Optical Transmittance of Dichroic Crystals with “Isotropic Point”

[1]Kushnir O., [1]Dzendzelyuk O., [1]Hrabovskyy V. and [2]Vlokh O.

[1]Electronics Department, Lviv National University, 107 Tarnavskii Str., 79017 Lviv, Ukraine, e-mail: o_s_kushnir@rd.wups.lviv.ua

[2]Institute of Physical Optics, 23 Dragomanov Str., 79005 Lviv, Ukraine

Received: 02.02.2004

Abstract

The coupled wave theory is modified for the case of electromagnetic wave propagation in semiconductor crystals possessing a so-called isotropic point (IP) and a linear dichroism (LD). Modifications, due to the LD, imposed on the optical transmission spectra of band-pass and band-reject narrow-band optical filters built upon the chalcopyrite, wurtzite and zinc blend crystals are quantitatively explained and compared with the available experimental data. The main performance characteristics of the filters are re-calculated.

Key words: coupled mode theory, optical transmittance, dichroism, isotropic point, optical interference filters.

PACS: 78.20.Ci

Introduction

Crystal optical properties occurring in a wide number of semiconductor materials (chalcopyrite, wurtzite and zinc-blend compounds) in the vicinity of a wavelength λ_i, where the ordinary (n_o) and extraordinary (n_e) refractive indices coincide (the point which is, quite conveniently, referred hereafter to as the “isotropic point” or IP), represent an interesting topic within the solid state optics and offer a promising opportunity for constructing a unique type of ultra narrow-band optical interference filters [1,2]. Because of a great impact on characteristics of various optoelectronic devices, the coupled-wave filters have still remained a subject of extensive experimental and theoretical studies (see, e.g., [3,4]).

Nevertheless, many results concerned with the filters, based on conspicuously absorbing crystals, have not yet been satisfactorily explained and contradict the predictions of the commonly adopted version of coupled wave theory [5-7]. So, the side-band minima of the transmittance spectra $J_c(\lambda)$ of band-pass filters (the construction of filters and the experimental geometry see, e.g., in [5]) do not reach zero, while the side-band maxima of the transmittance $J_p(\lambda)$ of band-reject filters appear to be lower than the maximum (or “unit”) allowable transmittance level. The effects have been clearly detected at least in the studies [5,8-12]. Even under the optimum condition $|\beta| d = \pi/2$ for the energy transfer between the coupled light waves (with β being the coupling constant and d the crystal thickness), the value $J_p(\lambda_i)$ at the IP $\lambda = \lambda_i$ floats notably up above a zero level (see again the results [5,8-12]). All of these facts seem to be quite strange since, according to [5-7], the transmittance extrema are governed by the standard quadric sine or cosine functions. The attempts for explanations in terms of experimental inaccuracies alone [5,11,12] clearly fail in view of a general character of those phenomena [13]. The problems become still more urgent, if one remembers that, in case of analogue interference Solc filters, even such refined and feeble effects as the influence of multiple light reflections on the transmittance are well understood.

On the other hand, the coupled-wave approach so far applied to the effects related to the IP in semiconductor crystals [5-7] has completely disregarded the influence of linear dichroism (LD), which should lead to appearance of non-zero imaginary part $\Delta k''$ of the phase mismatch $\Delta k = \Delta k' + i\Delta k''$ (see the analysis [5]). This is the more so surprising, since the LD in the objects under test could be sometimes larger than 10 – 100 cm^{-1}. The aim of this work is to study the effect of LD in frame of the coupled wave theory, find out its implications in the spectral transmittance functions of the filters and so reconsider their main performance characteristics.

The coupled wave transmittance solutions

Let us re-derive the solutions for the functions $J_c(\lambda)$ and $J_p(\lambda)$. Below we shall represent in brief only the main points of standard procedure for obtaining and solving the coupled wave equations. We start with the material relation $\mathbf{P} = \kappa\mathbf{E}$ (see, e.g., [7]) that links the electric polarization **P** and the wave field **E** and takes a first-order spatial dispersion (i.e., gyration) into account. Unlike [7], we put the symmetric contribution to the dielectric susceptibility tensor ($\kappa_{ij} = \kappa_{ji}$) to be complex, with its real and imaginary parts describing respectively the ordinary (linear) birefringence and the LD. Another crystal optical effects might be, in principle, regarded in this respect. So, one can try to account for weaker real spatial dispersion terms [14], as well as a piezo-dichroism relevant for the wurtzites and zinc-blend materials. However, in this work we dare not upon the analysis of all those effects, keeping in mind the corresponding analytical difficulties. Instead, we shall concentrate on the case of superposition of the largest parameters (i.e., the linear birefringence, optical activity and the LD).

