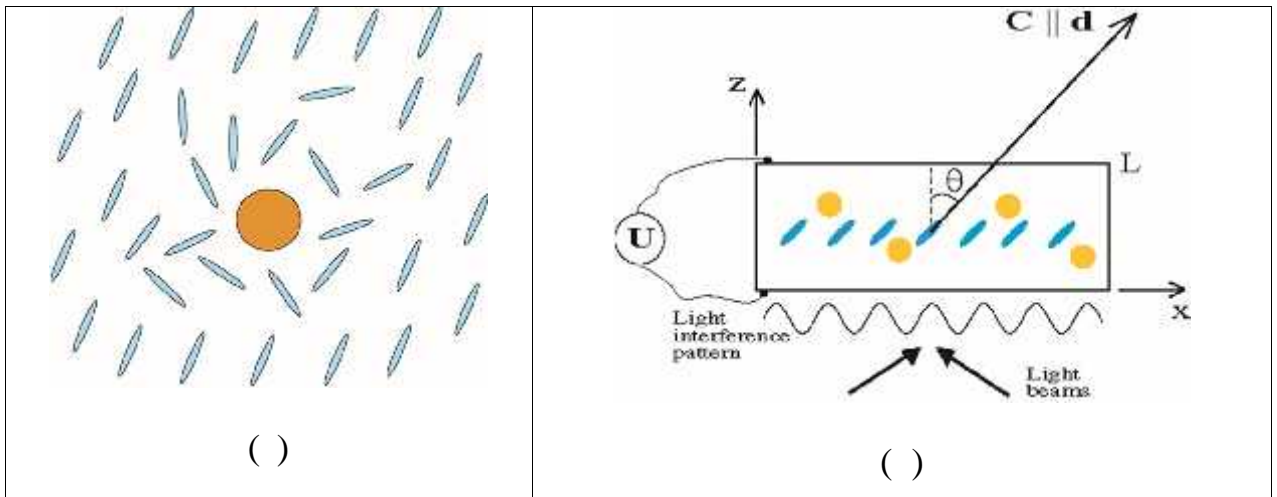
$\epsilon_{||}$.

ϵ_{\perp} .

$\epsilon_{||}$

ϵ_{\perp}

$$: n_{||}^2 = \epsilon_{||} \quad n_{\perp}^2 = \epsilon_{\perp} .$$



4.1. ()

(Au). ()

(Au)

(3-10).

(Au)

() ,

() .

$\epsilon_N = \epsilon_1 + i\epsilon_2$, $n_N = n_N + i\kappa_N$. [105, 109]:

$$\epsilon_N = n_N^2 ; \epsilon_1 = n_N^2 - \kappa_N^2 ; \epsilon_2 = 2n_N \kappa_N \quad (4.1)$$

[106]:

$$\epsilon_N = 1 - \frac{(w_p)^2}{w(w + i)} \approx 1 - \left(\frac{w_p}{w}\right)^2 + i \frac{w_p^2}{w^2 \tau} \quad (4.2)$$

$w -$

$w_p -$

$$w_p^2 = 4\pi n_e e^2 / m, n_e -$$

$m -$

$\tau -$

$w \gg 1$

(4.2)

[] . $\gamma -$ ' ,

$$\tau = m_{\epsilon} / \gamma$$

[98, 99]:

$$\epsilon_s = \frac{1}{3}(\epsilon_{\parallel} + 2\epsilon_{\perp}) \quad (4.3)$$

$\epsilon_{\parallel} \quad \epsilon_{\perp} -$

[105, 107, 109]:

$$\alpha_N = \alpha^2 \epsilon_s \frac{\epsilon_N - \epsilon_s}{2\epsilon_s + \epsilon_N} \quad (4.4)$$

[107]

$$R(\epsilon_N) = -2\epsilon_s,$$

$w =$

$$w_{rL} = w_p (1 + 2\epsilon_s)^{-1/2}.$$

4.1.2

109]: $i-$ [105,

$$E_e \quad \alpha_t = \alpha_N E_e \quad (4.5)$$

$P:$

$$E_e = E + 4\pi \hat{\Lambda} P \quad (4.6)$$

$$\hat{f} : E_e = \hat{f} E .$$

$$\hat{f} = \frac{1}{3}(\epsilon + 2) \quad (4.7)$$

[105]:

$$\hat{f} = \frac{1}{3}(\epsilon_a + 2) \quad (4.8)$$

$\epsilon_a -$ [100],

[98, 99]:

$$\frac{\epsilon - \hat{1}}{\epsilon + 2\hat{1}} = \frac{4\pi}{3} [\rho_L \langle \gamma_e \rangle + \rho_N \alpha_N] \quad (4.9)$$

(Au)

$$\rho_N = \varphi / a^3, \quad a - \varphi \quad (Au) \quad \langle \gamma_e \rangle$$

$$(4.4) \quad (4.9).$$

ϵ_L , [98, 99]:

$$\frac{\epsilon_L - \hat{1}}{\epsilon_L + 2\hat{1}} = \frac{4\pi}{3} \rho_L \langle \gamma_e \rangle \quad (4.10)$$

