

Study of luminescent characteristics of a composite two-layer ceramic converter based on LuGdAG:Ce solid solutions

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This study investigates the luminescence properties of a two-layer composite ceramic converter consisting of LuAG:Ce (S1) and LuGdAG:Ce (S2) layers. The results reveal that reducing the total composite thickness from 2 to 0.2 mm significantly modifies key spectral parameters: the color rendering index (CRI) for the S1 side increases from 45 to 56, the correlated color temperature for the S2 side rises from 3267 to 4670 K, and the conversion efficiency peaks at a thickness of 0.6 mm. Internal quantum efficiency measurements yield values of 73 % for the LuAG:Ce layer and 69 % for the LuGdAG:Ce layer. These findings demonstrate that the proposed composite architecture successfully integrates high conversion efficiency with tunable color characteristics, offering a promising approach for advanced phosphor applications.

Keywords: LuAG:Ce, ceramics, white LEDs, CRI, LuGdAG:Ce, luminescence.

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Modern lighting technology imposes stringent requirements on white light sources, which must simultaneously achieve high energy efficiency and excellent color rendering. The most widely adopted solution in LED lighting involves phosphors based on cerium-doped yttrium aluminum garnet (YAG:Ce) [1,2]. While YAG:Ce delivers high luminous efficacy, it suffers from a limited color rendering index ($R_a < 60$) due to the absence of a red emission component in its spectrum [3]. A promising alternative is solid-solution phosphors based on lutetium gadolinium aluminum garnet (LuGdAG:Ce), where partial substitution of Lu^{3+} with Gd^{3+} enables precise tuning of spectral properties [4–7]. Research has demonstrated that increasing the Gd^{3+} content shifts the Ce^{3+} luminescence band toward longer wavelengths (from 513 to 561 nm), a phenomenon attributed to local crystal field modifications around Ce^{3+} ions and adjustments in the band gap [7]. This redshift significantly enhances color rendering: for the composition $\text{Ce}_{0.01}\text{Lu}_{1.19}\text{Gd}_{1.8}\text{Al}_5\text{O}_{12}$, a record R_a value of ≈ 77 has been achieved — unprecedented for single-phase garnet-structured ceramics [5].

This study investigates the luminescent properties of a two-layer composite system consisting of $\text{Ce}_{0.01}\text{Lu}_{2.99}\text{Al}_5\text{O}_{12}$ and $\text{Ce}_{0.01}\text{Lu}_{1.79}\text{Gd}_{1.2}\text{Al}_5\text{O}_{12}$, with varying thicknesses of the ceramic composite. The novelty of this work lies in the development of a two-layer composite ceramic converter, where the highly efficient LuAG:Ce layer ensures the overall system efficiency, while the LuGdAG:Ce layer with increased gadolinium content enhances the spectral saturation with long-wavelength components and improves the color rendering index [7–10]. Accordingly, for the fabrication of the composite layers, we selected ceramics

of the $\text{Ce}_{0.01}\text{Lu}_{2.99}\text{Al}_5\text{O}_{12}$ composition — where disorder is minimized across all LuGdAG:Ce compositions — as well as ceramics of the $\text{Ce}_{0.01}\text{Lu}_{1.79}\text{Gd}_{1.2}\text{Al}_5\text{O}_{12}$ composition, which provides strong long-wavelength emission. Beyond lighting applications, these composite ceramic materials show potential for use in scintillation detectors and solid-state lasers, where controlled spectral characteristics and high optical homogeneity are critical.

To fabricate the composite converter, the following compositions were selected based on previous studies [4,5]. The precursor powders were synthesized via chemical coprecipitation in an aqueous solution. The resulting ceramic powders, calcined at 1150 °C, were then uniaxially pressed at 7 MPa to form disk-shaped green bodies. For composite fabrication, the powders were sequentially loaded into the mold: first, one composition was added and leveled, followed by the second composition. The layered structure was then pressed at 7 MPa. The green bodies were subsequently sintered in a vacuum furnace at 1820 °C for 10 hours. The final ceramic samples were ground to a uniform thickness of 2 mm, with each layer measuring 1.00 ± 0.05 mm. In this study, the layer composed of $\text{Ce}_{0.01}\text{Lu}_{2.99}\text{Al}_5\text{O}_{12}$ is designated as S1, while the layer composed of $\text{Ce}_{0.01}\text{Lu}_{1.79}\text{Gd}_{1.2}\text{Al}_5\text{O}_{12}$ is designated as S2. Optical transmission spectra (200–1100 nm) were recorded using an SF-56 spectrophotometer (OKB Spektr, Russia). The integrated luminescence of the LuGdAG:Ce ceramics was measured using a Lisun LMS-9000C spectroradiometer with an integrating sphere. A 448 nm blue LED, operated at an electrical power of 5.55 W, served as the excitation source. The conversion efficiency was calculated as the ratio of the measured luminous flux to the electrical input

