буждения ЭЛ, оценить величину напряжения пробоя исследуемого образца.

Установка была апробирована на структурах Si/SiO_2, $Si/SiO_2/Si_3N_4$, $Si/SiO_2/SiN_x/SiO_2$. На рисунке 3 представлены спектры ЭЛ образцов $Si/SiO_2/SiN_{0,9}/SiO_2$, зарегистрированные при различных плотностях протекающего тока. Диэлектрические слои оксида и нитрида кремния сформированы методом химического осаждения из газовой фазы на кремниевой пластине p-типа. Общая толщина диэлектрических слоев составляет 140 нм. Спектры ЭЛ зарегистрированы при анодной поляризации кремниевой подложки.

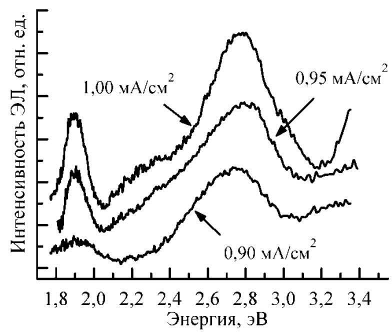

Рисунок 3 – Спектры электролюминесценции образца $p\text{-}Si/SiO_2/SiN_{0,9}/SiO_2$

Спектры ЭЛ характеризуется полосами с энергиями в красной (1,9 эВ), зеленой (2,3 эВ) и синей (2,7 эВ) области, причем последняя полоса имеет наибольшую интенсивность. Полоса в красной области спектра ЭЛ связана с наличием в слоях SiO_2 силанольных групп (Si-OH). ЭЛ в зеленой области объясняется внутрицентровыми переходами в атомах трехкоординированного кремния в слоях SiO_2. Интенсивная полоса ЭЛ с максимумом при 2,7 эВ характерна для излучательной релаксации силиленовых центров [2]. Наличие этих центров присуще слоям оксинитрида кремния, что позволило сделать заключение о формировании таких слоев на границах оксида и нитрида кремния. Установлено, что интенсивность свечения этой полосы обладает наибольшей устойчивостью к воздействию сильных электрических полей после протекания через образец заряда 1-3 Кл/см^2.

Таким образом, реализованный метод электролюминесценции позволяет изучить состав, структурные особенности, определить концентрацию центров люминесценции, исследовать деградацию диэлектрических слоев в результате воздействия сильного электрического поля.

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ANISOTROPY OF THERMO-OPTICAL COEFFICIENTS OF ALEXANDRITE LASER CRYSTAL

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Alexandrite (Cr^{3+}:$BeAl_2O_4$) is a well-known crystal for tunable lasers relying on vibronic coupling [1–3]. Alexandrite provides intense emission between 0.7 and 0.85 μm with a maximum at around 0.75 μm [4, 5]. The corresponding stimulated-emission cross-section is relatively small, $\sigma_{SE} = 0.7 \times 10^{-20}$ cm^2, which is compensated by a relatively long lifetime of the upper laser level $\tau \sim 260$ μs at room temperature. Thus, the ($\sigma_{SE}\tau$) product is large and the efficient and low-threshold continuous-wave laser operation of alexandrite is possible [6]. The Cr^{3+} ions in orthorombic $BeAl_2O_4$ exhibit strong polarization-anisotropy of the spectroscopic properties (the high-gain light polarization is $\boldsymbol{E} \parallel \boldsymbol{b}$) [4, 5] and linearly polarized laser output is easily achievable.

The Alexandrite lasers have relevant applications in medicine (dermatology), space LIDAR technologies, spectroscopy [7] and can replace Ti:Sapphire lasers in nonlinear microscopy.

Alexandrite exhibits a combination of attractive thermal and mechanical properties, namely very high thermal conductivity κ ~23 W/(mK), weak and almost isotropic thermal expansion $\alpha \sim 7 \times 10^{-6}$ K^{-1}, and high optical damage threshold [3, 8]. However, thermo-optical properties of alexandrite have not been studied in detail to date.

In the present report, we aimed to measure the thermo-optic coefficients (TOCs, dn/dT) and to characterize thermal variation of the optical path length of alexandrite with respect to light polarization.

Alexandrite is orthorhombic (sp. gr. *Pnma*) and thus optically biaxial [9]. Its optical properties are characterized in the frame of the optical indicatrix. The optical indicatrix axes are mutually orthogonal and they coincide with the crystallographic axes ***a***, ***b***, ***c***. The corresponding principal refractive indices are n_a, n_b and n_c (for polarizations $\boldsymbol{E} \parallel \boldsymbol{a}$, $\boldsymbol{E} \parallel \boldsymbol{b}$ and $\boldsymbol{E} \parallel \boldsymbol{c}$, respectively) with $n_c < n_a < n_b$. Similarly to the refractive indices, three principal TOCs exist for alexandrite, namely dn_a/dT, dn_b/dT and dn_c/dT. No predefined relation for the corresponding TOCs is expected.