(4.10) (4.9) :

$$\frac{\epsilon - \hat{1}}{\epsilon + 2\hat{1}} = (1 - \varphi) \frac{\epsilon_L - \hat{1}}{\epsilon_L + 2\hat{1}} + \varphi \frac{\alpha_N}{a^3} \quad (4.11)$$

$$(4.11) \quad (4.4),$$

[98, 99]:

$$\epsilon = \frac{(\epsilon_L + 2\hat{1})(\epsilon_N + 2\epsilon_3) + 2[(1-\varphi)(\epsilon_L - \hat{1})(\epsilon_N + 2\epsilon_3) + \varphi\epsilon_3(\epsilon_N - \epsilon_3)(\epsilon_L + 2\hat{1})]}{(\epsilon_L + 2\hat{1})(\epsilon_N + 2\epsilon_3) - [(1-\varphi)(\epsilon_L - \hat{1})(\epsilon_N + 2\epsilon_3) + \varphi\epsilon_3(\epsilon_N - \epsilon_3)(\epsilon_L + 2\hat{1})]} \quad (4.12)$$

103, 109]:

$$\varepsilon_{\parallel} = \frac{(\varepsilon_{\parallel}^f + 2)(\varepsilon_N + 2\varepsilon_3) + 2[(1-\varphi)(\varepsilon_{\parallel}^f - 1)(\varepsilon_N + 2\varepsilon_3) + \varphi\varepsilon_3(\varepsilon_N - \varepsilon_3)(\varepsilon_{\parallel}^0 + 2\hat{1})]}{(\varepsilon_{\parallel}^f + 2\hat{1})(\varepsilon_N + 2\varepsilon_3) - [(1-\varphi)(\varepsilon_{\parallel}^f - 1)(\varepsilon_N + 2\varepsilon_3) + \varphi\varepsilon_3(\varepsilon_N - \varepsilon_3)(\varepsilon_{\parallel}^0 + 2\hat{1})]} \quad (4.13)$$

$$\varepsilon_{\perp} = \frac{(\varepsilon_{\perp}^f + 2)(\varepsilon_N + 2\varepsilon_3) + 2[(1-\varphi)(\varepsilon_{\perp}^f - 1)(\varepsilon_N + 2\varepsilon_3) + \varphi\varepsilon_3(\varepsilon_N - \varepsilon_3)(\varepsilon_{\perp}^0 + 2\hat{1})]}{(\varepsilon_{\perp}^f + 2\hat{1})(\varepsilon_N + 2\varepsilon_3) - [(1-\varphi)(\varepsilon_{\perp}^f - 1)(\varepsilon_N + 2\varepsilon_3) + \varphi\varepsilon_3(\varepsilon_N - \varepsilon_3)(\varepsilon_{\perp}^0 + 2\hat{1})]} \quad (4.14)$$

$$\varepsilon_{\parallel}^0 \quad \varepsilon_{\perp}^0 \quad , \quad , \quad (4.13) \quad (4.14),$$

, $\varphi \ll 1$.

$$\varepsilon_N = \varepsilon_1 + i\varepsilon_2 \quad (4.1).$$

[108-110].

$$\varepsilon_1 \quad \varepsilon_2$$

[109, 110]

$$n_{NP} \quad \kappa_N$$

(4.1)

$$\varepsilon_1 \quad \varepsilon_2$$

4.1

$$\lambda = 0.532 \mu \quad \lambda = 0.6328 \mu$$

(4.4), (4.13), (4.14).

4.1.

μ	n_N	κ_N	ε_1	ε_2
0.532	0.5439	2.2304	-4.6811	2.4266
0.6328	0.1838	3.4313	-11.7400	1.2611

. 4.2

(Au) (

1)

LC1264,

$$: n_{0\parallel} = 1.71 \quad n_{0\perp} = 1.53 \quad 25 \text{ } ^\circ\text{C}$$

[102-104].

$$: \epsilon_{\parallel}^0 = n_{0\parallel}^2 \quad \epsilon_{\perp}^0 = n_{0\perp}^2. \quad (4.3)$$

$$\epsilon_s = 2.5353.$$

(4.4).

$n_N \quad \kappa_N$,

$\epsilon_1 \quad \epsilon_2$

4.1.

(Au)

0.57μ ,

α_N ,

(Au),

(4.4),

(Au), α^{a} ,

(Au)

$$\lambda \in [0.52 \div 0.57] \mu \quad ($$

α_N).

(4.13)-(4.14): $\epsilon_{\parallel} \quad \epsilon_{\perp}$.

φ (Au) LC1264

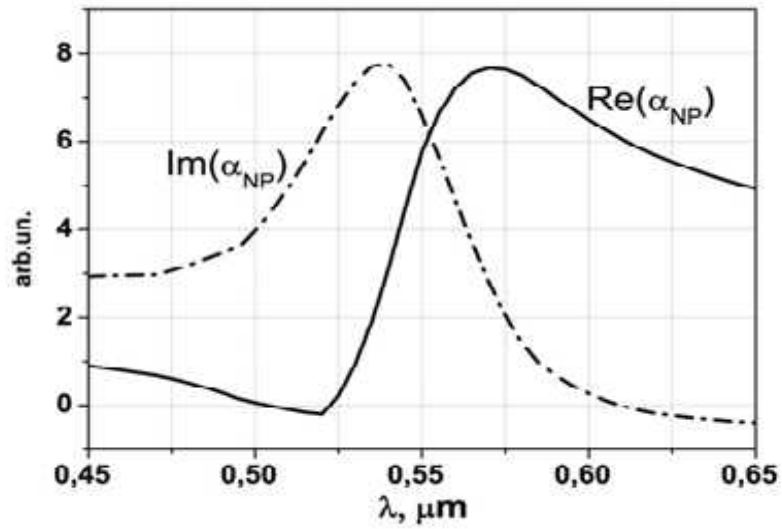
. 4.3

$$= 0.532 \mu$$

$$, \quad = 0.6328 \mu$$

, $I(\alpha_N)$

φ



. 4.2.

