

REFLECTION OF ELECTROMAGNETIC WAVES AT THE BOUNDARY OF OPTICALLY ACTIVE MEDIA

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ABSTRACT

This paper contains a review of the results concerning the reflection of the electromagnetic waves (e.m.w.) at the boundary between nonactive isotropic medium and optically active medium. Condon constitutive relations and Maxwell boundary conditions are used. Both isotropic and anisotropic optically active media are subjects of consideration. Strong birefringence masks optical activity but it is not an obstacle for demonstration of optical activity in single and multiple reflection. Reflection spectroscopy is the unique possibility for experimental manifestation of the weak optical activity in crystal classes C_{3v} , C_{4v} , C_{6v} .

1. Introduction

Optical activity (OA) is a circle of phenomena, which manifest the interaction of electromagnetic waves (e.m.w.) with chiral media. They could be crystals, solutions, liquid crystals, helical polymers, biological structures and others. The chiral media consist of the molecules of helical structure or helical arranged atoms and molecules. Optical activity is a property of noncentrosymmetrical and mirror asymmetrical media.

The manifestation of OA in linear optics are result of nonequal response of the medium in the processes of interaction with left- and right- circularly polarized e.m.w. The most well known OA phenomena are the following: a) optical rotation of the plane of polarization caused by nonequal refractive indices of both types circularly polarized e.m.w.; b) circular dichroism- nonequal absorption coefficients of the same e.m.w.; c) Raman optical activity; d) reflection optical activity- slightly different reflection from OA medium of left- and right- circularly polarized e.m.w.

Reflection at the boundary of OA medium is connected with a "new" polarizations of incident e.m.w. The electric field of this "new" wave is proportional to the parameters of optical activity (so called gyration tensor). The order of magnitude of the gyration tensor is $10^{-3} \div 10^{-5}$ times smaller than birefringence in anisotropic media. Despite of the small magnitude of OA parameters they could be measured through reflection spectra. The appearance of the new polarization in reflected light is the only method for studying weak optical activity in classes C_{3v} , C_{4v} , C_{6v} , $C_{\infty v}$ in which gyration tensor is antisymmetrical and as a result these media do not manifest optical rotation.

The structure of the paper is the following: in Section 2 we expose two sets of constitutive relation of OA media: Born set and Condon set [1,2]. The processes of single reflection of e.m.w. from OA-medium (both isotropic and anisotropic medium) are considered in Section 3. In Section 4 the multiple reflection from optically active Fabry -Perrot etalon was studied [3,4,5]. Section 5 contains results of the studies of weak OA through multiple reflection.

2. Constitutive relations of OA-medium.

Constitutive relations of OA-media are nonlocal, i.e. the electric displacement vector \mathbf{D} and the magnetic induction \mathbf{B} depend on the electric field intensity \mathbf{E} and magnetic field \mathbf{H} in the same point but they depend also on space derivatives of the intensities. The most convenient set of constitutive relations are the following:

1. Born set

$$(1) \quad \mathbf{D} = \epsilon \cdot \mathbf{E} + (\rho \cdot \nabla) \times \mathbf{E}; \quad \mathbf{B} = \mu \mathbf{H},$$

where ϵ and μ are tensors of dielectric and of magnetic permeabilities, ρ - gyration tensor, ∇ - space derivatives operator.

2. Condon set

$$\mathbf{D} = \epsilon [\mathbf{E} + \Gamma \cdot (\nabla \times \mathbf{E})]$$

$$\mathbf{B} = \mu [\mathbf{H} + \Gamma^T \cdot (\nabla \times \mathbf{H})],$$

where Γ is the tensor of optical activity, connected with ρ by the relation:

$$(2) \quad \rho = \text{Sp}(\epsilon \cdot) - (\epsilon \cdot \Gamma)^T \quad (\text{T denotes transposed tensor}).$$

Two tensors are equivalent if we neglect terms of ρ^2 , ρ^3 , ... But Condon set preserves the usual form of the following expressions:

a) Poynting vector $\mathbf{S} = \mathbf{E} \times \mathbf{H}$:

b) density of energy:

$$(3) \quad u = \frac{1}{2} (\mathbf{D} \cdot \epsilon^{-1} \cdot \mathbf{D} + \mathbf{B} \cdot \mu^{-1} \cdot \mathbf{B})$$

c) Maxwell boundary conditions at the boundary between two dielectrics 1 and 2:

$$(4) \quad E_{t1} = E_{t2}; \quad H_{n1} = H_{n2}; \quad D_{n1} = D_{n2}; \quad B_{n1} = B_{n2}$$

t- tangential component; n- normal to the boundary.