Simplifying, in frame of the slowly varying amplitude approximation (i.e., for the case of a weak optical anisotropy – see [15]), the wave equation for the wave field components E_y and E_z propagating along the *x* direction, one gets the equations for the amplitudes A_y and A_z ($E_{y,z}(x) = A_{y,z}(x)\exp(ik_{y,z}x)$, with $k_y = k_o$ and $k_z = k_e$ being the wave vector components), which formally coincide with those obtained in [6,7]:

$$dA_y / dx = \beta A_z e^{-i\Delta kx}, \; dA_z / dx = -\beta A_y e^{i\Delta kx}, \quad (1)$$

where

$$\Delta k = (2\pi / \lambda)(\Delta n_l + i\Delta\eta_l), \beta = \pi\Delta n_c / \lambda. \quad (2)$$

Here $\Delta n_l = n_e - n_o$ means the ordinary (linear) birefringence, $\Delta\eta_l = \eta_e - \eta_o$ the LD, Δn_c the circular birefringence (i.e., optical activity). There is no need to retain the ratios k_x / k_y, k_x / k_z and $k_x^2 /(k_y k_z)$ in formulae (1), (2) and what follows (see [7,10]), because $k_x / k_z \approx 1 + \Delta n_l / \bar{n} \approx 1$ (with $\bar{n}$ being the mean refractive index), whenever the optical anisotropy is weak and the wave polarizations remain nearly orthogonal (see [16], Chapter 2).

Dropping the formulae for the wave amplitudes, we write out the final expressions for the transmittances in cases of the initial polarizations "1" ($E \parallel c$ or $\varphi = 0$ – see [7,10]) and "2" ($E \perp c$ or $\varphi = 90^\circ$):

$$J_c = J_{c1} = J_{c2} = e^{-\alpha d} \frac{\Delta_c^2}{4A_\Delta^2}(\sin^2 a + \sinh^2 b)$$

$$J_{p1,2} = e^{-\alpha d}[\cos^2 a + \sinh^2 b + + \frac{\Delta_l^2 + \delta_l^2}{4A_\Delta^2}(\sin^2 a + \sinh^2 b) \mp \Delta J], \quad (3)$$

$$\Delta J = \frac{\sqrt{\Delta_l^2 + \delta_l^2}}{2A_\Delta} \times$$
$$\times[\sin(\arctan\frac{\delta_l}{\Delta_l} - \varphi_\Delta)\sin 2a +$$
$$+\cos(\arctan\frac{\delta_l}{\Delta_l} - \varphi_\Delta)\sinh 2b], \qquad (4)$$
$$a + ib = A_\Delta e^{i\varphi_\Delta} = \frac{\sqrt{(\Delta_l + i\delta_l)^2 + \Delta_c^2}}{2}$$
$$A_\Delta = \frac{1}{2}\sqrt[4]{(\Delta_l^2 + \Delta_c^2 - \delta_l^2)^2 + 4\Delta_l^2\delta_l^2},$$
$$\varphi_\Delta = \frac{1}{2}\arctan\frac{2\Delta_l\delta_l}{\Delta_l^2 + \Delta_c^2 - \delta_l^2}$$

In (3) and (4) the mean absorption coefficient $\alpha = k_y'' + k_z''$ is introduced and the set of parameters Δk, β and Γ [10] (see Eq. (2)) is reduced to that of the phase retardations due to the linear ($\Delta_l = (2\pi d/\lambda)\Delta n_l$) and circular ($\Delta_c = (2\pi d/\lambda)\Delta n_c$) birefringences and the corresponding LD parameter $\delta_l = (2\pi d/\lambda)\Delta\eta_l$ associated with the imaginary part of the dielectric susceptibility (the relevant dichroic absorption difference $\Delta\alpha$ being equal to $\Delta\alpha = \alpha_\parallel - \alpha_\perp \equiv \alpha_e - \alpha_o = 2\delta_l/d$). The parameters a and b in (3) and (4) mean respectively the real and imaginary parts of half the complex total “retardation” $\sqrt{(\Delta_l + i\delta_l)^2 + \Delta_c^2}$ defined with the well-known superposition principle.

