is characterized by the ratio $\alpha_g > \alpha_m > \alpha_p$. With increasing temperature, the value of α increases, but at temperatures exceeding ~ 180 °C it remains practically unchanged. The α values for each direction as a function of ytterbium content *x* at temperature 200 °C are shown in Fig. 2 (*b*). An increase in the ytterbium content *x* leads to an decrease in the α_g value which can be can be approximated by a linear dependence $\alpha_g = (18.0 - 1.12x)\ 10^{-6}\ K^{-1}$, the linear approximation gives a fairly high rate of the coefficient of determination $R^2 = 0.70$. The difference between the α_g values for $x = 0$ (KYW) and $x = 1.0$ (KYbW) is ~$1.1 \cdot 10^{-6}$ K^{-1}, which is about four times large as the uncertainty in the α determination (~$0.3 \cdot 10^{-6}$ K^{-1}). Along the N_m and N_p directions, doping with the Yb ions (increasing of *x*) does not results in change in the values of α_m and α_p (within the experimental error). The linear fitting of this dependences gives low values of R^2 (0.032 and 0.24, respectively). Moreover, the difference between the LTECs values for $x = 0$ and $x = 1.0$ (~$0.2 \cdot 10^{-6}$ K^{-1}) is less than the LTEC measurement error (~$0.3 \cdot 10^{-6}$ K^{-1}).

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THERMO-OPTIC COEFFICIENTS OF MONOCLINIC Er^{3+}:$(GdY)_2SiO_5$ CRYSTAL

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Abstract. Thermo-optic coefficients of the Er^{3+}-doped gadolinium-yttrium oxyorthosilicate crystal Er^{3+}:GdYSO are determined at a wavelength of 632.8 nm for light polarizations $E // N_p$, N_m and N_g. Linear thermal expansion coefficients are estimated for this crystal in the directions of the optical indicatrix axes N_m and N_g.
Key words: monoclinic crystal, thermo-optic coefficient, $(GdY)_2SiO_5$ crystal, thermal coefficients of the optical path.

ТЕРМООПТИЧЕСКИЕ КОЭФФИЦИЕНТЫ МОНОКЛИННОГО КРИСТАЛЛА Er^{3+}:$(GdY)_2SiO_5$

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Аннотация. Определены термооптические коэффициенты кристалла оксиортосиликата гадолиния-иттрия, легированного ионами Er^{3+} (Er^{3+}:GdYSO, на длине волны 632,8 нм для поляризаций света E // N_p, N_m и N_g. Произведена оценка термических коэффициентов линейного расширения данного кристалла в направлениях осей оптической индикатрисы N_m и N_g.
Ключевые слова: моноклинный кристалл, термооптический коэффициент, кристалл $(GdY)_2SiO_5$, термический коэффициент оптического пути.

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Yttrium and gadolinium oxyorthosilicates [Y_2SiO_5 (YSO) and Gd_2SiO_5 (GSO)] are used as laser crystal hosts for doping with trivalent lasing rare-earth ions such as Dy^{3+}, Nd^{3+}, Yb^{3+}, Er^{3+}, Tm^{3+}. Mixed $(Gd_{1-x}Y_x)_2SiO_5$ (GYSO) crystals have been introduced to eliminate cleavage of the GSO and to combine the benefits of the ground state splitting of the GSO with good mechanical properties of YSO (Nd^{3+}:GYSO, Yb^{3+}:GYSO). A continuous tenability from 1004 to 1110 nm has been realized for a continuous-wave Yb^{3+}:GYSO laser. A passively mode-locked Nd^{3+}:GYSO laser has been demonstrated using a SESAM with the pulse width of as short as 5 ps. Using Yb:GYSO crystals, mode-locked laser pulses

as short as 55 fs have been demonstrated by Kerr-Lens mode-locking and 210 fs pulses using a SESAM. However, anisotropy of thermo-optic coefficients of the GYSO gadolinium-yttrium oxyorthosilicates (optically biaxial) crystals has not been studied in detail to date. These parameters are important for application of these crystals as laser crystal hosts. In the present work, we report on the measurements of the thermal coefficients of the optical path (TCOP) and characterizations of anisotropy of thermo-optic coefficients (TOCs, dn/dT) of the gadolinium-yttrium oxyorthosilicate crystal doped with Er^{3+} ions.

A 0.1 at.% Er-doped gadolinium-yttrium oxyorthosilicate crystal (Er:GYSO) was grown by the Czochralski method. Raw materials such as Er_2O_3, Gd_2O_3, Y_2O_3, and SiO_2 were weighed according to the formula $(Er_{0.001}Gd_{0.8995}Y_{0.0995})_2SiO_5$. Thus, in the crystal under study, approximately 10 % of Gd^{3+} ions are replaced by Y^{3+} ions. The growth direction was [100]. The crystal structure was analyzed by X-ray diffraction (XRD). The results reveal the as-grown Er:GYSO crystal has a primitive monoclinic structure with a space group of $P2_1/c$. This agrees with the fact that the space group $P2_1/c$ in the GSO matrix retains at 20 % substitution of Gd^{3+} ions by Y^{3+} ions [1].

