

# Excitation and Photoluminescence Spectra of Solid Solutions Based on Lanthanum Indate $\text{LaInO}_3$ of a Perovskite Structure Doped with $\text{Nd}^{3+}$ and $\text{Cr}^{3+}$ Ions

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**Abstract**—Using a solid-phase method, single-phase solid solutions of  $\text{La}_{1-x}\text{Nd}_x\text{InO}_3$  ( $x = 0.007, 0.02, 0.05$ ),  $\text{LaIn}_{0.99}\text{Cr}_{0.01}\text{O}_3$ , and  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$  have been obtained and their excitation and photoluminescence (PL) spectra have been studied at room temperature. It is found that the intensity of excitation and PL bands for  $\text{La}_{1-x}\text{Nd}_x\text{InO}_3$  solid solutions depends on the degree of the substitution of  $\text{La}^{3+}$  ions by  $\text{Nd}^{3+}$  ions. A solid solution with  $0.02 < x < 0.05$  possesses the largest intensity of the PL bands in IR wavelength range of 850–950, 1040–1100, and 1350–1370 nm. It is found that replacing 0.5% of  $\text{In}^{3+}$  ions in a solid solution of  $\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$  by  $\text{Cr}^{3+}$  ions leads to a substantial increase in the intensity of all the PL bands by exciting with light of the wavelength of  $\lambda_{\text{exc}} = 490$  nm and a decrease in the intensity of all the PL bands by an excitation with light of the wavelengths of  $\lambda_{\text{exc}} = 358, 532, \text{ and } 585$  nm.

**Keywords:** solid solutions, lanthanum indate, X-ray phase analysis, luminescence excitation spectra, photoluminescence spectra

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## INTRODUCTION

In the past decade, interest in investigations into the luminescence excitation spectra and the PL of solid solutions based on  $\text{LaInO}_3$  with a crystalline structure of orthorhombically distorted perovskite doped with ions of the rare earth elements  $\text{Pr}^{3+}$ ,  $\text{Sm}^{3+}$ ,  $\text{Eu}^{3+}$ , and  $\text{Tb}^{3+}$ , which radiate light in a visible region, has been substantially enhanced [1–5]. The PL properties of solid solutions based on  $\text{LaInO}_3$  doped with  $\text{Nd}^{3+}$  ions luminescing in an IR spectral region (1.06  $\mu\text{m}$ ) have been studied to a lesser degree [6, 7]. Active elements of the first solid-state lasers were prepared from  $\alpha\text{-Al}_2\text{O}_3$  doped with  $\text{Cr}^{3+}$  ions and from yttrium aluminates and gallates with a structure of garnet and perovskite doped with  $\text{Nd}^{3+}$  neodymium ions. In this respect, numerous works are devoted to investigations into the optical spectra of  $\text{Nd}^{3+}$  and  $\text{Cr}^{3+}$  ions in crystals and glass of various compounds [8–10]. The advantages and disadvantages of such active elements in solid-state lasers are given in [9]; the mechanisms of the concentration quenching effect are described there, including the process of cross-relax-

ation; and the scheme of the energy levels of  $\text{Nd}^{3+}$  ions and the transitions between them in a crystalline matrix of yttrium aluminium garnet  $\text{Y}_3\text{Al}_5\text{O}_{12}$  are discussed. The luminescence excitation and PL spectra of the  $\text{La}_{0.9}\text{Nd}_{0.1}\text{InO}_3$  solid solution, in which 10% of  $\text{La}^{3+}$  lanthanum ions are replaced by  $\text{Nd}^{3+}$  ions that is larger than the critical value ( $\approx 5\%$ ), above which the concentration quenching of the luminescence of  $\text{Nd}^{3+}$  ions is observed, are studied in [7]. The PL of  $\text{Cr}^{3+}$ – $\text{Eu}^{3+}$  ion pairs was observed in  $\text{EuAlO}_3$  and  $\text{Eu}_3\text{Ga}_5\text{O}_{12}$  crystals doped with  $\text{Cr}^{3+}$  ions [11]. The studies of the PL of  $\text{Cr}^{3+}$ – $\text{Tb}^{3+}$  ion pairs in  $\text{TbAlO}_3$  doped with  $\text{Cr}^{3+}$  ions are presented in [12]. It is noted in [7] that introducing 0.5% of  $\text{Cr}^{3+}$  ions into the  $\text{La}_{0.9}\text{Nd}_{0.1}\text{InO}_3$  solid solution leads to an increase of the PL of  $\text{Nd}^{3+}$  ions under a visible light excitation. However, a systematic study of the influence of  $\text{Cr}^{3+}$  ions on the PL of  $\text{Nd}^{3+}$  ions introduced into the crystalline lattice of  $\text{LaInO}_3$  is absent.