Formulae (3) and (4) refer equally to chalcopyrite and wurtzite crystals, though in the latter case Δ_c parameter describes only the induced electrogyration or the Faraday optical activity (see [16]), while the stress-induced piezooptic retardation Δ_d may be described with formal replacement $\Delta_c \leftrightarrow \Delta_d$ (see [13]). If the dielectric perturbation is absent ($\Delta_c = 0$), Eqs. (3) and (4) yield $J_c = 0$ and $J_{p1,2} = J_{\parallel,\perp} = \exp(-\alpha_{\parallel,\perp}d)$, where $J_{\parallel,\perp}$ denote the polarized transmittances for the input linear polarizations $E \parallel c$ and $E \perp c$. For the non-dichroic crystals ($\Delta_c \neq 0$, $\delta_l = 0$) we have the known results [5-12]

$$J_c = e^{-\alpha d}\frac{\Delta n_c^2}{\Delta n_l^2 + \Delta n_c^2}\sin^2\sqrt{\Delta n_l^2 + \Delta n_c^2}$$
$$J_{p1} = J_{p2} = J_p \qquad (5)$$
$$J_c + J_p = J_{\parallel,\perp} = e^{-\alpha d}$$

Notice also that the relations (3) and (4) enable one to describe quantitatively spectral anomalies of the LD $\Delta\alpha_{ob}$ “observed” just at the IP in $J_\parallel(\lambda)$ and $J_\perp(\lambda)$ dependences (see, e.g., [5,7,9,10]), as well as the non-polarized transmittance anomalies $\Delta\alpha_{np}$ at the IP detected for the first time by Vlokh et. al. [7,10]. The relevant relations are $\Delta\alpha_{ob} \approx \Delta\alpha_i \,\mathrm{sinc}\,\Delta$ and $\Delta\alpha_{np} \approx (\Delta\alpha_i^2 d/8)[1 - \mathrm{sinc}^2(\Delta/2)]$, where $\Delta\alpha_i = \Delta\alpha(\lambda_i)$ is the “true” LD, $\Delta = \sqrt{\Delta_c^2 - \delta_l^2}$ the total phase retardation at the IP and $\mathrm{sinc}\,x = \sin x / x$. From the viewpoint of conciseness we drop more or less comprehensive analysis of the presented results, paying a closest attention to the narrow-band filters.

Characteristics of band-pass and band-reject filters

Let us consider ideal filters, for which Δ_c (or Δ_d), δ_l and α parameters manifest no dispersion and the birefringence near the IP behaves as $\Delta n_l = \gamma(\lambda - \lambda_i)$. Let the retardation Δ at the IP be equal to π, thus ensuring the optimum wave coupling peculiar for the filters ($|\beta| d = \pi/2$). It is now convenient to introduce the retardation $\Delta_{l\pi}$ and the LD parameter $\delta_{l\pi}$ normalized at π ($\Delta_{l\pi}$, $\delta_{l\pi} = \delta_l/\pi$), together with the re-normalized transmittance functions $J_{Nc} = J_c / J_c(\lambda_i)$ for the band-pass and $J_{Np2} = J_{p2}/J_{p2\max}$ for the band-reject filters (we use the J_{p2} function since $\alpha_\perp < \alpha_\parallel$ and $J_{p2\max}$ implies the maximum allowed transmittance level at the IP determined with interpolation of $J_{p2}(\lambda)$ function from far away the IP region).