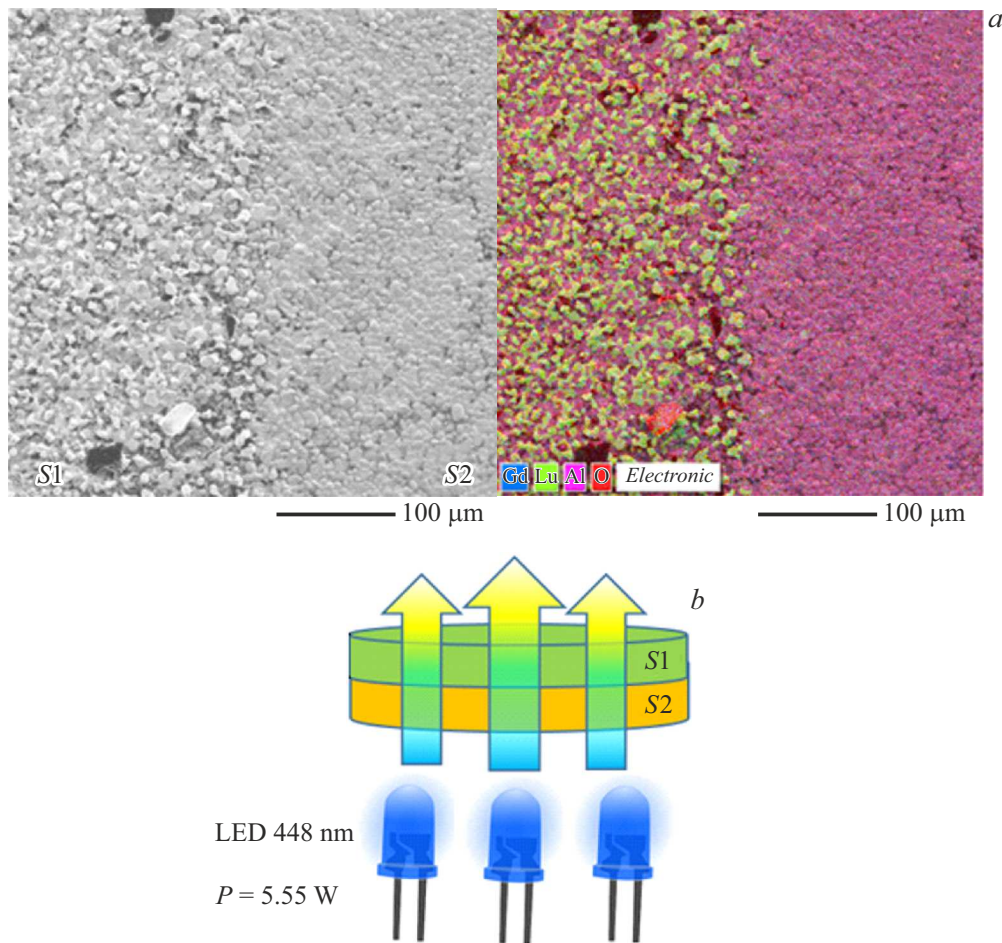


Figure 1. *a* — SEM image of the interface between composite layers (left) and element distribution map at the interface (right); *b* — schematic diagram of the converter setup for measuring luminescence properties. The colored figure is presented in the article's electronic version.

power, representing the system's overall energy efficiency. Luminescence spectra were acquired over the 350–800 nm range with a 1 nm resolution. Microstructural analysis and elemental mapping of the LuGdAG:Ce ceramics were performed using a Tescan Mira3 LMH scanning electron microscope (SEM).

