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 $(112.4 \pm 1.5)$ rad/(T m) and $F_{33}' = 0.9995 F_{33} + 0.0005 F_{11} = (12.96 \pm 0.18) \times 10^{-13}$ 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 $90^\circ$ 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 $\beta = 90.17$ deg in a standard setting or, alternatively, $\beta = 100.21$ 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 $\sim$725 m/s, thus leading to extremely high acousto-optic figures of merit.
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\((-2200 \text{to } 9000) \times 10^{-15} \text{ s}^3/\text{kg} \ [8]\). 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 \(\lambda = 632.8 \text{ nm}\), 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 \(2\Theta\) between the optic axes. We have measured the angle \(\Theta\) between the optic axes and the \(c\) axis at \(\lambda = 632.8 \text{ nm}\) 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 \(\Delta \rho\) are defined by the relations

\[
B_{jk} = B_{jk}^0 + i e_{jkl} F_{lm} H_m, \tag{1}
\]

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

where \(B_{jk}^0\) 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:

\[
\Delta \rho_1 = \frac{\pi n^3}{\lambda} F_{11} H_1, \quad \Delta \rho_2 = \frac{\pi n^3}{\lambda} F_{12} H_2, \quad \Delta \rho_3 = \frac{\pi n^3}{\lambda} F_{33} H_3. \tag{3}
\]

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:

\[
\Delta \rho_X = \frac{\pi n^3}{\lambda} \left( F_{11} \cos^2 \Theta + F_{33} \sin^2 \Theta \right), \quad \Delta \rho_Y = \frac{\pi n^3}{\lambda} F_{12} \cos \Theta, \quad \Delta \rho_Z = \frac{\pi n^3}{\lambda} \left( F_{33} - F_{11} \right) \sin \Theta \cos \Theta. \tag{4}
\]
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Then the magnetically induced rotation of the polarization plane reduces to

$$\Delta \rho_Z = \frac{\pi n_b^3}{\lambda} F_{33}' Z H_Z$$,

(5)

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

$$F_{33}' = F_{33} \cos^2 \Theta + F_{11} \sin^2 \Theta = 0.9995 F_{33} + 0.0005 F_{11} = \frac{\lambda}{\pi n_b^3} \left( \frac{\Delta \rho_Z}{H_Z} \right)$$.

(6)

Finally, the Verdet constant $V_F$ is determined by the expression

$$V_F = \frac{1}{\mu_0} \left( \frac{\Delta \rho_Z}{H_Z} \right)$$,

(7)

where $\mu_0 = 4\pi \times 10^{-7}$ N/A$^2$ is the magnetic constant. Hence, one can determine the effective Faraday coefficient $0.9995 F_{33} + 0.0005 F_{11}$ 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 $\lambda = 632.8$ 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 $d = 1.92$ 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 $(12.96 \pm 0.18) \times 10^{-13}$ m/A, while the appropriate Verdet constant $V_F$ amounts to $(112.4 \pm 1.5)$ rad/(T m).

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 rad/(T m) for Sn$_2$P$_2$S$_6$ [10], 82 rad/(T m) for Tl$_3$AsS$_4$, 70 rad/(T m) for AgGaGe$_2$S$_8$ and 8 rad/(T 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.

Fig. 1. Dependence of specific rotatory power on the magnetic field applied to TlInS$_2$ ($\lambda = 632.8$ nm): circles correspond to experimental data and solid line to linear fitting.
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 TlInS₂ 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 mâ). Notice that these values exceed the corresponding parameters of Tl₃AsS₄, AgGaGe₃S₈ and AgGaGeS₄ crystals. Issuing from this data, TlInS₂ can be regarded as an efficient magnetooptically non-ordered crystalline material.

References