Normal e.m.w. are solutions of Maxwell equations and constitutive relations (1) or (2).

The properties of normal e.m.w. in isotropic media are known since Fresnel times. Two circularly polarized e.m.w. of opposite orientation exist and their refractive indices are:

$$(6) \quad n_{r,l} = n \pm \rho/2 \quad n = \sqrt{\epsilon}$$

We consider also the normal e.m.w. in uniaxial OA- medium (z is its optical axis). In nonmagnetic media $\mu = \mu_0 = 4\pi \cdot 10^{-7} \text{H/m}$. The shape of tensors ϵ , $\gamma = \Gamma(\omega/c)$ is: (ω - eigen frequency, c - velocity of light in vacuum)

$$\epsilon = \begin{vmatrix} \epsilon_{or} & 0 & 0 \\ 0 & \epsilon_{or} & 0 \\ 0 & 0 & \epsilon_c \end{vmatrix}; \quad \gamma = \begin{vmatrix} \gamma_1 & \gamma_{12} & 0 \\ -\gamma_{12} & \gamma_1 & 0 \\ 0 & 0 & \gamma_3 \end{vmatrix}$$

(In classes D_3, D_4, D_6 : $\gamma_{12}=0$; in classes C_{3v}, C_{4v}, C_{6v} $\gamma_1 = \gamma_3 = 0$).

It is easy to establish the following properties of normal e.m.w.:

1. in the case of propagation along optical axis z ; $\mathbf{k} = (0,0,k)$, two circularly polarized e.m.w. have refractive indices:

$$(8) \quad n_{r,l} = \sqrt{\epsilon_{or} \pm \epsilon_{or} \cdot \gamma_1}$$

2. in the case of propagation of e.m.w. normally to z ; $\mathbf{k} = (k,0,0)$, two elliptically polarized e.m.w. exist:

a) ordinary e.m.w. with refractive index $n_{or} = \sqrt{\epsilon_{or}}$ and field intensity:

$$(9) \quad E_{1or} = 0; \quad E_{2or}; \quad E_{3or} = \frac{i n_{or} \rho_1}{\epsilon_{or} - \epsilon_c} E_{2or}$$

$\rho_1 = \epsilon_{or}\gamma_1 + \epsilon_c\gamma_1$
 b) extraordinary e.m.w. of refractive index $n_e = \sqrt{\epsilon_c}$ and field intensity:

$$(10) \quad E_{1e} = i\epsilon_c\gamma_{12} E_{3e} ; E_{2e} = \frac{i n_e \rho_1}{\epsilon_0 - \epsilon_c} E_{3e} ; E_{3e}$$

3. Single reflection

We consider the processes of reflection and refraction at the boundary between isotropic nonactive medium of refractive index n_1 and optical active medium (isotropic or anisotropic) (Fig 1).

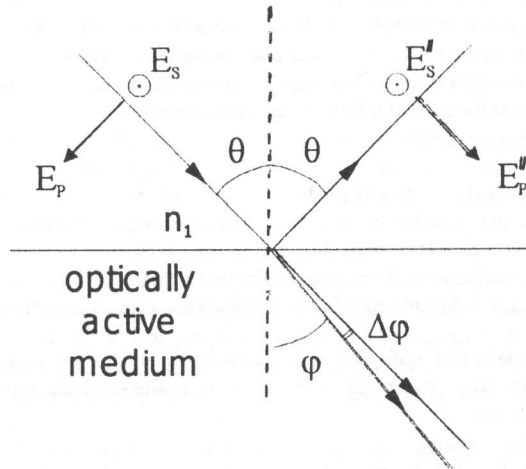


Fig.1: Single reflection at the boundary of a nonactive medium and optically- active medium. $\Delta\varphi$ denotes the difference between refractive angles of two normal e.m.w. in optical active medium

This is Fresnel type boundary problem (see eq. (5)). The incident and reflected e.m.w. in nonactive medium are the usual s- and p- type e.m.w. Two normal e.m.w. are propagating in OA medium. In the case of isotropic OA medium the circular birefringence exists only and $\Delta\varphi \approx 10^{-4} \div 10^{-6}$. In anisotropic OA- medium the usual birefringence $n_e - n_o = \sqrt{\epsilon_c} - \sqrt{\epsilon_{or}} \approx 0.1$ is $10^3 \div 10^5$ times bigger and correspondingly $\Delta\varphi \approx 0.1$.