Figure 1, *a* (left) presents an SEM image of the interfacial region, revealing a distinct boundary between the composite layers characterized by differences in grain morphology. In region S1, the grains exhibit a coarser shape and greater size heterogeneity, whereas in region S2, the grains are more rounded. These morphological differences arise from variations in the sintering kinetics of the compositions. Previous studies [4,5] have demonstrated that in LuGdAG:Ce solid solutions, increasing gadolinium concentration enhances crystal lattice disorder and the number of point defects. Consequently, compositions with higher gadolinium content sinter at lower temperatures, as lattice defects promote sintering processes. Elemental mapping of the region (Fig. 1, *a*, right) confirms a significant difference in the chemical composition of the composite layers. Region S1 contains a substantial lutetium-rich phase, and the

distribution of lutetium and aluminum appears non-uniform. The non-uniform elemental distribution at the interface between the composite layers on the S1 side may result from incomplete sintering of the LuAG:Ce composition under the selected temperature and dwell time conditions. However, the high ceramic transparency (78 % at 1000 nm) and measured internal quantum efficiency (73 %) indicate that this microstructural feature does not cause significant optical losses. The close refractive indices of the phases minimize scattering at the interphase boundaries. In the S2 region, no pronounced lutetium-phase inclusions are observed, and the elemental distribution appears much more uniform, supporting the hypothesis that sintering processes were more intensive in the $\text{Ce}_{0.01}\text{Lu}_{1.79}\text{Gd}_{1.2}\text{Al}_5\text{O}_{12}$ (S2) composition. Notably, no visible macrodefects, such as overgrown grains or pores, are present at the interface between the composite layers, suggesting that the sintering conditions were appropriately selected. At the interface between compositions S1 and S2, a solid solution of an intermediate composition forms. A test rig for studying luminescence properties was assembled according to the schematic shown in Fig. 1, *b*. A ceramic sample was

positioned over a blue LED (emission wavelength: 448 nm) to completely block the LED's emission. Luminescence was measured on both the S1 and S2 sides of the sample using the integrating sphere of a spectrofluorimeter. The sample was then ground on both sides, removing equal-thickness material layers ($\pm 5 \mu\text{m}$), and luminescence was measured again. This procedure yielded the thickness-dependent luminescence properties of the composite (Fig. 2).

Analysis of the obtained dependencies reveals an inflection point at a composite thickness of approximately 0.4 mm. As the thickness decreases below 400 μm , the luminescence characteristics exhibit a more pronounced change. This behavior arises because, at thicknesses above 400 μm , nearly all the blue radiation emitted by the LED is absorbed within the bulk of the luminescence converter. With further thinning, the proportion of blue radiation transmitted through the ceramic without absorption increases rapidly. The convergence of characteristics upon excitation from different sides (S1 and S2) as the sample thins can be explained by the fact that, at small thicknesses, blue pump light reaches the opposite layer of the composite. Consequently, the final emission spectrum is formed by the luminescence of both layers and the transmitted blue radiation, rather than solely by the layer receiving the excitation. This results in a convergence

of the color characteristics and their dependence on the choice of the excitation side. To separate the effects of spectral redistribution and internal losses, internal quantum efficiency (IQE) measurements were performed using an integrating sphere. The IQE for sample S1 (LuAG:Ce) was found to be 73 %, while for sample S2 (LuGdAG:Ce), it was 69 %. These values confirm that the decrease in conversion efficiency in the S2 layer, measured in lm/W, is due not only to a spectral shift toward a region of lower eye sensitivity but also to an objective reduction in quantum yield due to lattice disordering caused by the introduction of Gd^{3+} ions.