For the measurements of TOCs of alexandrite, the laser beam deviation method for a material with a linear thermal gradient was used [10]. The measurements were done using a 0.06 at.% Cr^{3+}:$BeAl_2O_4$ crystal (Solix Ltd.) which was cut to a rectangular sample with dimensions of 5.58(***a***) × 6.22(***b***) × 6.87(***c***) mm^3. All six surfaces were polished to a laser grade quality. A set of probe lasers emitting in the spectral range of 0.4-1.1 μm was used. The probe radiation was linearly polarized. The measurements were done at 298 K. The linear temperature gradient in the sample was ~1-2 K/mm. It was determined separately for each sample orientation. The actual temperature of the hot and cold surfaces of the crystal was measured using sensitive thermocouples with a precision of 0.1 K.

The laser beam deviation method allows one to measure the so-called thermal coefficients of the optical path (TCOP), dn/dT + (n – 1)α. The precision of the TCOP measurements was 7-10% depending on the crystal cut. The n and dn/dT are determined by light polarization $\boldsymbol{E}$ and α (the linear thermal expansion coefficient) is determined by light propagation direction $\boldsymbol{k}$. For orthorhombic Alexandrite, there are three principal α values along the ***a***, ***b*** and ***c*** directions (αa, αb and αc, respectively). For any biaxial crystal incl. alexandrite, a total of 6 independent TCOPs can be measured leading to 3 principal TOCs each of which is determined from two measurements [10].

At first, we measured the six principal thermal coefficients of the optical path (TCOPs). Their dispersion is illustrated in Fig. 1 (a-c). All TCOPs are positive in the whole studied spectral range. The TCOP values show a polarization-anisotropy which is especially clear for the ***a***-cut and ***b***-cut crystals. In order to calculate the TOCs, i.e., dn/dT = TCOP – (n–1) α, we used the literature data on the refractive index (calculated from the Sellmeier equations reported in [16]) and on the linear thermal expansion coefficients (α_a = 5.9, α_b = 6.1, α_c = 6.7 × 10^{-6} K^{-1} [3, 7]). The results are shown in Fig. 1 (d). All three principal TOCs for alexandrite are positive and show a notable anisotropy. For the whole studied spectral range, dn_c/dT > dn_b/dT > dn_a/dT. The TOCs determined from the measurements for different crystal cut were in good agreement with each other, as indicated by the error bars in Fig. 1 (d).

To calculate the TCOPs and dn/dT at the particular laser wavelength, the dispersion of the dn/dT was modeled taking into account (i) volumetric thermal expansion (expressed by the $\alpha_{vol} = \alpha_a + \alpha_b + \alpha_c$ coefficient) and (ii) temperature dependence of the electronic bandgap E_g (expressed by a temperature derivative, dE_g/dT) [10]:

$$dn_i/dT = -\alpha_{vol}\frac{(n_{i\infty}-1)}{2n_i(\lambda)}\frac{\lambda^2}{\lambda^2-\lambda_{ig}^2} - \frac{1}{E_{ig}}\frac{dE_{ig}}{dT}\frac{(n_{i\infty}-1)}{2n_i(\lambda)}\left(\frac{\lambda^2}{\lambda^2-\lambda_{ig}^2}\right)^2. \quad (1)$$

In the Eq. (1), i = a, b, c, λ is the light wavelength; λ_g [μm] = 1.2398/E_g [eV], $n(\lambda)$ is the Sellmeier equation, n_∞ is the refractive index in the long-wavelength infrared limit, see Ref [9]. The dn/dT value can be represented as a sum of two terms related to (i) and (ii) effects, $(dn/dT)_\alpha + (dn/dT)_g$, which have negative and positive values, respectively. The experimental data in Fig. 1 (d) were modeled with Eq. (1) with E_g and dE_g/dT as free parameters leading to the thermooptic dispersion curves. The best-fit parameters, depending on the light polarization, are in the range of 5.7-6.3 eV and −1.4 – 2.7 × 10^{-4} eV/K, respectively. For alexandrite, the density functional theory predicts a direct bandgap of 6.45 eV [11] while the UV absorption edge is located at about 9 eV [3]. According to the Eq. (1), the positive dn/dT coefficients of alexandrite are related to the weak thermal expansion, so that the contribution of the $(dn/dT)_g$ term is dominant.