In this work we have first carried out the synthesis of solid solutions based on lanthanum indate with a perovskite structure  $\text{La}_{1-x}\text{Nd}_x\text{InO}_3$  using a solid-

**Table 1.** Parameters  $a$ ,  $b$ , and  $c$ , the volume  $V$  of the unit cell, and the degree of the orthorhombical distortion  $\varepsilon$  for solid solutions based on  $\text{LaInO}_3$  doped with  $\text{Nd}^{3+}$  and  $\text{Cr}^{3+}$  ions

Composition	Crystal lattice parameters					$c/\sqrt{2}$ , Å
	$a$ , Å	$b$ , Å	$c$ , Å	$V$ , Å <sup>3</sup>	$\varepsilon$ , $10^{-2}$	
$\text{La}_{0.993}\text{Nd}_{0.007}\text{InO}_3$	5.732	5.943	8.226	280.2	3.68	5.817
$\text{La}_{0.98}\text{Nd}_{0.02}\text{InO}_3$	5.736	5.944	8.229	280.6	3.63	5.819
$\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$	5.724	5.937	8.220	279.3	3.72	5.812
$\text{LaIn}_{0.99}\text{Cr}_{0.01}\text{O}_3$	5.725	5.937	8.225	279.5	3.70	5.816
$\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$	5.726	5.941	8.225	279.8	3.75	5.816
$\text{LaInO}_3$ [14]	5.712	5.933	8.220	278.5	3.87	5.812
$\text{NdInO}_3$ [14]	5.631	5.897	8.133	270.1	4.72	5.751

phase method with  $0.007 \leq x \leq 0.05$ , as well as  $\text{LaIn}_{0.99}\text{Cr}_{0.01}\text{O}_3$  and  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$ . Their excitation and PL spectra are obtained and analyzed in the wavelength region of 250–1450 nm.