(Au),

LC1264,

$a = 1$.

. 4.3 (),

$I(\epsilon)$

,

$\varphi \approx 0.075$

$I(\epsilon_{\parallel})$, $\varphi \approx 0.086$ $I(\epsilon_{\perp})$.

(Au) $\varphi < 0.055$.

$R(\epsilon)$,

φ ,

φ :

$\varphi \approx 0.007$ $R(\epsilon_{\parallel})$ $R(\epsilon_{\perp})$.

$\varphi R(\epsilon)$

(Au) - .

, .4.3 (),

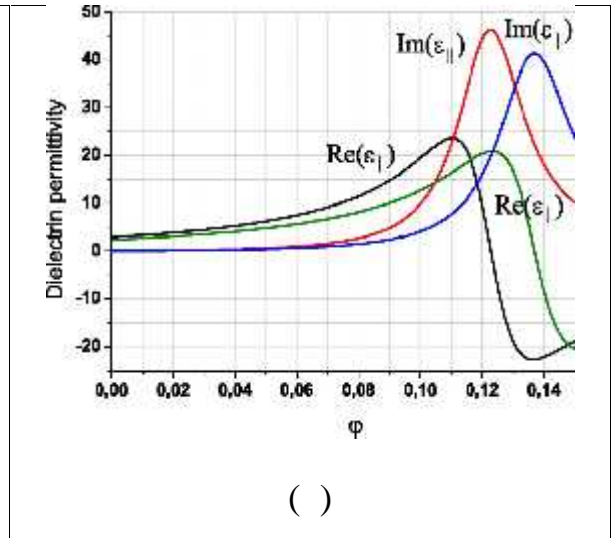
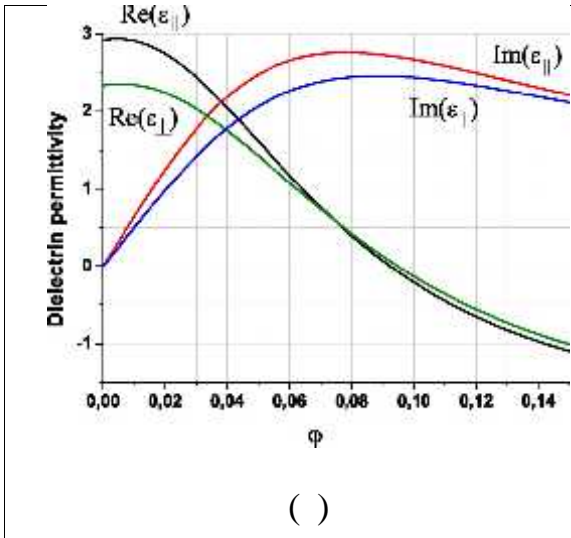
(Au) .

$I(\epsilon)$ $R(\epsilon)$

$\varphi > 0.1$,

$\varphi < 0.09$,

φ , $I(\varepsilon)$,
 $0 < \varphi < 0.08$.



4.3. (Au) $\mu = 0.532 \mu_0$; $\mu = 0.6328 \mu_0$

4.2.

Au

[55, 62, 72]

ε_{\parallel} , ε_{\perp} ,

n

α

(4.1), [109]:

$$n_b = \left[R(\varepsilon_b) + \sqrt{R^2(\varepsilon_b) + I^2(\varepsilon_b)} \right]^{1/2} / \sqrt{2} \quad (4.15)$$

$$\kappa_b = I(\varepsilon_b) / (2n_b), \quad \alpha_b = \frac{2\pi}{\lambda} \kappa_b \quad (4.16)$$

$b = \parallel$, $b = \perp$.