Figure 3, *a* presents the light transmittance spectrum of the 2-mm-thick ceramic composite. The transmission spectrum exhibits two absorption bands centered at 345 and 450 nm, attributed to the $^4f \rightarrow ^5d_2$ and $^4f \rightarrow ^5d_1$ transitions of Ce^{3+} ions, respectively [7]. Additionally, a narrow absorption band at approximately 275 nm is observed, corresponding to the $^8S_{7/2} \rightarrow ^6I_J$ transition of Gd^{3+} ions [11]. The light transmittance reaches approximately 78 % at a wavelength of 1000 nm. The inset photograph in Fig. 3, *a* demonstrates the composite ceramic's high transparency, as text is easily discernible through the sample. This high transmittance, close to the theoretical limit for a single crystal, indicates a low concentration of scattering centers (e.g., residual pores, secondary phases) within the ceramic bulk. Figure 3, *b* illustrates the CIE diagram of the composite at various thicknesses under excitation from the S1 and S2 sides. The data reveal that the emission spectrum initially recorded upon irradiation of the S1 side falls within the green region of the diagram, whereas the spectrum for the S2 side lies in the orange region. As the composite thickness decreases, the emission spectrum of the LED assembly for both the S1 and S2 sides shifts toward an increased blue component. This shift also reduces the separation between the S1 and S2 points, consistent with the thickness dependence of the correlated color temperature (CCT) (Fig. 2, *c*). At a composite thickness of approximately 200 μm , the spectra of the S1 and S2 sides become nearly identical and approach the blackbody line, achieving a CCT of 4700 K. The luminescence spectra (Fig. 3, *c*) reveal a change in the spectral composition of the composite emission. Notably, for sample S1 at a thickness of 2 mm, a significant reduction in the red region of the spectrum is observed, which substantially decreases its color rendering index R_a to 45 (Fig. 2). At a thickness of 0.2 mm, a sharp increase in the blue component occurs because a portion of the LED radiation begins to pass through the ceramic without absorption. To quantitatively assess the advantages of the developed composite converter, a comparison was made with literature data on single-phase LuGdAG:Ce ceramics. In [5], the maximum color rendering index ($R_a = 77$) was achieved for the composition $\text{Ce}_{0.01}\text{Lu}_{1.19}\text{Gd}_{1.8}\text{Al}_5\text{O}_{12}$; however, the conversion efficiency was only 98.1 lm/W. In [7], an efficiency of 171.5 lm/W at $R_a = 56$ was obtained for the composition $\text{Ce}_{0.05}\text{Lu}_{2.1}\text{Gd}_{0.9}\text{Al}_5\text{O}_{12}$. The two-layer composite we developed, with a thickness of 0.6 mm,

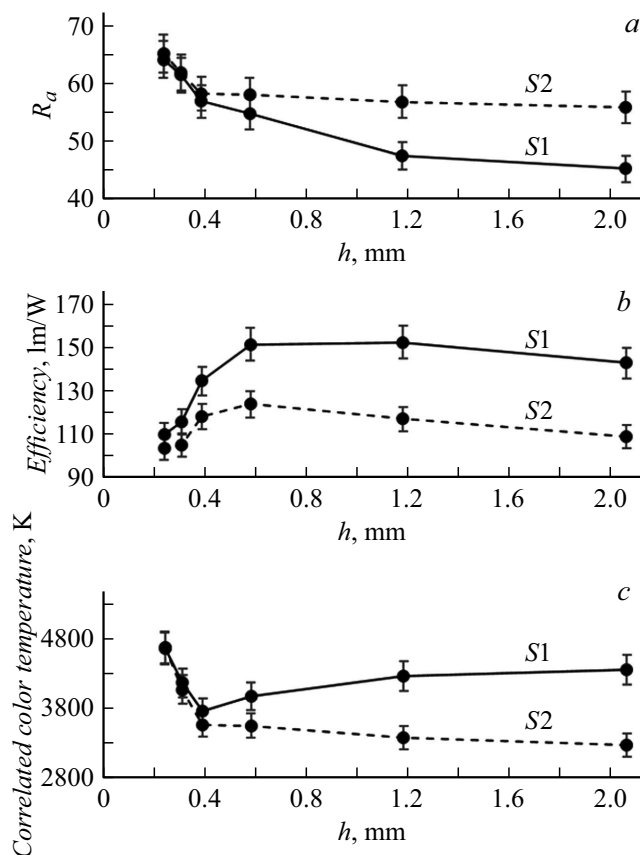


Figure 2. Dependence of color rendering index (*a*), conversion efficiency (*b*), and correlated color temperature (*c*) on composite thickness.