The example of the calculated dependences $J_{Nc}(\Delta_{l\pi})$ and $J_{Np2}(\Delta_{l\pi})$ displayed in Figure 1 reveals all the principled features mentioned in the Introduction, which have earlier lacked any explanation. They have been observed earlier in the spectral dependences $J_c(\lambda)$ and $J_{p1,2}(\lambda)$ for CdS [5,8], ZnTe [8], $CdGa_2S_4$ [9], $AgGa_{0.98}In_{0.02}S_2$ [10], $AgGaSe_2$ [11,12] and some other crystals. It is to be stressed that the positions of the side-band extrema $J_{Nc}(\Delta_{l\pi})$ and $J_{Np2}(\Delta_{l\pi})$ do not coincide when the LD is available, and the same holds true of $J_{Nc}(\lambda)$ and $J_{Np2}(\lambda)$ dependences. The calculated characteristics of the first side-band J_{Nc} extrema, which are the most important in practice, are represented in Figure 2. It is clearly seen that the first minimum height grows progressively with increasing LD. The first J_{Nc} maximum height, which is equal to the contrast ratio Y ($Y = J_{Nc}^{\pm 1\max} / J_{Nc}(\lambda_i) = J_{Nc}^{\pm 1\max}$), behaves in the same manner. Moreover, we have recently shown [13] that the LD broadens the half-width at half maximum $\Delta_{l\pi,1/2}$ of the filters, too.

Since the transmittance J_{Nc} is no longer described with the standard function $J_{Nc}(\Delta_{l\pi}) = (\pi/2)^2 \operatorname{sinc}^2 \sqrt{\Delta_{l\pi}^2 + 1}$, as for transparent crystals, the bandwidth can no longer be regarded as sufficient for defining the filter selectivity. We have chosen to introduce a more practical parameter

$$W = \frac{\int_0^{\Delta_{l\pi,1/2}(\delta_{l\pi})} J_{Nc}(\Delta_{l\pi}, \delta_{l\pi}) d\Delta_{l\pi}}{\int_0^{\infty} J_{Nc}(\Delta_{l\pi}, \delta_{l\pi}) d\Delta_{l\pi}} \qquad (6)$$

whose dependence on the LD value is shown in Figure 2, insert.

As seen from Figure 1 (curve 3), LD causes the characteristics of the band-pass and band-reject filters to become "non-reciprocal" (i.e., $J_{N\Sigma} = J_{Nc} + J_{Np2} \neq 1$ or $J_{N\Sigma} \neq \exp(-\alpha d)$), thus explaining the experimental findings by Yamamoto et. al. [12]. Experimental illustration of this effect of LD is presented in Figure 3 for the filters based upon CdS. In order to make comparison with the ideal filter theory, we have used the relevant results of Figure 8 from [5] and then eliminated the "background" related to spectral dependence $J_{p2}(h\nu)$ due to the term $\exp(-\alpha d)$. The so obtained resulting $J_{N\Sigma}(h\nu)$ curve manifests pronounced extrema in the IP

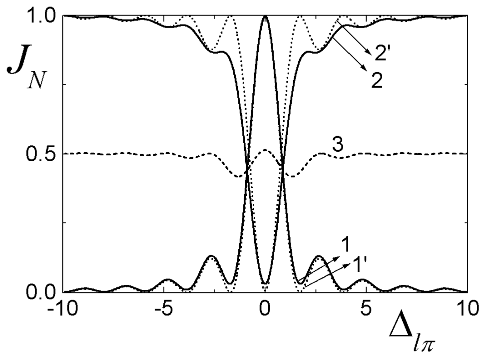

Fig. 1. Theoretical dependences of re-normalized transmittances for the ideal band-pass (J_{Nc} – curves 1, 1') and band-reject (J_{Np2} – 2, 2') filters and the half-sum $J_{N\Sigma} = (J_{Nc} + J_{Np2})/2$ –(3) on the normalized phase retardation $\Delta_{l\pi}$: 1', 2' – for the LD $\delta_{l\pi} = 0$ and 1, 2, 3 – $\delta_{l\pi} = 0.25$.