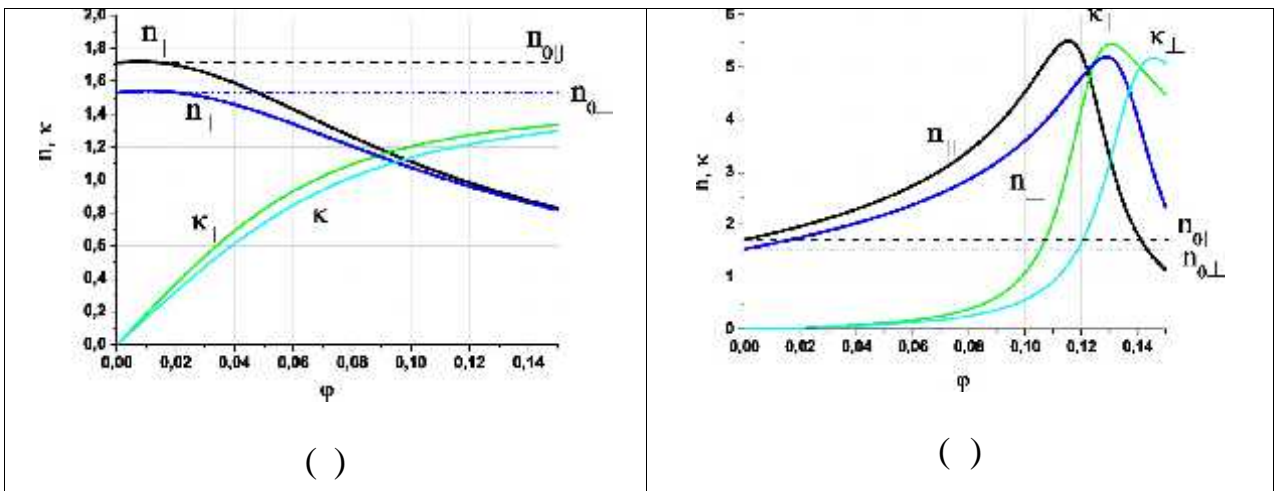
α_{\parallel} ,

$(n_{\perp}, \alpha_{\perp})$.

b

$n_{\parallel}, n_{\perp} \quad \kappa_{\parallel}, \kappa_{\perp} \quad \lambda = 0.532 \mu$
 $\lambda = 0.6328 \mu \quad . 4.4 [102, 109].$

$\alpha_{\parallel} \quad \alpha_{\perp} \quad . 4.5 \quad , \quad . 4.5$
 $() \quad \lambda = 0.6328 \mu \quad \varphi < 0.8,$



. 4.4.

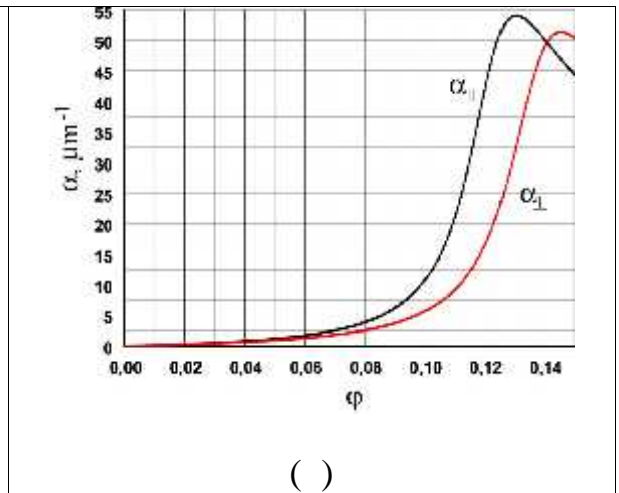
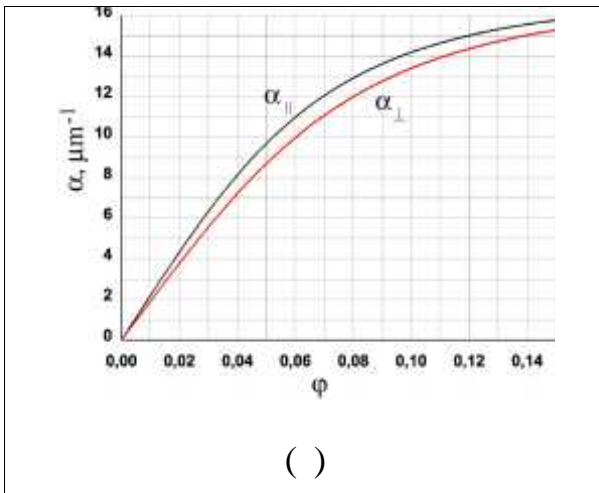
(Au). $n_{\parallel} = 1.71 \quad n_{\perp} = 1.53$
 $\lambda = 0.532 \mu \quad () \quad \lambda = 0.6328 \mu \quad ()$
 LC1264

(25 °C).

$\lambda = 0.532 \mu$

(Au).

$\lambda = 0.6328 \mu$,



4.5. $\lambda = 0.532 \mu$ () $\lambda = 0.6328 \mu$ (Au).

(4.4), через $I(\alpha_N)$ 4.2. (Au) с

4.4 4.5. $\lambda = 0.6328 \mu$ (He-Ne)

Nd:YAG $\lambda = 0.532 \mu$ ()

$\varphi < 0.01$. α , $\varphi > 0.08$. φ

() : (/) (/) .

η ,

[61, 91, 95]:

$$\eta_D = \frac{I_{\{+1\}}}{I_{\{0\}}} = \frac{I_{\{-1\}}}{I_{\{0\}}} = T_D \cdot J_1^2(\delta_D) \quad (4.17)$$

$$\delta_D = \frac{2\pi}{\lambda} (n_D - n_{0D}) \cdot L_D \quad (4.18)$$

$$L_D = (1 - T_D) / \alpha_D ; \quad T_D = \frac{I_{\{0\}}}{I_0} = e^{-\alpha_D L} \quad (4.19)$$

$I_{\{+1\}}$ $I_{\{-1\}}$ - $\{+1\}$ $\{-1\}$
 $I_{\{0\}}$ - L -
 L_D T_D -
 J_1 -
 I_{0-}
 (4.17)–(4.19) , -

[56, 77].

$$: n = n_{01} + n_2 L, \quad n_2 - ,$$

L -

$$(4.17) \quad (4.18) \quad \Delta n_D =$$

$n_D - n_{0D}$

. 4.6

- , (Au) φ [102-104, L=5 μ .

$$(\lambda = 0.532 \mu \text{)}$$

$\varphi < 0.005$.