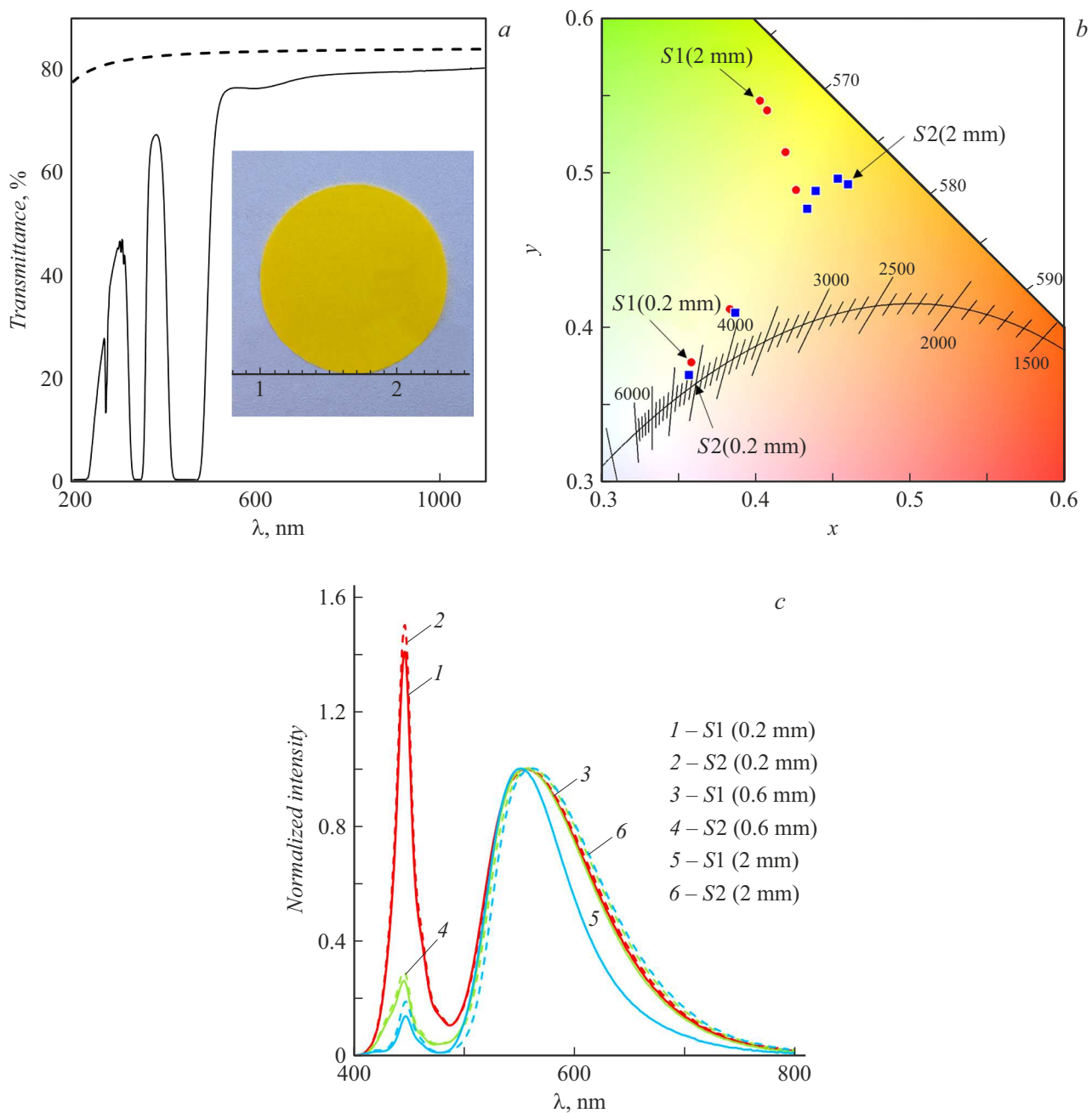


Figure 3. *a* — light transmittance spectrum of a 2 mm thick ceramic composite. The dotted line represents the theoretical transmittance of a LuAG single crystal, calculated using the Fresnel formula with a refractive index of $n = 1.84$. Inset: photograph of the sample. *b* — CIE chromaticity diagram of the composite at different thicknesses with excitation from the S1 and S2 sides. *c* — luminescence spectra of samples at varying thicknesses.

demonstrates an efficiency of 151 lm/W at $R_a \approx 56$, which is comparable to the best single-phase analogs. However, it offers an additional advantage: the ability to adjust color characteristics (CCT from 3267 to 4700 K) by changing the thickness and the excitation side, as well as by bringing the color coordinates closer to the blackbody line at minimum thickness. Thus, the composite approach enables flexible control of spectral parameters without significant loss of efficiency.