## EXPERIMENTAL TECHNIQUE

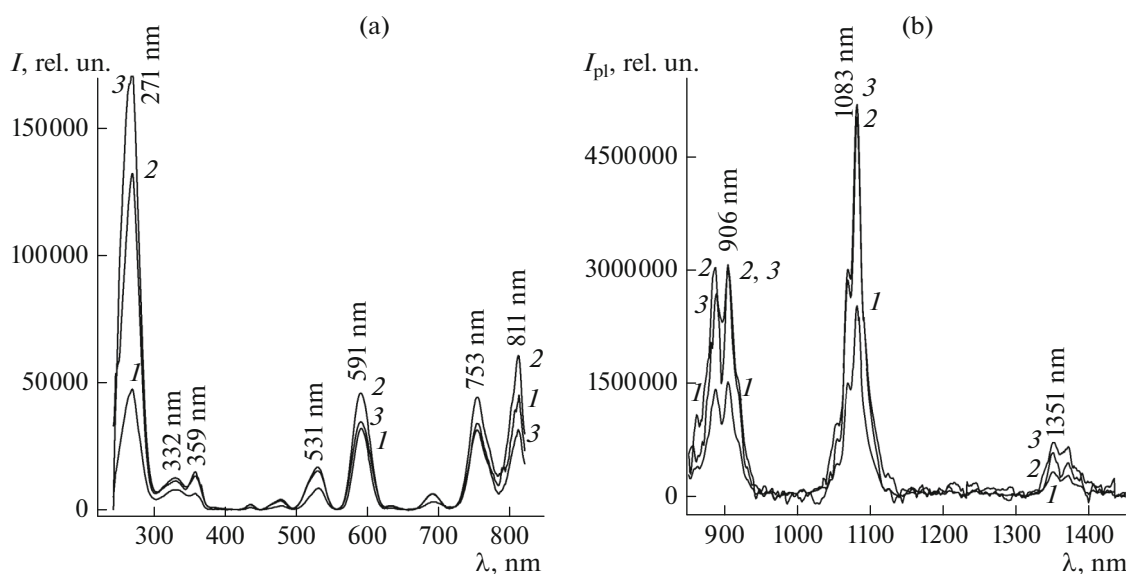
The synthesis of ceramic samples of  $\text{La}_{1-x}\text{Nd}_x\text{InO}_3$  ( $x = 0.007, 0.02, 0.05$ ),  $\text{LaIn}_{0.99}\text{Cr}_{0.01}\text{O}_3$ , and  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$  solid solutions was carried out by a solid-phase method from the  $\text{La}_2\text{O}_3$ ,  $\text{Nd}_2\text{O}_3$ ,  $\text{In}_2\text{O}_3$ , and  $\text{Cr}_2\text{O}_3$  oxides. All the reagents were of the reagent-grade qualification. The  $\text{La}_2\text{O}_3$  and  $\text{Nd}_2\text{O}_3$  were preliminarily baked in air at a temperature of 1273 K for 1 h. The initial oxides taken in a preset molar relationship were mixed and grinded in a Fritch Pulverizette planetary mill with the addition of ethanol in cups with zirconia balls. The resulting blend was pressed under the pressure of 50–75 MPa into tablets and baked in air at a temperature of 1523 K for 6 h on substrates from aluminum oxide. In order to exclude the interaction between the tablets and the substrate material, the samples were separated from the substrate by a thin layer of blend of the same composition as the tablets (the tablets did not contact each other). During the first baking, solid-phase reactions resulting in the formation of a solid solution were probably not completed. In order to accomplish them and to achieve a homogeneous distribution of the doping  $\text{Nd}^{3+}$  and  $\text{Cr}^{3+}$  ions over the resulting solid solution bulk, the tablets after the first baking were chipped, grinded again, and pressed into rods of 30 mm length and cross section of  $5 \times 5$  mm, which were baked at a temperature of 1523 K in air for 6 h. The resulting ceramic samples were used for studying the thermal expansion of the synthetic samples. Pieces of ( $\approx 5$ –7 mm) length were chipped off these rods and used for studying their luminescence and magnetic properties. The X-ray diffractograms of the samples were obtained on a Bruker D8 Advance diffractometer ( $\text{CuK}_\alpha$ -radiation) at room temperature. The parameters of the unit cell of the

crystal lattice were calculated using an RTP tabular processor for X-ray diffractometry. The measurements of the luminescence excitation and PL spectra were carried out at 300 K using an automatic SDL-2 spectrofluorimeter composed of an MDR-12 high-aperture excitation monochromator and an MDR-23 recording monochromator at the Institute of Physics of the National Academy of Sciences of Belarus. A DKsSh-120 xenon lamp was used as the excitation source.

## RESULTS AND DISCUSSION

An analysis of the X-ray diffractograms has shown that the resulting samples of  $\text{La}_{1-x}\text{Nd}_x\text{InO}_3$  ( $x = 0.007, 0.02, 0.05$ ),  $\text{LaIn}_{0.99}\text{Cr}_{0.01}\text{O}_3$ , and  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$  indates are single-phase. The parameters  $a$ ,  $b$ , and  $c$ , which were determined to an accuracy of  $\pm 0.001$  Å, correspond to the unit cell of the orthorhombically distorted perovskite structure of  $\text{GdFeO}_3$  type ( $a < c/\sqrt{2} < b$ ) [13] (Table 1). The single-phase of the resulting samples and the values of parameters  $a$ ,  $b$ , and  $c$  agree with the data of [14], in which it was shown that in the  $\text{LaInO}_3$ – $\text{NdInO}_3$  system a continuous series of  $\text{La}_{1-x}\text{Nd}_x\text{InO}_3$  solid solutions is formed with an orthorhombically distorted perovskite structure whose degree of distortion ( $\varepsilon = (b - a)/a$ ) gradually increases with an increase in the content of the  $\text{Nd}^{3+}$  ions in the solid solution from a value of  $3.87 \times 10^{-2}$  for  $\text{LaInO}_3$  to  $4.72 \times 10^{-2}$  for  $\text{NdInO}_3$ .