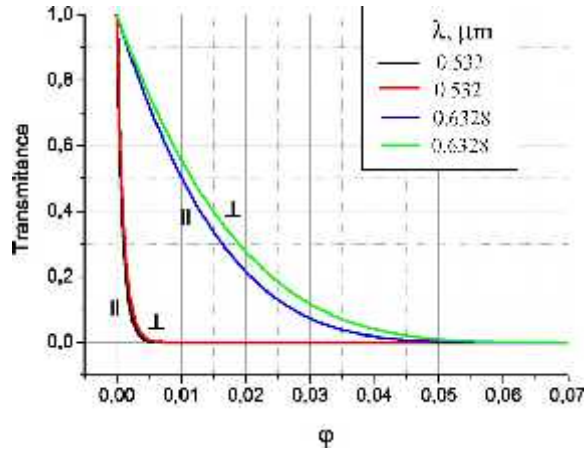
($\lambda = 0.6328 \mu$) , (Au)

$\varphi < 0.055$.

φ

(4.17)-(4.19).

4.7.



. 4.6.

(Au)

φ ,

$L = 5 \mu$,

(||)

(⊥) .

. 4.7

$\eta_1 = 0.06\%$,

$\varphi <$

0.005

(. 4.7 ()).

(Au).

[55, 101, 111, 112].

– 30 % (. 4.7 ()).

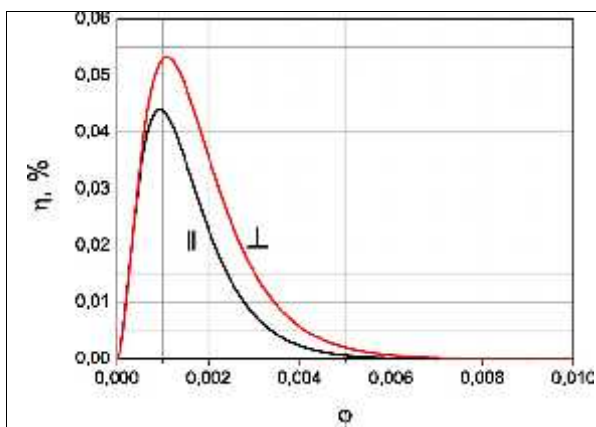
φ :

η_1

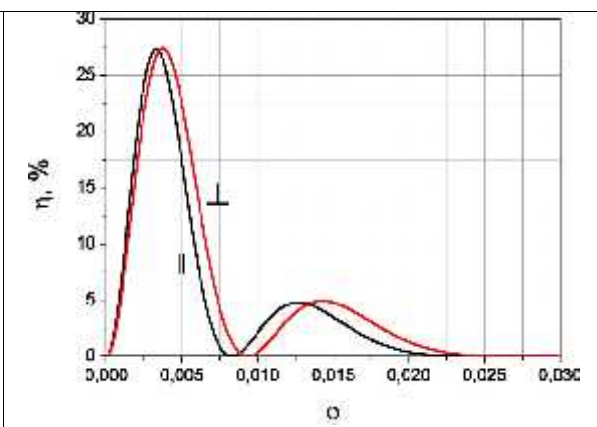
$\varphi \approx 0.005$,

η ,

η



()



()

. 4.7.

(Au): ()
 $= 0.532 \mu$; ()
 $= 0.6328 \mu$.

(Au) (10).

() .

(Au), $\varphi < 0.02$.

(Au)

30%

=0.6328 μ

p-

s-

θ

$x,$

θ [26].

n_{\parallel} α_{\parallel}

\perp

(),

\parallel

\perp

(p-), (s -).

4.3

4

1.

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, (Au).
(Au),
(Au) , ;
, ;
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2.

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, ,
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-

3.

, - (Au)
, (Au), 0.03.

, , .

(Au)

4.

(Au)

(=0.532 μ),

~0.005 %.

(=0.6328 μ),

- 30 % (L=5 μ).

5.

(Au)

(Au).

5.

,

()

-

, ,

(Au)

. ,

(-)

.

.

[113-115].

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[71, 116, 117].

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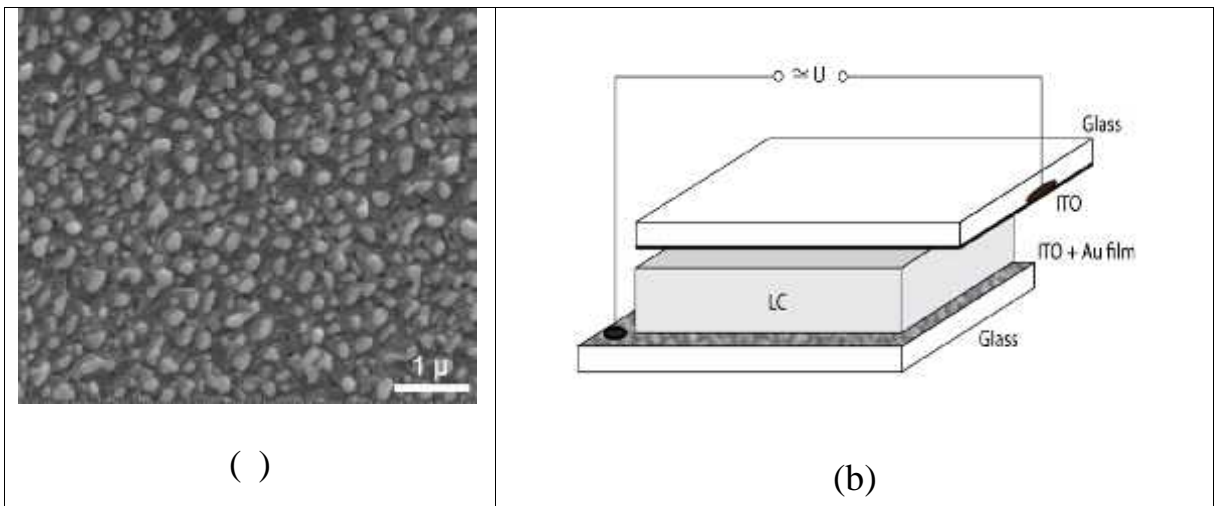
-

