I.V. LINCHEVSKYI, T.I. SHEVCHENKO

National Technical University of Ukraine “Kyiv Polytechnical Institute”
(37, Peremogy Ave., Kyiv 03056, Ukraine; e-mail: igorvl2009@gmail.com)

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APPLICATION OF MAGNETO-OPTICAL CRYSTALS FOR MECHANICAL STRESS REGISTRATION

The theory of inverse magneto-mechanical effect in cubic crystals has been developed. The proposed model involves changes of the magnetostrictive material magnetization in the external polarizing magnetic field when creating a compression-tension or shear deformation. The magnetic field direction is shown to significantly affect the inverse magneto-mechanical effect. Using the bismuth yttrium ferrite garnet as an example, it is demonstrated that the Villari effect in combination with optical methods used to register magnetization changes enables one to measure minimum stresses at a level of 10^{-4} $Pa \cdot m$ for compression-tension deformations and 10^{-3} $Pa \cdot m$ for shear ones.

Keywords: Faraday effect, Villari effect, magneto-optical crystal, deformation.

1. Introduction

Magnetostriction sensors on the basis of the inverse magneto-mechanic effect (the Villari effect, VE [1, 2]) are a subject of the permanent interest for manufacturers, engineers, and developers. Up to now, the VE has been studied in ferro- and ferrimagnets (Fe, Ni, Co, Gd, Tb, and others), as well as in a number of alloys and ferrites. A certain progress in this direction is related to the appearance of novel materials with a high (of an order of 10^{-3}) magnetostriction λ, e.g., Terfenol-D ($Tb_xDy_{1-x}Fe_y$) [3] and Galfenol (Fe_x Ga_{1-x}) [4]. A positive effect on the researches dealing with the VE was exerted by achievements attained in the adjacent direction aimed at creating the composite structures with magneto-electric properties [5].

Let us recall the main features of the VE. From thermodynamic relations, we obtain that, at low varying stresses,

$$(\partial\lambda)/\partial H)_\sigma = (\partial B)/\partial\sigma)_H, \tag{1a}$$

where $(\partial\lambda)/\partial H)_\sigma$ is the magnetostriction variation at the variation of the magnetic field (MF) strength H provided that the mechanical stress σ is constant, and $(\partial B)/\partial\sigma)_H$ is the variation of the MF induction B at the stress variation provided the constant MF [6]. From expression (1a), it follows that the quantity $\partial M/\partial\sigma$, where M is the magnetization, is a parameter that characterizes the VE, and its value is high for media with the maximum λ-values.

The dependence $M(\sigma)$ was studied in works [7–9]. While attempting to obtain an analytical expression for it in work [7], the elastic energy of the specimen was not taken into account. However, it was shown in work [9] that the variation of the MF induction depends on the strain amplitude and sign. In works [10, 12], using polycrystalline specimens as an example, it was demonstrated that the dependence $M(\sigma)$ is asymmetric at compression-tension deformations, and the VE magnitude decreases as the stress grows [13]. However, the practical formulas, which would allow the corresponding calculations to be made, were absent. The VE was studied, as a rule, under the conditions when some mechanical compression-tension stress [5] or hydrostatic pressure [6] was applied to the specimen, and the magnitude of MF induction was measured, with the variations in the specimen magnetization curves being also monitored [7]. As far as we know, no theoretical model has been proposed for the VE at compression-tension deformations and shear shifts in cubic crystals. Therefore, its development became one of the aims of this work.