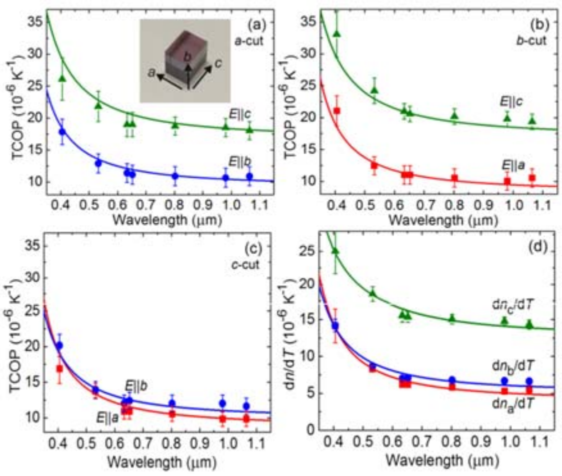

Fig. 1. Thermo-optical properties of alexandrite: (a-c) dispersion of TCOP for the ***a***-cut (a), ***b***-cut (b) and ***c***-cut (c) crystals: *symbols* – experimental data, *curves* – data calculated using the thermo-optic dispersion formulas, Eq. (2), *error bars* indicate the uncertainty arising from the laser beam deviation method; (d) dispersion of TOCs: *symbols* – experimental data, *curves* – their fitting with Eq. (1), *error bars* indicate the uncertainty arising from the averaging of the dn/dT values for two different crystal cuts. *Inset* in (a) – photo of the studied crystal

The thermo-optic dispersion formulas can be also represented in a simplified form [10]:

$$dn/dT = A_0 + \frac{A_1}{\lambda^2} + \frac{A_2}{\lambda^4} + \frac{A_3}{\lambda^6}, \quad 10^{-6}K^{-1}. \quad (2)$$

Here, λ is in μm; $A_{0\text{-}3}$ are the expansion coefficients (A_0 corresponds to the dn/dT value in the long-wavelength limit, $A_{1\text{-}3}$ represent its dispersion), see Table 1.

Using the derived thermo-optic dispersion formulas, we calculated TOCs at 0.75 μm as dn_a/dT = 5.9, dn_b/dT = 6.9 and $dn_c/dT = 15.2 \times 10^{-6}$ K^{-1}. The anisotropy of the dn/dT values is much stronger than that of the refractive indices, n_a = 1.737, n_b = 1.742, n_c = 1.735 at 0.75 μm [9]. The values of the dn_a/dT and dn_b/dT are lower than 9.4 and 8.3×10^{-6} K^{-1}, respectively, previously measured at 1150 nm [2]. There is no previous data on the dn^c/dT. Furthermore, we calculated the dispersion curves for the TCOP values, TCOP(λ) = $dn/dT(\lambda) + [n(\lambda) - 1]\alpha$, see Fig. 1 (a-c). The six principal TCOPs at 0.75 μm are listed in Table 2. In particular, for a ***c***-cut crystal and light polarization ***E*** || ***b***, TCOP = 11.9×10^{-6} K^{-1}.

Table 1. Coefficients in the Thermo-Optic Dispersion Formulas for Alexandrite Crystal, Eq. (2)

TOC	A_0	A_1, μm^2	A_2, μm^4	A_3, μm^6
dn_a/dT	3.95	1.1842	0.0786	0.0246
dn_b/dT	5.12	0.9848	0.0129	0.0141
dn_c/dT	12.72	1.3275	0.0320	0.0121

Table 2. Thermal coefficients of the optical path (10^{-6} K^{-1}) of alexandrite crystal at 0.75 μm

Crystal cut	Polarization		
	E || a	***E*** || ***b***	***E*** || ***c***
a-cut	–	+11.2	+19.5
b-cut	+10.4	–	+19.7
c-cut	+10.8	+11.9	–

To conclude, we have studied dispersion and anisotropy of the dn/dT coefficients and TCOPs of alexandrite laser crystal. All three principal dn/dT are positive (due to the dominant effect of temperature variation of the bandgap over the weak thermal expansion) and they exhibit a notable polarization-anisotropy, $dn_c/dT > dn_b/dT > dn_a/dT$. For the high-gain laser polarization (***E*** || ***b***), dn/dT has an intermediate value of 6.9×10^{-6} K^{-1} at 0.75 μm. Positive dn/dT underlies positive (focusing) thermal lens of alexandrite lasers. We believe that a detailed knowledge of the thermo-optical properties of alexandrite crystal will help in designing laser cavities of high-power oscillators based on this laser crystal.

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УДК 535-7

ОПРЕДЕЛЕНИЕ ПОКАЗАТЕЛЯ ПРЕЛОМЛЕНИЯ БИОЛОГИЧЕСКИХ МУТНЫХ СРЕД МЕТОДАМИ ЭЛЛИПСОИДАЛЬНЫХ РЕФЛЕКТОРОВ

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В основе методов исследования показателя преломления биологических сред лежат три основных физических явления: рефракция, интерференция и полное внутреннее отражение (ПВО). Измерительные средства могут быть реализованы как на одном явлении, так и нескольких [1]. Наиболее распространенными можно считать методы технической реализации, базирующиеся на измерении критического угла (полного внутреннего отражения) в отраженном от объекта свете [2–6]. В общем случае они дают высокую точность, но, анализируя применение этих методов относительно мутных биологических сред и полученные с их помощью результаты, можно сделать вывод, что значения показателя преломления для одинаковых биологиче-