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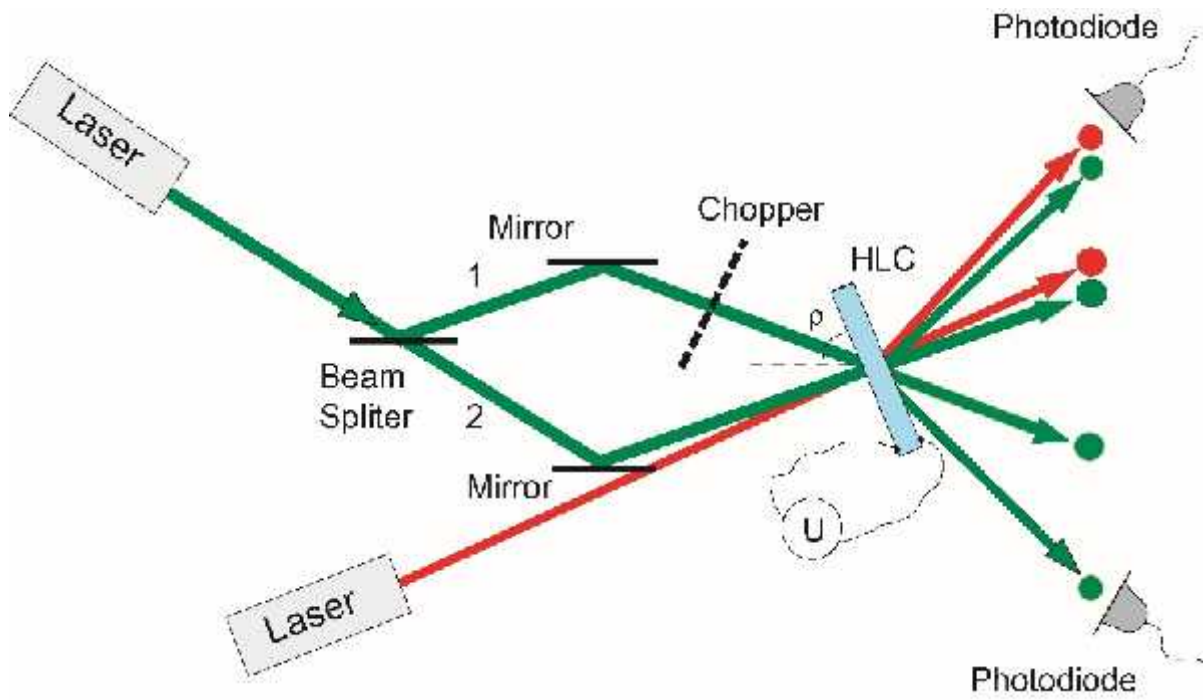
[12, 24, 48, 54].

ITO. (Au) [70]. (Au) ITO Au 460 °C Au Au 70-150 . 5.1. ().

E7. 9 . 5.2 (b).



5.1. () [113]. (b) [113].



. 5.2.
[113].

5.3.

[22, 121, 122]:

$$\partial E_1 / \partial z = -i \varepsilon_1 e^{i\psi} E_2; \quad \partial E_2 / \partial z = i \varepsilon_1 e^{i\psi} E_1 \quad (5.1)$$

$$E_{1,2}(t, z) = E_{1,2}(t, z) e^{i\psi_{1,2}(t, z)}$$

“*” –

$$z = z' k_0^2 / (4k_z) -$$

$$z', \quad k_0 = 2\pi/\lambda -$$

$$, k_z = k -$$

$$k \quad z, 2\theta - \quad (5.1)$$

z.

$$\varepsilon_1(t, z) = \varepsilon_1 e^{i\psi}$$

, ψ'

$$: (\varphi_1 - \varphi_2).$$

ε_1

[123].

ϵ_1 .

[22]:

$$\frac{\partial \epsilon_1}{\partial} e^{i\psi'} + \epsilon_1 e^{i\psi'} \cdot \frac{\partial \psi'}{\partial} = (\gamma_L + i\gamma_N) \cdot \frac{I_m}{I_0} \cdot \left(\frac{1}{r_1}\right) - \epsilon_1 e^{i\psi'} \cdot \left(\frac{1}{r_2}\right) \quad (5.2)$$

(5.2)

(

)

(

(5.2)).

