Faraday effect in $TlInS_2$ crystals

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Abstract. We have studied experimentally the Faraday effect in $TlInS_2$ crystals. The Verdet constant V_F and the effective Faraday coefficient F'_{33} are determined at the light wavelength $\lambda = 632.8$ nm under normal conditions. These parameters are equal to $V_F = (112.4 \pm 1.5)$ rad/(T × m) and $F'_{33} = 0.9995F_{33} + 0.0005F_{11} = (12.96 \pm 0.18) \times 10^{-13}$ m/A, respectively. We have shown that, among magnetically non-ordered substances, $TlInS_2$ represents an efficient magnetooptic material.

Keywords: Faraday effect, $TlInS_2$ crystals, Verdet constant

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1. Introduction

Semiconductor-ferroelectric chalcogenide crystals $TlInS_2$ belong to a centrosymmetric point symmetry group 2/m (space symmetry C_2/c). They have a layered structure with a 1:1 ratio of InS and TlS [1, 2]. The crystalline lattice of $TlInS_2$ consists of alternating two-dimensional layers parallel to (001) plane, with each successive layer rotated by 90° with respect to preceding layer [1, 2]. The unit-cell parameters of $TlInS_2$ crystals are equal to a = 10.90 Å, b = 10.94 Å, c = 15.18 Å and β = 90.17 deg in a standard setting or, alternatively, β = 100.21 deg in a rhombic setting. The cleavage plane in $TlInS_2$ is parallel to the mirror symmetry plane and perpendicular to the crystallographic axis c. A very small difference between a and b parameters gives rise to a weak deviation from tetragonal unit cell [1, 2]. $TlInS_2$ is transparent in the spectral range from 500 to 12500 nm [2]. From the ellipsometric measurements limited to layer-plane surfaces, it is known that the refractive indices at the wavelength $\lambda = 632.8$ nm are equal to 2.594 and 2.744 respectively for the parallel-to-layer and perpendicular-to-layer directions of light propagation [3].

It has been suggested in a number of studies that $TlInS_2$ can be applied in various optical industries. For example, the studies of the electrical properties have indicated that the crystals are very promising for creating solid-state electronic devices [4]. Moreover, one can mention possible applications of the $TlInS_2$ crystals in optoelectronics associated with their high photosensitivity in the visible spectral range (the two-photon absorption coefficient being $\beta = (9.4 \pm 1.5) \times 10^{-9}$ cm/W [5]), high optical birefringence [3] and peculiar photoinduced phenomena that enable memory effects [6]. A specific feature of thermal expansion, the existence of elliptical conical surface of zero thermal expansion, whose orientation does not depend on the temperature in the wide interval (160–280 K) [7], can also stimulate some practical applications of $TlInS_2$. Finally, the acousto-optic studies of $TlInS_2$ have demonstrated that the velocities of some of the quasi-transverse waves are very low ~725 m/s), thus leading to extremely high acousto-optic figures of merit

(~(2200÷9000)×10^{-15} s^3/kg [8]). The latter implies that the $TlInS_2$ crystals represent a very efficient acousto-optic material.

It should be noted that, recently, there is an increasing interest to magneto-optical properties of various layered structures (see, e.g., Ref. [9]). In the present work we study the Faraday rotation in the layered $TlInS_2$ crystals.

2. Experimental procedures and results

At the normal conditions and the light wavelength $\lambda = 632.8$ nm, the plane containing the optic axes of $TlInS_2$ coincides with the crystallographic plane *ca*, where the *c* axis represents the acute bisector of the angle 2Θ between the optic axes. We have measured the angle Θ between the optic axes and the *c* axis at $\lambda = 632.8$ nm and found it to be equal to 1.3 deg. Suppose that the light wave propagates along one of the optic axes and the magnetic field is applied in the same direction. Then the Faraday effect manifests itself as a rotation of polarization plane of linearly polarized light. Under these conditions, the magnetically perturbed optical-frequency dielectric impermeability tensor B_{jk} and the specific optical rotation angle $\Delta\rho_l$ are defined by the relations

$$B_{jk} = B^0_{jk} + ie_{jkl}F_{lm}H_m, \tag{1}$$

$$\Delta\rho_l = \frac{\pi n^3}{\lambda}F_{lm}H_m, \tag{2}$$

where B^0_{jk} implies the impermeability tensor in the absence of external magnetic field H_m, e_{jkl} is the unit Levi-Civita antisymmetric axial tensor, n the refractive index for the light propagation direction, and F_{lm} the Faraday tensor. For the case of point group 2/m, the latter tensor acquires the following form:

$$\begin{array}{c|ccc} & H_1 & H_2 & H_3 \\ \hline \Delta\rho_1 & \frac{\pi n_b^3}{\lambda}F_{11} & \frac{\pi n_b^3}{\lambda}F_{12} & 0 \\ \Delta\rho_2 & \frac{\pi n_b^3}{\lambda}F_{12} & \frac{\pi n_b^3}{\lambda}F_{22} & 0 \\ \Delta\rho_3 & 0 & 0 & \frac{\pi n_b^3}{\lambda}F_{33} \end{array} . \tag{3}$$

Here the crystallographic axes *a*, *b* and *c* correspond respectively to the principal axes *X*, *Y* and *Z* of the Fresnel ellipsoid abbreviated as the axes 1, 2 and 3, and n_b is the refractive index for the light propagation direction along one of the optic axes.