Optical properties of the biaxial crystals are described within the frame of the optical indicatrix with orthogonal principal axes N_p, N_m, and N_g. Like the three principal refractive indices, the Er:GYSO crystal should be characterized by the three principal TOCs, namely, dn_p/dT, dn_m/dT and dn_g/dT. For crystals belonging to the space group $P2_1/c$, the principal axis N_p coincides with the crystallographic axis b (= N_p), the other two principal axes N_m and N_g lie in the perpendicular plane [2].

To characterize the anisotropy of the TOCs, a sample from the grown Er:GYSO crystal is prepared in a shape of a rectangular parallelepiped with dimensions of 7.0 (N_p)·8.0 (N_m)×8.5 (N_g) mm^3. Each face of the sample was perpendicular to one of the optical indicatrix axes N_p, N_m and N_g. The orientation of the sample was accomplished firstly identifying the b axis of the crystal by X-raying the crystal sample in a backscattered Laue geometry, with a precision of 0.2°. Preparation of the sample with faces normal to the ***b*** direction then allowed the remaining two principal axes to be found by identifying extinction directions (with a precision of 0.4°) when the sample was viewed in the b direction between crossed polarizers [3].

For determination of the TOCs, the laser beam deflection technique for a material with a linear temperature gradient is used [4]. The measurements are performed at the wavelength of 632.8 nm by means of a continuous-wave He-Ne laser. The uncertainty in the TCOP determination is ~(0.3–0.4)·10^{-6} K^{-1}. When determining the dn/dT (or α) coefficient, an additional error arises which is associated with the error in determining the α (or dn/dT) value, and the accuracy of the dn/dT (or α) measurements increases to ~(0.6–0.9)·10^{-6} K^{-1}.

The TCOP for the Er:GYSO crystal measured at different light polarization E and propagation direction k are presented in Fig. 1. All TCOP are positive. The values of the TCOP (W) show polarization anisotropy in their absolute values which is most evident for the N_m-cut and N_g-cut crystals.

To extract the dn/dT values from the TCOP, the formula dn_i/d$T = W_{ij} - (n_i - 1)\alpha_j$ should be used where i = p, m, g is a light polarization index, j = p, m, g is an index of the light propagation direction k ($i \neq j$). Therefore, literature data are needed on the refractive indices n_p, n_m and n_g and the linear thermal expansion coefficients α_p, α_m and α_g. At present, the values of n and α of Er:GYSO studied in this work are still unknown. We therefore used the refractive indices and the linear thermal expansion coefficient reported for GSO, namely $n_p = 1.871$, $n_m = 1.884$, $n_g = 1.910$ at the wavelength of 632.8 nm [34], $\alpha_p = 12.8 \cdot 10^{-6}$ K^{-1} at the temperature of 100 °C [5]. It can be assumed that the n- and α-values do not change significantly when 10% of Gd^{3+} ions in GSO are replaced by Y^{3+}ions, without changing the crystal structure. It may be also suggested that the refractive indices of the GYSO do not change significantly with Er doping because it is very small (only 0.001 part of the Gd and Y ions is replaced by the Er ones).

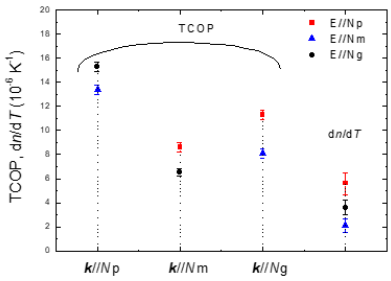

Figure 1 – Thermal coefficients of optical path (TOCP) and thermo optic coefficients (dn/dT) of Er:GYSO crystal for light polarizations E//N_p, N_m and N_g

Using the measured W_{mp} and W_{gp} the values of dn_m/dT and dn_g/dT are determined to be $(2.1 \pm 0.6)10^{-6}$ K^{-1} and $(3.6 \pm 0.6)10^{-6}$ K^{-1}, respectively. These values of dn_m/dT and dn_g/dT in combination with the measured W_{mg} and W_{gm} enable to find $\alpha_g = (6.8 \pm 0.8)10^{-6}$ K^{-1} and $\alpha_m = (3.2 \pm 0.8)10^{-6}$ K^{-1}. The obtained α_g- and α_m-values with the values of W_{pg} and W_{pm} make it possible to evaluate dn_p/d$T = (5.6 \pm 0.9)10^{-6}$ K^{-1} as an average over the values of $(5.4 \pm 0.9)10^{-6}$ K^{-1} (k//N_g) and $(5.8 \pm 0.9)10^{-6}$ K^{-1} (k//N_m) for two directions of the light propagation k. The results on the obtained dn_p/dT, dn_m/dT, dn_g/dT, α_m and α_g are shown in Fig. 1.