Besides the necessity of using the materials with a high magnetostriction for the creation of deformation sensors, the issue concerning the measurement of a varying parameter is always on the agenda. A separate problem in studying the VE consists in the detection of magnetization changes in ferrimagnets. Nowadays, the inductive (transformer) technique for the measurement of the varying component of the MF induction that arises at mechanical deformations in a core fabricated from a magnetic mate-

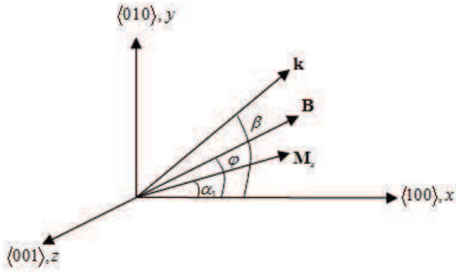

Fig. 1. Geometry of the problem

rial becomes widely spread. In practice, this method of magnetization measurement has a restricted upper limit of frequencies, which follows from the size reduction of the core made of a magnetostriction material and the growth of the leakage field of a coil at high frequencies (more than 100 kHz). The method cannot also be used, while measuring permanent mechanical stresses and in the case where tiny film-based sensitive elements are applied. Therefore, the choice of a material and the issue concerning the measurement of the varying magnetization component should be considered together.

An alternative to the inductive method of mechanical stress measurement can be the optical one, in which magneto-optical crystals revealing the magnetostriction phenomenon are used. In this method, external mechanical stresses change the specimen magnetization, and the varying component of the magnetization vector is measured with the help of optical effects (the Faraday and Cotton–Mouton ones) [14]. For this purpose, the crystals of yttrium, terbium, and europium ferrite garnets can be proposed, as well as the bismuth yttrium ferrite garnet ($Y_{3-x}Bi_xFe_5O_{12}$, $\lambda_{100} = -1.4 \times 10^{-6}$, $\lambda_{111} = -3.8 \times 10^{-6}$, the specific angle of polarization plane rotation $\theta_F = 10^3$ deg/cm [15]), the terbium gallate garnet ($Tb_3Ga_5O_{12}$, $\lambda_{100} = = -3.3 \times 10^{-6}$, $\lambda_{111} = 12 \times 10^{-6}$, $\theta_F = 3 \times 10^3$ deg/cm [16]), and other magneto-optical crystals characterized by a high magnetostriction and large specific values of magneto-optical effects. Taking into account that the polarimetric methods are able to register the insignificant (of an order of 10^{-6} deg [17]) angles of polarization plane rotation, the requirements to magnetostriction parameters can be considerably weakened. The advantages of the optical method for magnetization measurements include the possibility to measure separate projections of the magnetization vector. Therefore, there appears an additional opportunity to enhance the sensitivity of the method by optimizing the directions of light propagation and the magnetic field polarization with respect to the principal crystallographic axes.

In this work, we propose a technique to calculate the dependence of the specimen magnetization on the direction of a polarizing magnetic field and the magnitude of stresses at compression-tension and shear deformations. A magneto-optical crystal belonging to the cubic system is used as an example. By selecting the direction of optical radiation propagation, the optimization of the output signal is carried out from the viewpoint of attaining its maximum value optically registered with the use of the VE. The sensitivity of the proposed method is estimated on the basis of a specimen of bismuth yttrium ferrite garnet subjected to compression-tension and shear deformations.

2. Mathematical Model

When considering the VE, let us assume that the ferrimagnet has the cubic symmetry of its crystal lattice. For definiteness, we suppose that the vector of magnetic field induction $\mathbf{B}$ and the wave vector of optical radiation $\mathbf{k}$ lie in one of the crystallographic planes (Fig. 1). The specimen has a single-domain structure and is characterized by the magnetization vector $\mathbf{M}_s$.