Let the light wave vector and the magnetic field direction be indeed parallel to the optic axis. Note that the angle between the optic axis and the *c* axis is very small so that it can be neglected. However, to be precise with description, we are to rewrite the tensor given by Eq. (3) in the coordinate system of which the Z' axis is parallel to the optic axis:

$$\begin{array}{c|ccc} & H_{X'} & H_{Y'} & H_{Z'} \\ \hline \Delta\rho_{X'} & \frac{\pi n_b^3}{\lambda}\left(F_{11}\cos^2\Theta+F_{33}\sin^2\Theta\right) & \frac{\pi n_b^3}{\lambda}F_{12}\cos\Theta & \frac{\pi n_b^3}{\lambda}(F_{33}-F_{11})\sin\Theta\cos\Theta \\ \Delta\rho_{Y'} & \frac{\pi n_b^3}{\lambda}F_{12}\cos\Theta & \frac{\pi n_b^3}{\lambda}F_{22} & -\frac{\pi n_b^3}{\lambda}F_{12}\sin\Theta \\ \Delta\rho_{Z'} & \frac{\pi n_b^3}{\lambda}(F_{33}-F_{11})\sin\Theta\cos\Theta & -\frac{\pi n_b^3}{\lambda}F_{12}\sin\Theta & \frac{\pi n_b^3}{\lambda}\left(F_{33}\cos^2\Theta+F_{11}\sin^2\Theta\right) \end{array} \tag{4}$$

Then the magnetically induced rotation of the polarization plane reduces to

$$\Delta\rho_{Z'} = \frac{\pi n_b^3}{\lambda} F'_{33} H_{Z'} \,, \tag{5}$$

where F'_{33} denotes the effective Faraday coefficient corresponding to the rotated coordinate system. Then we have

$$F'_{33} = F_{33}\cos^2\Theta + F_{11}\sin^2\Theta = 0.9995F_{33} + 0.0005F_{11} = \frac{\lambda}{\pi n_b^3}\left(\frac{\Delta\rho_{Z'}}{H_{Z'}}\right). \tag{6}$$

Finally, the Verdet constant V_F is determined by the expression

$$V_F = \frac{1}{\mu_0}\left(\frac{\Delta\rho_{Z'}}{H_{Z'}}\right), \tag{7}$$

where $\mu_0 = 4\pi \times 10^{-7}\ \mathrm{N/A}^2$ is the magnetic constant. Hence, one can determine the effective Faraday coefficient $0.9995F_{33} + 0.0005F_{11}$ for the $TlInS_2$ crystals, using a simple and direct experimental technique for measuring optical rotatory power for the light propagating along one of the optic axes.

To measure the Faraday rotation, we employed a single-ray polarimetric technique. In our experiment, a He-Ne laser with the wavelength of $\lambda = 632.8\ \mathrm{nm}$ was used as a light source. The longitudinal magnetic field was produced using an electromagnet. A plane-parallel crystalline plate was placed in between the poles of electromagnet. The sample was aligned with the aid of conoscopic fringes. Finally, the crystal sample thickness was equal to $d = 1.92\ \mathrm{mm}$.

The dependence of specific optical rotation upon the external magnetic field is presented in Fig. 1. This dependence is exactly linear, as it should be for the case of pure Faraday rotation. The effective Faraday coefficient F'_{33} calculated using a standard linear fitting of the experimental data is equal to $(12.96 \pm 0.18) \times 10^{-13}\ \mathrm{m/A}$, while the appropriate Verdet constant V_F amounts to $(112.4 \pm 1.5)\ \mathrm{rad/(T \times m)}$.

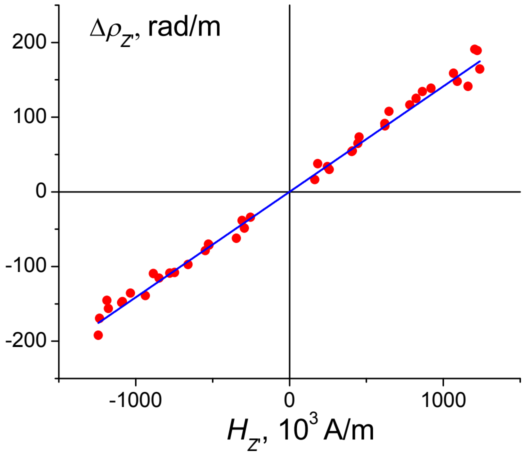

Fig. 1. Dependence of specific rotatory power on the magnetic field applied to $TlInS_2$ ($\lambda = 632.8\ \mathrm{nm}$): circles correspond to experimental data and solid line to linear fitting.