According to phenomenological model developed for frequencies between a fundamental lattice resonance and an electronic bandgap, the dn/dT value is controlled by two factors. The first factor (dn/dT)$_{tec}$ is the contribution from the volumetric thermal expansion coefficient and it is negative. The second factor (dn/dT)$_{bg}$ is the contribution from the

change of the electronic bandgap with temperature and it is normally positive. These two factors compete with each other giving positive or negative va lues of dn/dT. Therefore, the positive dn/dT coefficients of the Er:GYSO crystal are due to the fact that the contribution of the $(dn/dT)_{bg}$ term is dominant over the $(dn/dT)_{tec}$ one.

The anisotropy of the TOCs is characterized by $dn_p/dT > dn_g/dT > dn_m/dT$. Thermal coefficients of the natural birefringence are $\Delta_p = |dn_m/dT - dn_g/dT| = 1.5$ for $\boldsymbol{k}//N_p$ (N_p-cut crystal), $\Delta_m = |dn_p/dT - dn_g/dT| = 2.0$ for $k//N_m$ (N_m-cut crystal), and $\Delta_g = |dn_p/dT - dn_m/dT| = 3.5$ (10^{-6} K^{-1}) for $k//N_g$ (N_g-cut crystal). The values of Δ are relatively small, the maximum variation occurs for the N_g-cut Er:GYSO. For comparison, the monoclinic YSO, $Ca_4YO(BO_3)_3$, $Ca_4GdO(BO_3)_3$ $KY(WO_4)_2$ have similar values of Δ_p= 1.03, 1.2, 1.1, 3.5 Δ_m = 2.32, 1.3, 0.1, 2.2 and Δ_g = 3.35, 2.5, 1.0, 5.7 (10^{-6} K^{-1}), respectively [34, 39, 40].

The TCOP values are positive for all directions of the light propagation k // N_p, N_m, N_g. This means that the sign of the thermal lens, which is directly related to the TCOP value, will also be positive, and the positive thermal lens is then expected for N_p- N_m-, and N_g-cut Er:GYSO. The differences in the TCOP values for the same crystal cutting and the orthogonal light polarizations (1.9, 2.1, 3.2 for p-, m-, and g-cut crystals, respectively) are close to the corresponding values of the thermal coefficients of the natural birefringence Δ.

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ИССЛЕДОВАНИЕ КОРРЕЛЯЦИОННЫХ СВЯЗЕЙ ПРИ ЗАДАНИИ ТЕХНОЛОГИЧЕСКИХ РЕЖИМОВ ЛАЗЕРНОЙ ОБРАБОТКИ МАТЕРИАЛОВ

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Аннотация. Для обоснованного выбора режимов лазерной обработки материалов проведены исследования параметров профиля поверхности материала в зависимости от мощности лазерного излучения. Исследования показали, что задание и управление режимами лазерной обработки материалов необходимо производить на основании измеренных в реальном масштабе времени физико-механических характеристик материалов в условиях действия помех и неоднозначности существующих моделей динамики механических воздействий. Поскольку технология лазерной обработки материалов носит вероятностно-временной характер, при ее разработке следует учитывать корреляционные связи между состоянием поверхности (шероховатость, твердость и др.), и условиями (режимами) формирования поверхности (мощность лазерного излучения, скорость перемещения лазерного луча, частота импульсов, диаметр сфокусированного лазерного луча и др.
Ключевые слова: Микронеровности, коэффициент корреляции, мощность лазера, состояние поверхности.

INVESTIGATION OF CORRELATIONS WHEN SETTING TECHNOLOGICAL MODES OF LASER PROCESSING OF MATERIALS

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Abstract. To make a reasonable choice of the modes of laser processing of materials, studies of the parameters of the surface profile of the material depending on the power of laser radiation were carried out. Studies have shown that the assignment and control of laser processing modes of materials must be carried out on the basis of the physical and mechanical characteristics of materials measured in real time under conditions of interference and the ambiguity of existing models of the dynamics of mechanical influences. Since the technology of laser processing of materials is of a probabilistic-temporal nature, its development should take into account correlations between the state of the surface (roughness, hardness, etc.), and the conditions (modes) of surface formation (laser radiation power, speed of movement of the laser beam, pulse frequency, diameter of the focused laser beam, etc.
Key words: micro-dimensions, correlation coefficient, laser power, surface state.

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