I_m ,

, r_1 r_2 ,

$I_m = E_1 E_2 -$

; $I_0 = I_1 + I_2 -$

; $t -$

. (5.2)

([18, 54, 64]).

$\gamma = \gamma_L + i\gamma_N$,

γ_L

γ_N

(5.1)–(5.2).

5.1

$= kd \cdot n$,

5.1.

τ_1 τ_2

Δ	0.05	
λ	0.532	
d	20	
k	1	
$\Gamma = k \cdot \Delta$	11.8	
ρ	45°	
$\gamma_L = \Gamma$	8.34	
$\gamma_N = \Gamma$	8.34	
l_U	1.6 / ²	
$l_1 = l_2$	0.8 / ²	
τ_1	3200	
τ_2	600	

5.4.

5.4.1.

1,

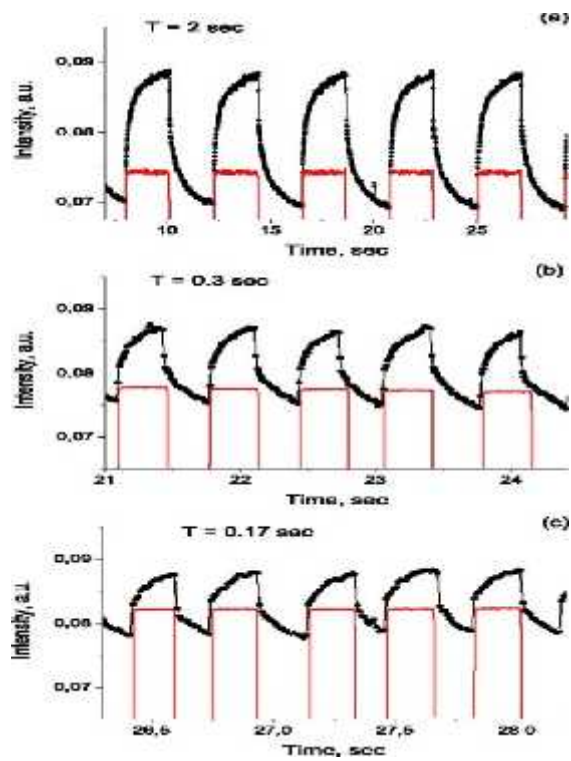
T

3 V

[94, 113-115]. . 5.3

=10

=0.17 .



. 5.3.

2

1

. 5.3 (a).

T

(. 5.3 (b), (c)).

5.4.2

. 5.4

(5.1) (5.2)

[113-

132

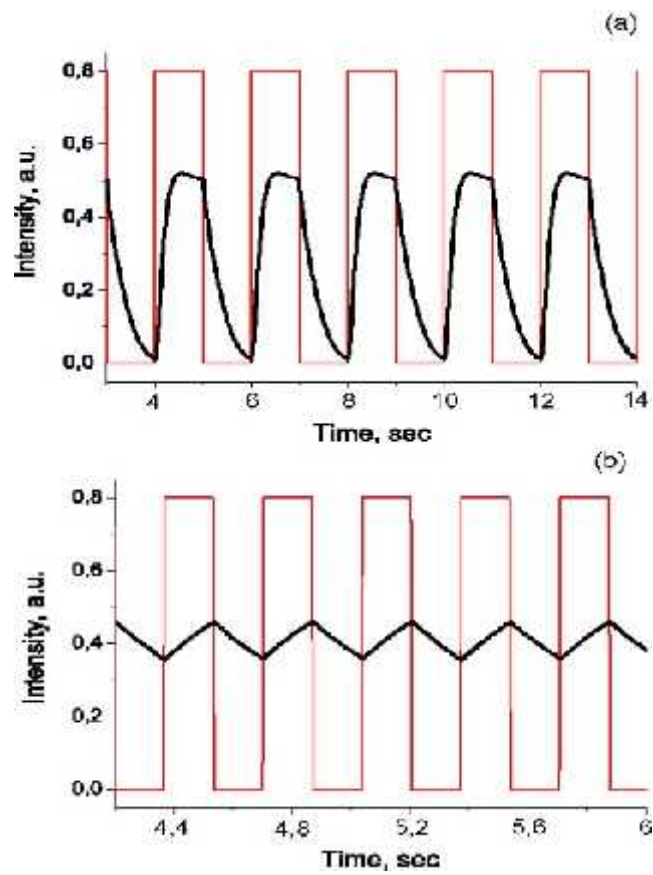
$\tau_1 \quad \tau_2$

5.1.

$\tau_1=3200 \quad \tau_2=600$

τ_2

τ_1



. 5.4.

5.1.

: () $T=2$; () $=0.17$.

(5.2),

τ_1 ,

: $\tau_1 \geq 3200$, $\tau_2 \leq 600$

$$\tau_1^m = 3200 \quad \tau_2^m = 600$$

$$\tau_1 : \tau_2$$

τ_2 ,

$$\frac{\tau_1}{\tau_2} = \frac{3200}{600} = \frac{16}{3} \quad (16:3)$$

τ_2

5.5,

$\tau_1 \tau_2$,

$$5.1 \quad 400 \quad 5.5 (a) \quad \tau_2$$

τ_1 ,

I_1 .