We illustrate here this reflection considering the OA medium, which possesses weak OA ($\gamma_1 = \gamma_3 = 0$) and the case in which optical axis is perpendicular to the place of incidence. Then OA influences the extraordinary e.m.w. only which possesses longitudinal component E_{1e} (see (10)). We obtain the following expressions for reflected e.m.w. [2]:

$$(11) \quad E''_s = R_e E_s + iC E_p ; E''_p = R_o E_p + iC E_s,$$

where R_e and R_o are Fresnel coefficients

$$(12) \quad R_e = \frac{n_1 \cos\theta - n_e \cos\varphi_e}{n_1 \cos\theta + n_e \cos\varphi_e}; \quad R_o = \frac{n_{or} \cos\theta - n_1 \cos\varphi_{or}}{n_{or} \cos\theta + n_1 \cos\varphi_{or}}$$

and C describes the gyrotropic "new polarization":

$$(13) \quad C = \gamma_{12} \frac{n_{or} n_1^2 \sin 2\theta}{(n_1 \cos\theta + n_e \cos\varphi_e)(n_{or} \cos\theta + n_1 \cos\varphi_{or})}$$

The "new polarization" can be studied using differential methods, especially the reflection of left and right circularly polarized e.m.w. of equal intensity I_0 . The differential circular reflection can be expressed by the quantity [2]:

$$(14) \quad \delta = \frac{I_l'' - I_r''}{I_l'' + I_r''} = 2 \frac{R_o + R_e}{R_o^2 + R_e^2} \cdot C,$$

I_l'' – intensities of reflected beams in the case of left and right circular polarization of incident beam.

This quantity is proportional to the weak gyrotropy parameter γ_{12} . The most convenient value of θ is $\theta \approx \pi/4$.

Namely this case was realized in [6] for studying weak OA in CdS near excitonic resonances. Another differential method includes total reflection from OA – medium ($n_1 > n_{or}$; n_e). It was applied in [7].

4. Multiple reflection

We study multiple reflection from OA Fabry – Perrot etalon which is plane parallel plate of thickness d (fig 2).

The normal e.m.w. are propagating through the plate and their number is twice multiplied in each act of reflection at each of both boundaries of the plate.

According the results of previous section each refraction in outer medium generates "new polarization" of gyrotropic origin. The influence of the parallel refracted or transmitted beams must be calculated taking into account the following expressions for additional optical path of the e.m.w. of type a in the plate:

$$(15) \quad \Delta_a = d \cdot n_a \cdot \cos\varphi_a$$

In the case of isotropic OA- etalon "a" denotes left and right circular e.m.w. We use (6) to express the qualities Δ_a as a sum:

$$(16) \quad \Delta_{r,l} = d \cdot n \cdot \cos\varphi \pm d \cdot \rho / \cos\varphi$$

Two effects are manifested in the case of reflection from OA isotropic plate:

a) The accumulation of phase of the e.m.w. propagating in the plate. This effect is depending on the second addend in (16), proportional to $d \cdot \rho$ and it is analogous to the optical rotation of the plane of polarization. This effect is strongly exposed at the grazing incidence. It could change the polarization of reflected wave compared with incident wave by several ten percent;

b) Interference of weak "new polarized" beams at each refraction including direct reflected beam 1. The detail calculations in [3] prove the possibility to neglect this contribution in isotropic case.

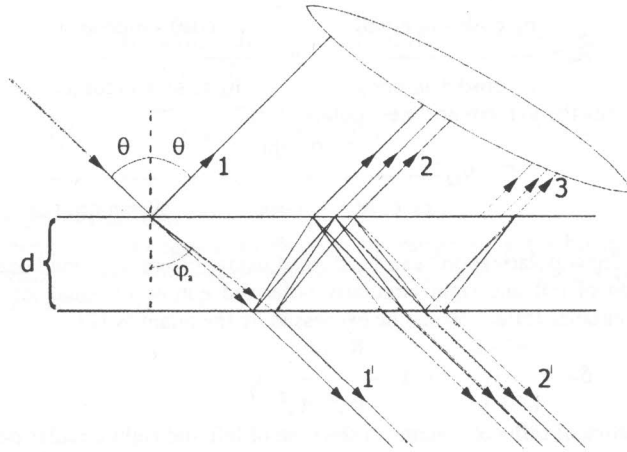


Fig. 2 : Multiple reflection from optically- active Fabry- Perrot etalon of thickness d . Reflected and transmitted parallel beam interfere in focal planes of lenses.

In anisotropic optically active Fabry- Perrot etalon OA influences the processes of reflection and refraction at each boundary, not propagation of e.m.w. We treat the same geometry as it is in single reflection (optical axis perpendicular to the plane of incidence). Then n_a denote the refractive indices n_{or} , n_e for ordinary and extraordinary e.m.w. Two interference sets $\{E_s''\}$ and $\{E_p''\}$ are connected through a relatively small impact of optical activity. However the interference of many reflected(or transmitted) beams can amplify the single reflection gyrotropic effects treated in the previous section [4,5].