Figure 1a shows that for the studied  $\text{La}_{1-x}\text{Nd}_x\text{InO}_3$  ( $x = 0.007, 0.02, 0.05$ ) solid solutions the intensity of all the luminescence excitation bands at  $\lambda_{\text{mon}} = 1080$  nm depends on the content of the  $\text{Nd}^{3+}$  ions in them. The largest intensity with a maximum at  $\lambda = 271$  nm is observed for the solid solution with  $x = 0.05$  (Fig. 1a, curve 3). For the solid solution with  $x = 0.02$ , the largest intensity of the bands is observed at the wavelengths of 592, 753, and 812 nm (Fig. 1a, curve 2). The intensity of the excitation bands with maxima at



**Fig. 1.** Luminescence excitation spectra at  $\lambda_{\text{mon}} = 1080$  nm (a) and PL spectra at  $\lambda_{\text{exc}} = 358$  nm (b) of the  $\text{La}_{1-x}\text{Nd}_x\text{InO}_3$  solid solutions with  $x = 0.007$  (1); 0.02 (2), and 0.05 (3).

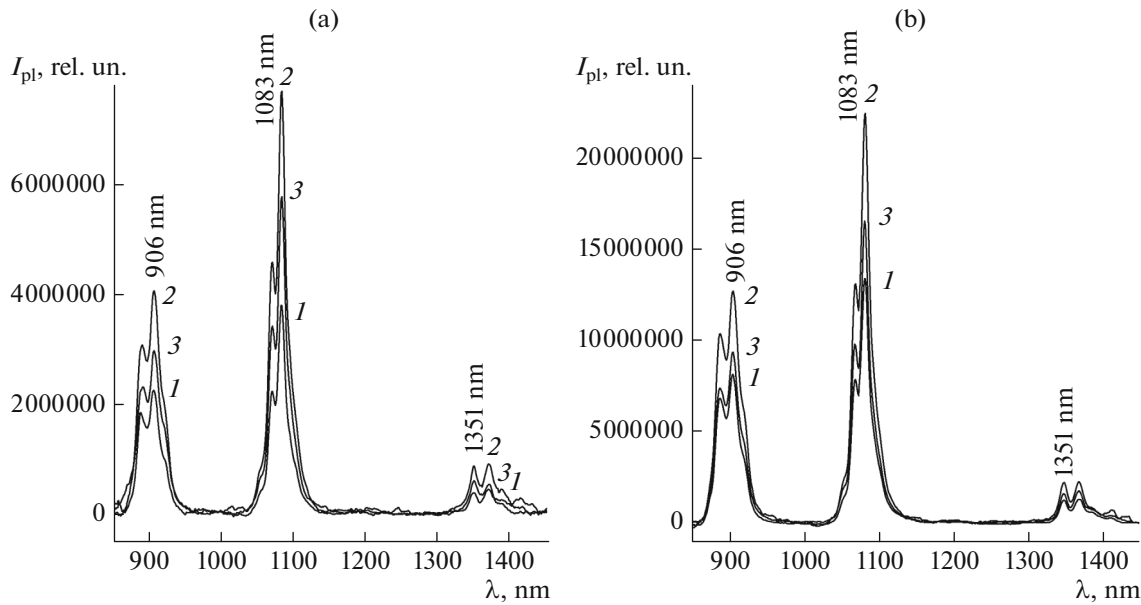
$\lambda = 332$  and  $359$  nm for  $\text{La}_{1-x}\text{Nd}_x\text{InO}_3$  solid solutions with  $x = 0.02$  and  $0.05$  is practically the same, while the intensity of these bands for the solid solution with  $x = 0.007$  is smaller than for those with  $x = 0.02$  and  $0.05$  (Fig. 1a).