The expressions for the energies in the thermodynamic potential can be presented as follows [6]:

$$\begin{aligned} &E_k = \frac{k_1}{8}(1 - \cos 4\alpha_1); \quad E_H = -BM_s\cos(\phi_0 - \alpha_1),\\ &E_y = \frac{c_{11}}{2}(e_{xx}^2 + e_{yy}^2 + e_{zz}^2) + \frac{c_{44}}{2}(e_{xy}^2 + e_{yz}^2 + e_{xz}^2) + \\ &+ \frac{c_{12}}{2}(e_{xx}e_{yy} + e_{yy}e_{zz} + e_{xx}e_{zz}), \\ &E_{my} = b_1\left\{e_{xx}\left(\cos^2\alpha_1 - \frac{1}{3}\right) + e_{yy} \times \right.\\ &\left.\times \left(\sin^2\alpha_1 - \frac{1}{3}\right) - \frac{e_{zz}}{3}\right\} + b_2 e_{xy}\cos\alpha_1\sin\alpha_1, \end{aligned} \qquad (1)$$

where E_k, E_H, E_y, and E_{me} are the anisotropy, Zeeman, elastic, and magneto-elastic energies, respectively; e_{ij} $(i, j = x, y, z)$ are strains; b_1 and b_2 are the magneto-elastic constants; c_{ij} are the members of the elasticity tensor; and k_1 is the anisotropy constant. In the absence of external stresses, by minimizing the total energy with respect to the strains e_{ij}, we obtain the following expressions for initial strains:

$$e_{xx}^{(0)} = \frac{\Delta_1}{\Delta}, \quad e_{yy}^{(0)} = \frac{\Delta_2}{\Delta},$$
$$e_{zz}^{(0)} = \frac{\Delta_3}{\Delta}, \quad e_{xy}^{(0)} = -b_2 \sin 2\alpha_1/2c_{44}, \tag{2}$$

where

$$\Delta = c_{11}^3 + \frac{c_{12}^3}{4} - 3c_{11}\frac{c_{12}^2}{4},$$
$$\Delta_1 = b_1\left[c_{11}^2\left(\frac{1}{3} - \cos^2\alpha_1\right) + \frac{c_{12}^2}{4}\cos 2\alpha_1 - \right.$$
$$\left. - \frac{c_{11}c_{12}}{2}\left(\frac{2}{3} + \sin^2\alpha_1\right)\right],$$
$$\Delta_2 = b_1\left[c_{11}^2\left(\frac{1}{3} - \sin^2\alpha_1\right) + \frac{c_{12}^2}{4}\left(\frac{1}{3} - \cos 2\alpha_1\right) - \right.$$
$$\left. - \frac{c_{11}c_{12}}{2}\left(\frac{2}{3} - \cos^2\alpha_1\right)\right],$$
$$\Delta_3 = \frac{b_1}{3}\left[c_{11}^2 - \frac{c_{12}^2}{2} + \frac{c_{11}c_{12}}{6}\right].$$

The equilibrium position of the vector $\mathbf{M}_s$ in the absence of external stresses is determined by means of the angle $\alpha_1^{(0)}$. In view of expressions (1a), this angle can be found by solving the equation

$$\frac{k_1}{2}\sin 4\alpha_1^0 - BM_s\sin(\phi - \alpha_1^0) +$$
$$+ c_{11}(e_{xx}^{(0)}(e_{xx}^{(0)})' + e_{yy}^{(0)}(e_{yy}^{(0)})') + c_{44}e_{xy}^{(0)}(e_{xx}^{(0)})' +$$
$$+ \frac{c_{12}}{2}(e_{xx}^{(0)}(e_{yy}^{(0)})' + 2e_{yy}^{(0)}(e_{xx}^{(0)})' + e_{zz}^{(0)}((e_{xx}^{(0)})' +$$
$$+ (e_{yy}^{(0)})') + b_1\left\{(e_{xx}^{(0)})'\left(\cos^2\alpha_1^0 - \frac{1}{3}\right) + \right.$$
$$\left. + e_{xx}^{(0)}\sin 2\alpha_1^0 + (e_{yy}^{(0)})'\left(\sin^2\alpha_1^0 - \frac{1}{3}\right) + e_{yy}^{(0)}\sin 2\alpha_1^0\right\} +$$
$$+ \frac{b_2}{2}(e_{xy}^{(0)})'\sin 2\alpha_1^0 + b_2 e_{xy}^{(0)}\cos 2\alpha_1^0 = 0. \tag{3}$$