5. Weak optically active Fabry – Perrot etalon

This case was considered in [8] supposing the same geometry (optical axis perpendicular to the plane of incidence). Following the procedure of calculation of resulting field in the case of multiple reflection [9,3], we find the following expressions for reflected e.m.w. (and similar expressions for transmitted waves):

$$(17) E_p'' = \frac{2i \sin(\delta_0) R_o \exp(i\delta_0)}{1 - R_o^2 \exp(2i\delta_0)} E_p - i E_s R_{ps} ; E_s = - \frac{2i \sin(\delta_0) R_e \exp(i\delta_0)}{1 - R_e^2 \exp(2i\delta_e)} E_s + i E_p R_{ps}$$

$$(18) R_{ps} = \frac{C}{(1 - R_o^2 \exp(2i\delta_0))(1 - R_e^2 \exp(2i\delta_e))} \{ (1 - R_o^2 \exp(2i\delta_0)) (1 - R_e^2 \exp(2i\delta_e)) - (1 - R_o)(1 - R_e) \times \exp(i(\delta_e + \delta_0)) \}$$

$$(19) \delta_{o,e} = (2\pi/\lambda_0) d n_{o,e} \cos \varphi_{o,e}$$

The first addend in formulas (17) describe usual multi- beam interference, strongly depending on reflectivity R_o^2 and R_e^2 of ordinary and extraordinary e.m.w. The terms proportional to R_{ps} connect two interference sets with maxima correspondingly at

$\delta_{o,e}=(2k+1)\pi/2, k=0,1,2,\dots$ and minima at $\delta_{o,e}=k\pi$. The general picture in s- polarized reflected wave will contain strong maxima at $\delta_e=(2k+1)\pi/2$ and additional weak maxima at $\delta_o=(2k+1)\pi/2$ (the picture of interference of reflected p- polarized e.m.w. will be similar). The quantity R_{ps} will assure maximal connection between two sets at the same values $\delta_{o,e}=(2k+1)\pi/2$ (formula (18)). There exists another interesting possibility: Both conditions could be fulfilled simultaneously[5] at fixed values of θ if:

$$(20) \quad \delta_o=(2k+1)\pi/2 ; \delta_e=(2k+1)\pi/2$$

Then the quantity R_{ps} will obtain maximal values if the integer k_1 or k_2 is even and the other is odd. Two odd or two even maxima (k_1, k_2) at the same angle of incidence θ_1 cause zero connection $R_{ps}(\theta_1)=0$. The strongest impact of weak optical activity on multiple reflection will be manifested namely near the coinciding maxima when the integers (k_1, k_2) governing the maxima have different parity.

The similar picture will appear in transmitted multi-beam light. The weak influence of OA on the reflection could be measured making comparison (difference) between experimental data for multi-beam interference from OA- Fabry- Perrot plate and calculated interference picture governed by the first addends in (17) for nonactive plate(the values of refractive indices n_1, n_o, n_e must be measured for the same wavelength λ_0 using another methods).

6. Conclusion

We emphasize here the basic results of the studies of reflection optical activity:

1. Reflection spectra are influenced by the optical activity of the "mirror"
2. Reflection optical activity is a good method to study the optical activity and structure of anisotropic media in the presence of strong birefringence.
3. Reflection spectroscopy is the only method for measuring weak optical activity.
4. Multibeam interference can amplify the optical activity effect in reflection spectra.

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REFERENCES:

- [1] Fedorov F.I., Theory of gyrotropy, Nauka I Technica(Minsk), 1976
- [2] Miteva A.I. and Lalov I.J., J. Phys. Condens. Matt.5, 6099(1993)
- [3] Lalov I.J. and Miteva A.I., J. Mod. Opt.38, 395(1991)
- [4] Silverman M.P. and Badoz J, J.Opt. Soc Am. A,11, 1894(1994)
- [5] Miteva A.I., Lalov I.J., Wen T., Raptis Y.S., Anastassakis E., J. Phys.. D. Appl. Phys. 29,2705(1996);28,2128(1995)
- [6] Ivchenko E.I., Permogorov S.A. and Selkin A.V., Sol St. Commun. 28,345(1978)
- [7] Jordanov B. and Schrader B., J. Mol. Struct. 141,247(1986)
- [8] Kojouharova N.A., Thesis, Faculty of Physics, Sofia University(1995)
- [9] Born M. and Wolf E., Principles of optics, Pergamon Press(Oxford), 1944