The excitation bands of the resulting spectra for  $\text{La}_{1-x}\text{Nd}_x\text{InO}_3$  solid solutions (Fig. 1a) have a small width. The full width at half maximum (FWHM) of the excitation bands ( $\Delta\lambda$ ) amounts to 13–47 nm for a solid solution with  $x = 0.05$  (Table 2). The intensity of the PL bands of the spectra obtained at excitation wavelengths ( $\lambda_{\text{exc}}$ ) equal to 358 nm (Fig. 1b), 532 nm

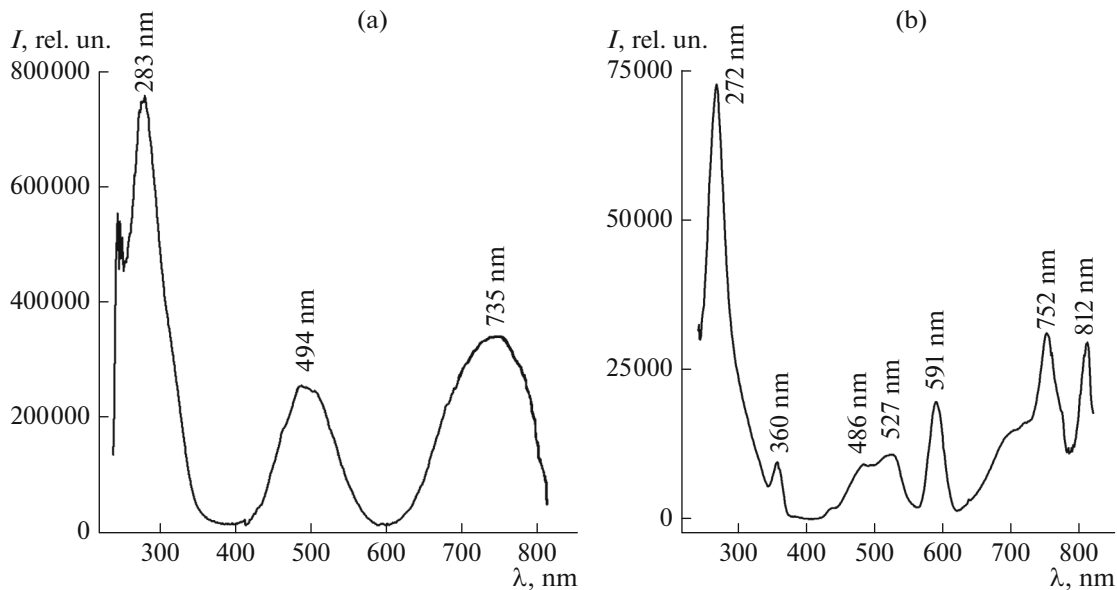
(Fig. 2a), and 585 nm (Fig. 2b), which corresponded to the maxima of the excitation bands (Fig. 1a), depends on the content of  $\text{Nd}^{3+}$  ions in  $\text{La}_{1-x}\text{Nd}_x\text{InO}_3$  indates. In this case, the intensity of all the PL bands for  $\text{La}_{1-x}\text{Nd}_x\text{InO}_3$  solid solutions with  $x = 0.02$  and  $0.05$  is substantially larger than for the solid solution with  $x = 0.007$ , while the intensity of the bands for  $\text{La}_{1-x}\text{Nd}_x\text{InO}_3$  solutions with  $x = 0.02$  and  $0.05$  differ insignificantly. In all the PL spectra ( $\lambda_{\text{exc}} = 358, 532,$  and  $585$  nm) two intense bands in the IR region of wavelengths of 850–950 nm and 1040–1100 nm are present; besides, a band of a small intensity in the

**Table 2.** Maxima of the wavelengths for the excitation bands ( $\lambda$ ), their reciprocal values ( $\nu$ ) for  $\text{La}_{1-x}\text{Nd}_x\text{InO}_3$  solid solutions with  $x = 0.02$  and  $0.05$ ,  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$  and  $\text{LaIn}_{0.99}\text{Cr}_{0.01}\text{O}_3$  solid solutions, and the FWHM values of the excitation bands ( $\Delta\lambda$ ) for  $\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$ ,  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$ , and  $\text{LaIn}_{0.99}\text{Cr}_{0.01}\text{O}_3$  solid solutions