In accordance with expressions (2) and (3), we can determine the initial strains: $e_{ii}^0 = e_{ii}\left(\alpha_1^0\right)$ and $e_{ij}^0 = e_{ij}\left(\alpha_1^0\right)$. In the case of external stresses, the strains are added [18],

$$e_{ii}^{=} = e_{ii}^{(0)} + e_{ii}^{\sigma}, \quad e_{ij}^{=} = e_{ij}^{(0)} + e_{ij}^{\sigma}, \tag{4}$$

where

$$e_{ii}^{\sigma} = \frac{\sigma_{ii}}{c_{11} - c_{12}} - \frac{c_{12}}{(c_{11} - c_{12})(c_{11} + 2c_{12})} \times$$
$$\times (\sigma_{xx} + \sigma_{yy} + \sigma_{zz}), \quad e_{ij}^{\sigma} = \sigma_{ij}/(2c_{44}).$$

One can see that external stresses result in the rotation of the magnetization vector, until it occupies the position α_1^σ. At deformations, the angle α_1^σ can be found from the condition of minimum of the thermodynamic potential, in which external stresses are taken into consideration. For example, in the case of a compression-tension deformation, when $\sigma_{xx} = \sigma \neq 0$ and $\sigma_{yy} = \sigma_{zz} = \sigma_{ij} = 0$, the corresponding condition is expressed by the equation

$$\frac{k_1}{2}\sin 4\alpha_1^\sigma - B_s\sin(\phi - \alpha_1^\sigma) + b_1\left[-(e_{xx}^{(0)} + \right.$$
$$\left. + e_{xx}^\sigma(\sigma))\sin 2\alpha_1^\sigma + (e_{yy}^{(0)} + e_{yy}^\sigma(\sigma))\sin 2\alpha_1^\sigma\right] +$$
$$+ b_2 e_{xy}^{(0)}\cos 2\alpha_1^\sigma = 0. \tag{5}$$

The solutions of Eq. (5) determine the dependence $\alpha_1^\sigma(\sigma)$. In particular, from Eq. (5), it follows that

$$\partial\alpha_1^\sigma/\partial\sigma_{xx} =$$
$$= \{-3\lambda_{100}\,(c_{11} + c_{12})\sin 2\alpha_1^\sigma/(c_{11} + 2c_{12})\}/$$
$$/\left\{\left[4k_1\cos 4\alpha_1^\sigma + 2BM_s\cos(\phi - \alpha_1^\sigma) + \right.\right.$$
$$\left. + 6\lambda_{100}\left(\left(e_{xx}^{(0)} - e_{yy}^{(0)}\right)(c_{11} - c_{12}) - \sigma_{xx}\right)\cos 2\alpha_1^\sigma\right] +$$
$$\left. + 12\lambda_{111}c_{44}e_{xy}^{(0)}\sin 2\alpha_1^\sigma\right\}, \tag{6}$$

where the quantity α_1^σ is the solution of Eq. (5).

In the case of a shear deformation, i.e. under the condition $\sigma_{xy} = \sigma \neq 0$, the angle α_1^σ is determined from the equation

$$\frac{k_1}{2}\sin 4\alpha_1^\sigma - BM_s\sin(\phi - \alpha_1^\sigma) +$$
$$+ b_1(e_{xx}^{(0)}\sin(-2\alpha_1^\sigma) + e_{yy}^{(0)}\sin 2\alpha_1^\sigma) +$$
$$+ b_2\left(e_{xy}^{(0)} + \frac{\sigma_{xy}}{2c_{44}}\right)\cos 2\alpha_1^\sigma = 0. \tag{7}$$