The study confirmed that the layer interface is free of macrodefects, with microstructural differences arising from variations in the sintering rates of the composites. It was observed that reducing the composite thickness to 200 μm increases both the color rendering index and correlated color temperature but results in a decrease in conversion efficiency. Based on these findings, the optimal composite thickness depends on the specific requirements of the final device. To maximize conversion efficiency

(up to 151 lm/W), a thickness of approximately 0.6 mm is ideal. For applications prioritizing high color temperature and proximity to the blackbody line ($CCT \approx 4700$ K), a thickness of approximately 0.2 mm is preferred. Thicknesses exceeding 1 mm provide stable characteristics and effective suppression of blue pumping, which may be advantageous in high-power light sources.

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Conflict of interest

The authors declare no conflict of interest.

References

- [1] T. Ma, F. Lei, H. Chen, L. Yin, J. Zhou, J. Liu, H. Sun, Y. Shi, L. Chen, J. Xie, L. Zhang, *Opt. Mater.*, **5**, 109226 (2019). DOI: 10.1016/j.optmat.2019.109226
- [2] R.F. Muniz, V.O. Soares, V.S. Zanuto, M.A.C. Melo, M. Sandrini, M.P. Belançon, A.N. Medina, M.L. Baesso, *J. Non-Cryst. Solids*, **574**, 121169 (2021). DOI: 10.1016/j.jnoncrysol.2021.121169
- [3] J. Ling, W. Xu, J. Yang, T. Mu, Y. Zhang, Y. Zhou, M. Hong, *J. Eur. Ceram. Soc.*, **41**, 5967 (2021). DOI: 10.1016/j.jeurceramsoc.2021.05.005
- [4] A.A. Kravtsov, V.A. Lapin, E.V. Medyanik, L.V. Tarala, K.V. Kungurtsev, V.E. Suprunchuk, D.S. Vakalov, F.F. Malyavin, E.A. Brazhko, D.P. Bedrakov, V.A. Tarala, *J. Am. Ceram. Soc.*, **109**, e70440 (2026). DOI: 10.1111/jace.70440
- [5] A.A. Kravtsov, V.A. Lapin, O.M. Chapura, E.V. Medyanik, L.V. Tarala, K.V. Kungurtsev, V.E. Suprunchuk, D.S. Vakalov, F.F. Malyavin, E.A. Brazhko, D.P. Bedrakov, V.A. Tarala, *J. Am. Ceram. Soc.*, **108**, e20497 (2025). DOI: 10.1111/jace.20497
- [6] A.A. Kravtsov, V.A. Lapin, E.V. Medyanik, L.V. Tarala, O.V. Devitsky, *Tech. Phys. Lett.*, **51** (4), 89 (2025). DOI: 10.61011/TPL.2025.04.61010.20211
- [7] J. Ling, Y. Zhou, C. Lin, H. Zhang, W. Xu, M. Hong, *J. Eur. Ceram. Soc.*, **44**, 6430 (2024). DOI: 10.1016/j.jeurceramsoc.2024.04.014
- [8] H. Ding, Z. Liu, P. Hu, Y. Liu, P. Sun, Z. Luo, X. Chen, H. Jiang, J. Jiang, *Adv. Opt. Mater.*, **9**, 2002141 (2024). DOI: 10.1002/adom.202002141
- [9] K. Park, T. Kim, Y. Yu, K. Seo, J. Kim, *J. Lumin.*, **173**, 159 (2016). DOI: 10.1016/j.jlumin.2016.01.014
- [10] J. Xu, L. Fan, Y. Shi, J. Li, J. Xie, F. Lei, *Opt. Mater.*, **36**, 1954 (2014). DOI: 10.1016/j.optmat.2014.02.008
- [11] P. Gupta, A.K. Bedyal, V. Kumar, Y. Khajuria, V. Sharma, O.M. Ntwacaborwa, H.C. Swart, *Mater. Res. Express*, **2**, 076202 (2015). DOI: 10.1088/2053-1591/2/7/076202