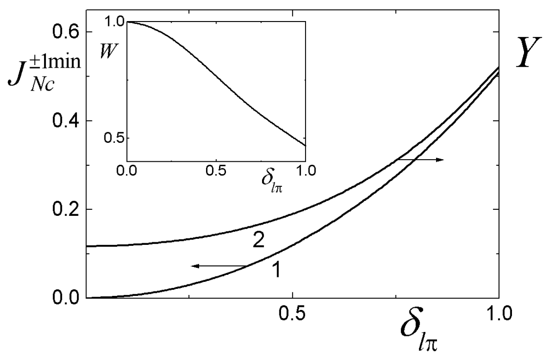

Fig. 2. Calculated dependences of re-normalized transmittance $J_{Nc}^{\pm 1\max}$ at the first side-band minimum (curve 1) and the rejection rate *Y* (2) on the LD parameter $\delta_{l\pi}$ for ideal band-pass filters. The insert shows the same dependence for the normalized value of selectivity parameter *W* (see text).

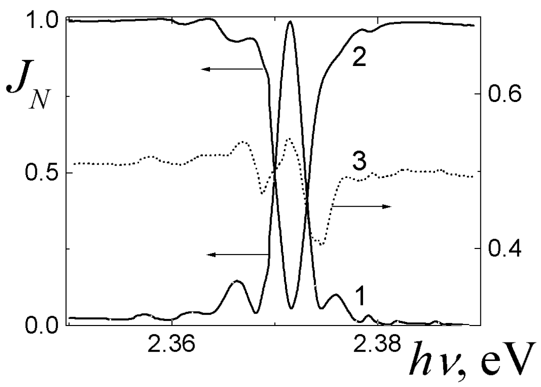

Fig. 3. Spectral dependence of re-normalized transmittances J_{Nc} (curve 1), J_{Np2} (2) and the half-sum $J_{N\Sigma}/2$ (3) for the filters based on CdS crystals, obtained with processing the data [5].

region, testifying the influence of LD for CdS crystals.

Conclusions

In the present work we have improved the coupled wave theory for electromagnetic wave propagation in the crystals possessing IP so as to take the LD into account. We have found a strong influence of LD on the parameters of optical filters built upon semiconductors. In particular, we have obtained the corrections for the spectral transmittance functions imposed by LD, analyzed the transmittance half-width and the rejection rate and revealed a "non-reciprocal" character of transmittances for the band-pass and band-reject filters. For improving their performance, we should recommend a modified technique by Horinaka et. al. [11] for designing composite filters, of which crystal plates' characteristics are adjusted such that to suppress the first side-bands. Further consideration of these points and the other effects of LD will be a subject of forthcoming paper.

References

1. Etxebarria J., Folcia C. L., Ortega J. J. Appl. Cryst. **33** (2000) 126.
2. Horinaka H., Yamamoto N. Ternary and Multinary Compounds in the 21th Century **1** (2001) 348.
3. Qiu M., Mulot M., Swillo M., Anand S., Jaskorzynska B., Karlsson A., Kamp M., Forchel A. Appl. Phys. Lett. **83** (2003) 5121.
4. Kato S., Ito H., Kachi T. USA Patent No US20030099445A1 (2003).
5. Henry C.H. Phys. Rev. **143** (1966) 627–633.
6. Yeh P. Appl. Opt. **21** (1982) 4054.
7. Vlokh O.G., Hrabovskyy V.A., Nekrasova I.M. Fiz. Tverd. Tela **27** (1985) 1300. (In Russian).
8. Laurenti J.P., Vaigot P., Rouzeyre M. Rev. Physique Appl. **12** (1977) 1755.
9. Suslikov L.M., Gadmashi Z.P., Kopinets I.F., Slivka V.Yu. Opt. Spektr. **51** (1979) 307. (In Russian).
10. Vlokh O.G., Hrabovskyy V.A. Opt. Spektr. **61** (1986) 1248. (In Russian).
11. Horinaka H., Sonomura H., Miyauchi T. Japan. J. Appl. Phys. **24** (1985) 463.
12. Yamamoto T., Takehara H., Horinaka H., Miyauchi T. Japan. J. Appl. Phys. **25** (1986) 1397.
13. Kushnir O.S., Hrabovskyy V.A., Dzendzelyuk O.S. Visnyk Lviv Univ., Ser. Fiz. **32** (1999) 64. (In Ukrainian).
14. Vlokh R.O. Private communication.
15. Kushnir O.S. J. Phys.: Condens. Matter. **16** (2004) 1245.
16. Vlokh O.G. Spatial dispersion phenomena in parametric crystal optics (Lviv, Vyshcha Skola) 1984 (in Russian).