From whence, it follows that the derivative $\partial\alpha_1^\sigma/\partial\sigma_{xy}$ takes the form

$$\partial\alpha_1^\sigma/\partial\sigma_{xy} = \{3\lambda_{111}\cos 2\alpha_1^\sigma\}/$$
$$/\left\{\left[4k_1\cos 4\alpha_1^\sigma + 2BM_s\cos(\phi - \alpha_1^\sigma) + \right.\right.$$
$$+ 6\lambda_{100}\,(c_{11} - c_{12})\left(e_{yy}^{(0)} - e_{xx}^{(0)}\right)\cos 2\alpha_1^\sigma -$$
$$\left.\left. - 12\lambda_{111}\sin 2\alpha_1^\sigma(e_{xy}^{(0)}c_{44} + \sigma_{xy})\right]\right\}, \tag{8}$$

where the quantity α_1^σ is the solution of Eq. (7).

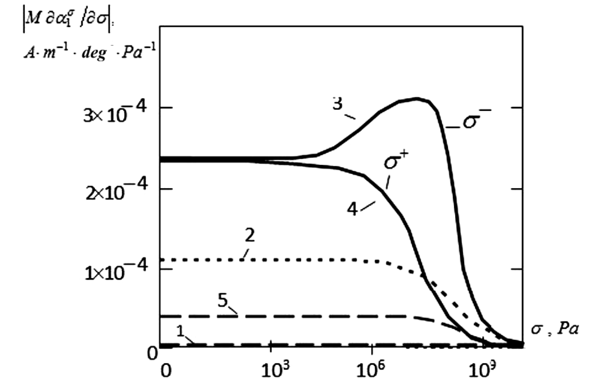

Fig. 2. Dependences of the quantity $M\partial\alpha_1^\sigma/\partial\sigma$ on the stress σ_{xx} at various MF directions $\varphi = 0$ (*1*), 10 (*2*), and 44° (*3* and *4*). Curves *3* (σ^-) and *4* (σ^+) correspond to the compressive and tension deformations, respectively. Curve *5* corresponds to the shear deformation (σ_{xy}, $\phi = \pi/6$)

The classical methods of magnetization measurement are based on the electromagnetic induction law and aimed at determining the varying component $M(\sigma) = M_s \cos(\phi - \alpha_1^\sigma)$ and, accordingly, the derivative

$$\partial M/\partial\sigma = M_s \sin(\phi - \alpha_1^\sigma)\partial\alpha_1^\sigma/\partial\sigma. \quad (9)$$

In particular, in the case where measurements are carried out with the use of expression (9) at the angles $\phi = 0$ or $\pi/2$, and the MF induction B equals 0.5 or 0.7 times B_s, where B_s is the saturation MF induction, and the quantity α_1^σ determined by expression (5) takes the value $\alpha_1^\sigma \approx \phi$. Then, according to expression (9), $\partial M/\partial\sigma \to 0$.

When the Faraday and Cotton–Mouton effects are used to detect changes in the crystal magnetization, the measured parameters are the magnetization components that are parallel, $M_\parallel$, and perpendicular, $M_\perp$, to the axis of light propagation (**k**). Therefore, if the VE is measured using the optical methods, there is an opportunity to measure the parameters

$$\begin{aligned} \Lambda_1 &= \partial M_\parallel/\partial\sigma = M\sin(\beta - \alpha_1^\sigma)\partial\alpha_1^\sigma/\partial\sigma, \\ \Lambda_2 &= \partial M_\perp/\partial\sigma = M\cos(\beta - \alpha_1^\sigma)\partial\alpha_1^\sigma/\partial\sigma, \end{aligned} \quad (10)$$

where the notation σ stands for either σ_{xx} or σ_{xy}.

Unlike expression (9), the maximum values of Λ_1 or Λ_2 in expression (10) are reached, when the relations

$$\begin{cases} \beta - \alpha_1^\sigma = \pi/2, \\ \beta - \alpha_1^\sigma = 0 \end{cases} \quad (11)$$

are satisfied.