$\lambda_{\text{mon}} = 1080$ nm					$\lambda_{\text{mon}} = 900$ nm					
$\text{La}_{0.98}\text{Nd}_{0.02}\text{InO}_3$		$\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$			$\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$			$\text{LaIn}_{0.99}\text{Cr}_{0.01}\text{O}_3$		
$\lambda$ , nm	$\nu$ , $\text{cm}^{-1}$	$\lambda$ , nm	$\nu$ , $\text{cm}^{-1}$	$\Delta\lambda$ , nm	$\lambda$ , nm	$\nu$ , $\text{cm}^{-1}$	$\Delta\lambda$ , nm	$\lambda$ , nm	$\nu$ , $\text{cm}^{-1}$	$\Delta\lambda$ , nm
272	36765	271	36900	29	272	36765	37	283	35 336	52
332	30120	332	30120	47	—	—	—	—	—	—
359	27855	359	27855	23	360	27778	19	—	—	—
436	22936	437	22883	13	440	22727	18	—	—	—
479	20877	479	20877	24	486	20576	53	494	20 243	79
531	18832	531	18832	29	527	18975	34	—	—	—
591	16920	591	16920	29	591	16920	26	—	—	—
691	14472	692	14451	26	705	14184	76	—	—	—
754	13263	753	13280	31	752	13298	40	735	13 605	128
811	12330	811	12330	26	812	12315	26	—	—	—



**Fig. 2.** PL spectra at  $\lambda_{\text{exc}} = 532$  nm (a) and  $\lambda_{\text{exc}} = 585$  nm (b) of the  $\text{La}_{1-x}\text{Nd}_x\text{InO}_3$  solid solutions with  $x = 0.007$  (1), 0.02 (2), and 0.05 (3).



**Fig. 3.** Luminescence excitation spectra of the  $\text{LaIn}_{0.99}\text{Cr}_{0.01}\text{O}_3$  solid solution at  $\lambda_{\text{mon}} = 900$  nm (a) and  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$  solid solution at  $\lambda_{\text{mon}} = 1080$  nm (b).

region of 1350–1370 nm is also observed. According to the data in the literature [9, 10, 15], these bands are caused by the transitions of  $f$  electrons of neodymium ions  $\text{Nd}^{3+}$  from an excited level  $^4F_{3/2}$  to lower levels  $^4I_{9/2}$ ,  $^4I_{11/2}$ , and  $^4I_{13/2}$ . The presence of two maxima in each PL band, which are located not more than 20 nm apart, is probably caused by the Stark splitting of  $^4I_{9/2}$ ,  $^4I_{11/2}$ , and  $^4I_{13/2}$  multiplets of the ground  $^4I$  term of the

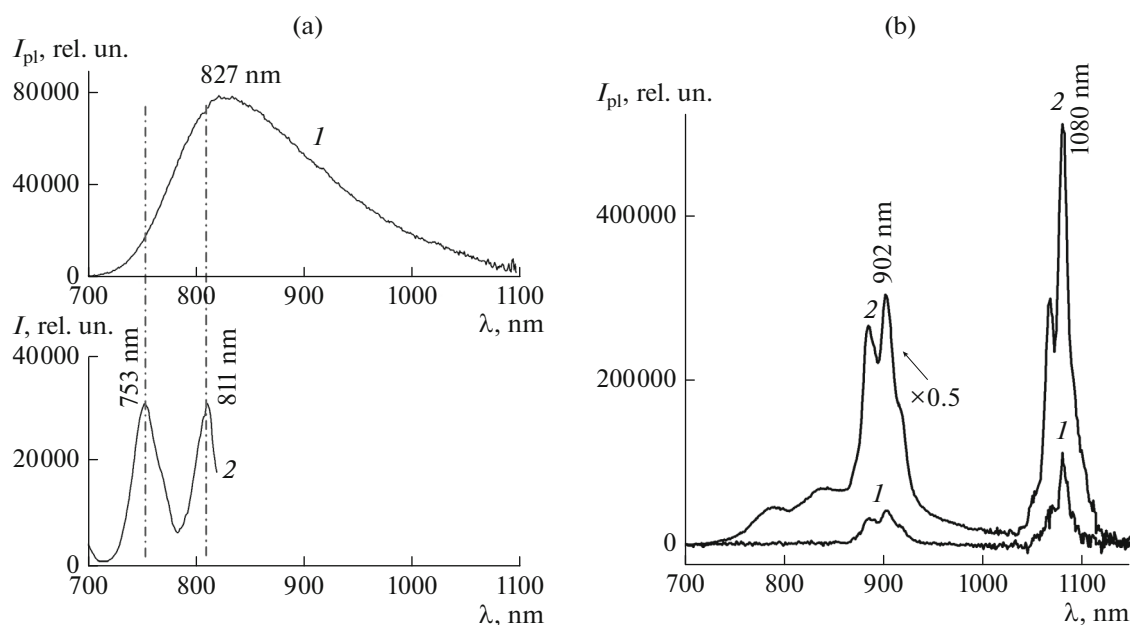
$\text{Nd}^{3+}$  ion by a crystalline field of a orthorhombically distorted perovskite structure of  $\text{La}_{1-x}\text{Nd}_x\text{InO}_3$  solid solutions with  $x = 0.007$ , 0.02, and 0.05. The values of the Stark splitting ( $\Delta\nu$ ) of the  $^4I$  term multiplets, which were calculated on the base of these pairs of closely located band maxima, are presented in Table 3. Their analysis shows that the Stark splitting of  $^4I_{9/2}$ ,  $^4I_{11/2}$ , and  $^4I_{13/2}$  multiplets is small (up to  $223\text{ cm}^{-1}$ ) and is