5.5 (b)

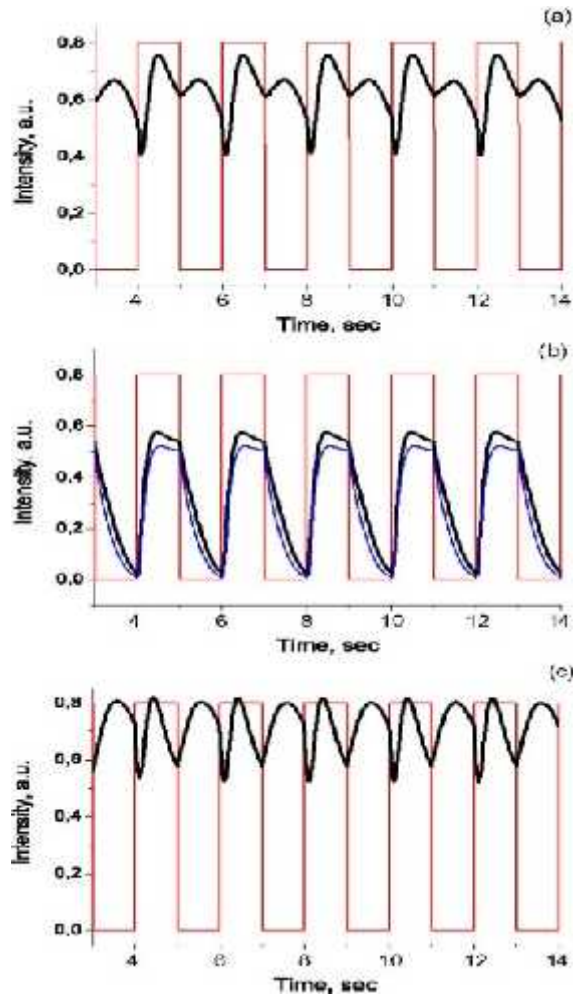
$$5.4 (a) \quad \tau_1 \left(\tau_1^m : \tau_2^m \right)$$

;

$$5.1. \quad \tau_2$$

$$5.5 (c) \quad \tau_1 < \tau_1^m$$

$$\tau_2 > \tau_2^m$$



5.5.

5.4. (a) $\tau_2 > \tau_2^m$, $\tau_2 = 1000$, $\tau_1 = \tau_1^m = 3200$; (b) $\tau_2 = \tau_2^m = 600$, $\tau_1 < \tau_1^m$, $\tau_1 = 2800$ ($\tau_1 = \tau_1^m = 3200$); (c) $\tau_2 > \tau_2^m$, $\tau_2 = 1000$, $\tau_1 < \tau_1^m$, $\tau_1 = 2800$. $=2$.

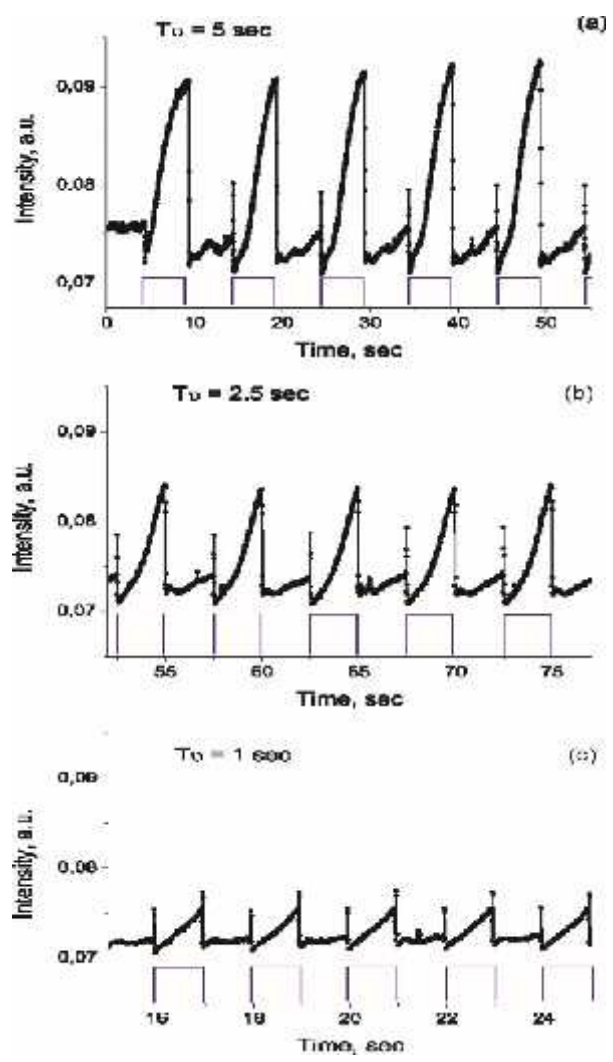
5.5.

[113].

0.05 0.8 ,
 T_v 10 0.625 .

T_v
 $T,$

. 5.6.



. 5.6.

1 2

T_v , . 5.3,

, [54, 90]).

5.6.

5

1.

: (1)

; (2)

2.

()

$$\tau_1 \tau_2, \quad (1)$$

$$: \tau_1 \geq 3200, \tau_2 \leq 600 \quad ($$

3.

$\tau_1 \tau_2$

4.

Au

),

1.

, -
 , ,
 , ,

2.

-
 .
 ,
 (0.5 (~28⁰)
)

3.

, :
 ,
 ,
 ()
 ()
).

4.

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(Au).

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