3. Results and their Discussion

By varying the direction of light propagation, it is easy to provide the satisfaction of either of conditions (11). In this case, if the stresses are low, the value of angle $\alpha_1^\sigma \approx \alpha_1^{(0)}$ is determined by expression (3). For definiteness, we adopt that the magneto-optical effect used to detect magnetization changes is linear in the magnetization. Then we should select the condition $\beta - \alpha_1^\sigma = \pi/2$. Hence, the optical methods of measurement of the VE make it possible to obtain the maximum possible values of Λ_1 or Λ_2 equal to $M\partial\alpha_1^\sigma/\partial\sigma$.

The results of calculations given below were obtained for the magneto-optical crystal of bismuth yttrium ferrite garnet ($Y_{3-x}Bi_xFe_5O_{12}$, $c_{11} = 108$ GPa, $c_{12} = 107.7$ GPa, $b_1 = -3.48 \times 10^{-5}$ J/m^3, $b_2 = -6.96 \times 10^{-5}$ J/m^3, $k_1 = 6.2 \times 10^2$ J/m^3, $J_s = 1.1 \times 10^4$ A/m), and $B = 0.5$ T.

In Fig. 2, the calculated dependences of $M\partial\alpha_1^\sigma/\partial\sigma$ at compression-tension ($\sigma = \sigma_{xx}$) and shear ($\sigma = \sigma_{xy}$) deformations are depicted. For the VE, the choice of the MF direction with respect to the crystallographic axes is crucial. In particular, at compression-tension deformations, the largest effect takes place if the magnetic field vector is directed at the angle $\phi \to \pi/4$ with respect to one of the crystallographic axes. If the direction of the MF induction vector coincides with the direction of one of those axes or is close to it, the VE disappears. On the contrary, at shear deformations, the VE is maximum if the MF vector is directed in parallel to one of the crystallographic axes, whereas the quantity $M\partial\alpha_1^\sigma/\partial\sigma \to 0$ at $\phi \to \pi/4$. The dependence of the VE on the absolute value of stresses starts to manifest itself at external stresses that induce deformations comparable with spontaneous ones by absolute value. Since the magneto-elastic energy depends on the deformation sign, this circumstance allows one to easily explain the different magnetization curves calculated in accordance with expressions (10) for different strain signs (curves σ^+ and $\sigma-$ in Fig. 2).

Numerical advantages of the optical method used to measure the magnetization is evident from the following example. According to expression (5), the angular difference between the directions of the magnetic field vector and the vector **M** amounts to $\phi - \alpha_1^\sigma \approx \pi/60$ in the case where the absolute value $\phi = \pi/6$. As a result, the absolute value of the derivative $\partial M/\partial\sigma$ measured, by using the induction method along the magnetic field direction, will be equal, according to expression (8), to only 5% of the corresponding result obtained by optical measurement methods in accordance with expressions (10).

In mechanical stress sensors designed on the basis of the inverse magneto-mechanic effect, the minimum measurable angle of the polarization plane rotation with the help of polarimetric methods has an order of $\Delta\theta_{\min} = 10^{-6}$ [17]. If the Faraday law is used for the modulation of optical radiation and the Malus law for the transformation of the polarization plane rotation angle $\Delta\theta$ into the corresponding intensity changes, the minimum measurable stress in the crystal can be estimated by the expression

$$\sigma_{\min} = \Delta\theta/\alpha_f l\Lambda_1, \quad (12)$$

where l is the optical path length in the crystal. For bismuth yttrium ferrite garnet, the minimum measurable stresses turn out to equal $\sigma_{xx}l = 10^{-4}$ Pa · m for compression-tension deformations and $\sigma_{xy}l = 10^{-3}$ Pa · m for shear ones.

4. Conclusion

The manifestation of the inverse magneto-mechanic effect in cubic crystals depends on the direction of the polarizing MF with respect to crystallographic axes and the type of a deformation induced by external forces in the specimen. The proposed model involves magnetization changes in the magnetostriction material under the condition that the specimen is in an external polarizing magnetic field when compression-tension and shear deformations are induced in it. In comparison with the induction methods, the application of optical methods to register magnetization variations in magneto-optical crystals makes it possible to measure the varying component of the magnetization arising owing to the VE that is an order of magnitude smaller.