Our experimental data obtained for the $TlInS_2$ crystals should be compared with the appropriate results known for the other magnetooptic crystalline materials. For instance, the Verdet constant amounts to $115\ \mathrm{rad/(T \times m)}$ for $Sn_2P_2S_6$ [10], $82\ \mathrm{rad/(T \times m)}$ for Tl_3AsS_4, $70\ \mathrm{rad/(T \times m)}$ for $AgGaGe_3Se_8$ and $8\ \mathrm{rad/(T \times m)}$ for $AgGaGeS_4$ [see Adamenko D., et al 2017. Ukr. J. Phys. Opt. 16: 134; 2016. Ukr. J. Phys. Opt. 17: 27; 2016. Ukr. J. Phys. Opt. 17: 105]. Hence, $TlInS_2$ can be reliably classified as a sufficiently good crystalline material, at least among magnetooptically non-ordered substances.

3. Conclusion

We have determined experimentally the effective Faraday coefficient $F_{33}^{'} = 0.9995F_{33} + 0.0005F_{11}$ and the Verdet constant V_F for the $TlInS_2$ crystals at the laser wavelength $\lambda = 632.8$ nm under normal conditions. Our experimental geometry corresponds to the light propagation and magnetic field directions parallel to one of the optic axes. The parameters mentioned above have been measured as $F_{33}^{'}$=$(12.96 \pm 0.18)\times 10^{-13}$ m/A and $V_F = (112.4 \pm 1.5)$ rad/(T × m). Notice that these values exceed the corresponding parameters of Tl_3AsS_4, $AgGaGe_3Se_8$ and $AgGaGeS_4$ crystals. Issuing from this data, $TlInS_2$ can be regarded as an efficient magnetooptically non-ordered crystalline material.

References

1. Kashida S and Kobayashi Y, 1999. X-ray study of the incommensurate phase of $TlInS_2$. J. Phys.: Condens. Matter. **11**: 1027–1035.
2. Isaaks T G and Feichtner J D, 1975. Growth and optical properties of $TlGaSe_2$ and β-$TlInS_2$. J. Solid State Chem. **14**: 260–263.
3. Shim Y, Okada W, Wakita K and Mamedov N, 2007. Refractive indices of layered semiconductor ferroelectrics $TlInS_2$, $TlGaS_2$ and $TlGaSe_2$ from ellipsometric measurements limited to only layer-plane surfaces. J. Appl. Phys. **102**: 083537.
4. Mustafaeva S N, Ismailov A A and Akhmedzade N D, 2006. Electric properties of $TlInS_2$ single crystals. Semiconduct. Phys., Quant. Electron. & Optoelectron. **9**: 82–84.
5. Allakhverdiev K R, 1999. Two-photon absorption in layered $TlGaSe_2$, $TlInS_2$, $TlGaS_2$ and GaSe crystals. Sol. State Commun. **111**: 253–257.
6. Ozdemir S, Suleymanov R A, Allakhverdiev K R, Mikailov F A and Civan E, 1999. Memory effect in layered semiconductor $TlInS_2$ with incommensurate phase. Sol. State Commun. **96**: 821–826.
7. Say A, Martynyuk-Lototska I, Adamenko D, Pogodin A, Kokhan O and Vlokh R, 2017. Thermal expansion anisotropy of β-$TlInS_2$ crystals in the course of phase transitions. Phase Trans. **90**: 1–8.
8. Martynyuk-Lototska I, Trach I, Kokhan O and Vlokh R, 2017. Efficient acousto-optic crystal, $TlInS_2$: acoustic and elastic anisotropy. Appl. Opt. **56**: 3179–3184.
9. Lei C, Chen L, Tang Z, Li D, Cheng Z, Tang S and Du Y, 2016. Enhancement of magneto-optical Faraday effects and extraordinary optical transmission in a tri-layer structure with rectangular annular arrays. Opt Lett. **41**:729–732.
10. Krupych O, Adamenko D, Mys O, Grabar A and Vlokh R, 2008. Faraday effect in $Sn_2P_2S_6$ crystals. Appl. Opt. **47**: 6040–6045.

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Анотація. *Експериментально досліджено ефект Фарадея в кристалах* $TlInS_2$. *Для довжини хвилі оптичного випромінювання* $\lambda = 632{,}8$ нм *і за нормальних умов визначено сталу Верде і ефективну компоненту тензора ефекту Фарадея. Вони дорівнюють відповідно* $V_F = (112{,}4 \pm 1{,}5)$ рад/(Тл × м) *і* $F_{33}^{'} = 0{,}9995F_{33} + 0{,}0005F_{11} = (12{,}96 \pm 0{,}18)\times 10^{-13}$ м/А . *Показано, що кристали* $TlInS_2$ *є достатньо ефективними магнітооптичними матеріалами серед магнітно-невпорядкованих середовищ.*