Using bismuth yttrium ferrite garnet as an example, we have demonstrated that the application of the Villari effect in combination with optical methods aimed at registering the magnetization change allows the specific stresses to be measured at a minimum level of 10^{-4} Pa · m for compression-tension deformations and 10^{-3} Pa · m for shear ones. The results obtained also allow us to speak about the promising potential of using the Faraday effect in combination with the inverse magneto-mechanic effect in magneto-optical crystals, while designing sensors of various physical parameters.

1. F.T. Calkins, A.B. Flatau, and M.J. Dapino, J. Intellig. Mater. Syst. Struct. **18**, 1057 (2007).
2. J.X. Zhang and L.Q. Chen, Acta Materialia **53**, 2845 (2005).
3. M J. Dapino, R.C. Smith, and F.T. Calkins, J. Intellig. Mater. Syst. Struct. **13**, 737 (2002).
4. D.A. Filippov, T.A. Galkina, and G. Srinivasan, Pis'ma Zh. Tekhn. Fiz. **38**, 82 (2012).
5. P.G. Evans and M.J. Dapino, J. Appl. Phys. **107**, 063906 (2010).
6. R.M. Bozorth, *Ferromagnetism* (Van Nostrand, New York, 1959).
7. W.D. Armstrong, Mater. Sci. Eng. A **285**, 13 (2000).
8. S. Datta, J. Atulasimha, and A.B. Flatau, J. Magn. Magn. Mater. **321**, 4017 (2009).
9. J. Scheidler and M. Dapino, Smart Mater. Struct. **22**, 085015 (2013).
10. R. Szewczyk, A. Bienkowski, and R. Kolano, Cryst. Res. Technol. **38**, 320 (2003).
11. I.J. Garshelis and C.R. Conto, J. Appl. Phys. **79**, 4756 (1996).
12. M.J. Sablik and D.C. Jiles, IEEE Trans. Magn. **35**, 498 (1999).
13. D.C. Jiles, J. Phys. D **28**, 1537 (1995).
14. I.V. Linchevskii, Opt. Spektrosk. **113**, 1 (2012).
15. P. Hanson, K. Witter, and W. Toldorf, Phys. Rev. B **27**, 6608 (1983).
16. B.Yu. Sokolov and M.Z. Sharipov, Fiz. Tverd. Tela **56**, 939 (2014).
17. V.D. Tron'ko, I.A. Deryugin, and Yu.A. Kuznetsov, Opt. Spektrosk. **28**, 415 (1970).
18. L.D. Landau and E.M. Lifshitz, *Theory of Elasticity* (Pergamon Press, New York, 1959).

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І.В. Лінчевський, Т.І. Шевченко

ВИКОРИСТАННЯ
МАГНІТООПТИЧНИХ КРИСТАЛІВ
ДЛЯ РЕЄСТРАЦІЇ МЕХАНІЧНИХ НАПРУЖЕНЬ

Р е з ю м е

Розроблено теорію зворотного магнітомеханічного ефекту в кубічних кристалах. Запропонована модель враховує зміни намагніченості магнітострикційного матеріалу, в зовнішньому поляризуючому магнітному полі, при створенні деформацій стиснення-розтягу та деформаціях зсуву. Показано, що напрямок магнітного поля значно впливає на величину зворотного магнітомеханічного ефекту. На прикладі вісмут ітрієвого ферит гранату отримано, що застосування ефекту Віллари в поєднанні з оптичними методами реєстрації зміни намагніченості дозволяє вимірювати мінімальні питомі напруження на рівні 10^{-4} Па·м для деформації стиснення-розтягу та 10^{-3} Па·м для деформації зсуву.