**Table 3.** Maxima of wavelengths for the PL bands ( $\lambda_{lum}$ ) and their reciprocal values ( $\nu_{lum}$ ), the Stark splitting of the terms by the crystalline field of the perovskite structure ( $\Delta\nu$ ), and  $f-f$  transitions causing radiation for solid solutions based on  $\text{LaInO}_3$  doped with  $\text{Nd}^{3+}$  and  $\text{Cr}^{3+}$  ions

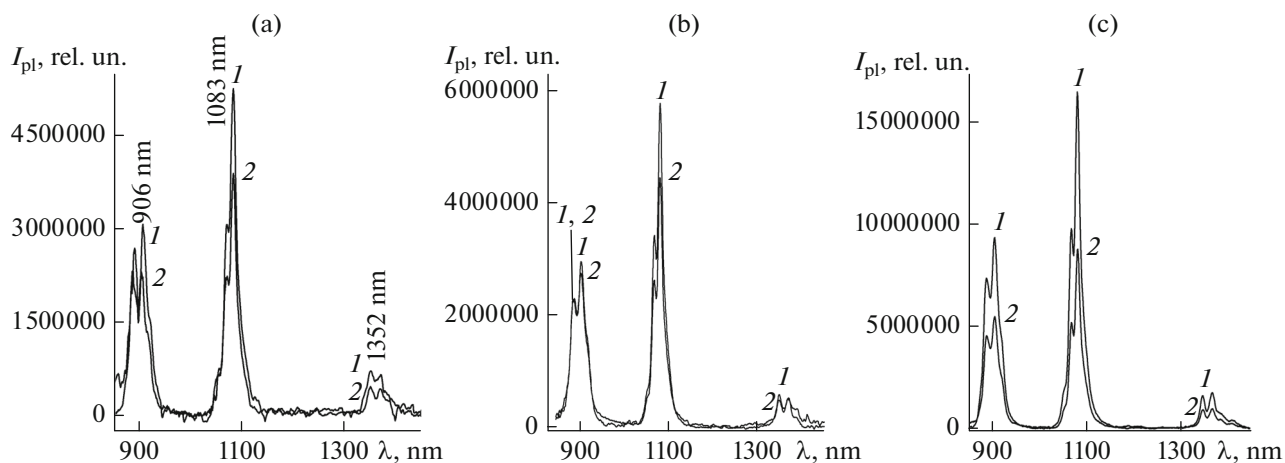
Composition	$\lambda_{exc} = 358 \text{ nm}$			$\lambda_{exc} = 532 \text{ nm}$			$\lambda_{exc} = 585 \text{ nm}$			$f-f$ transitions		
	$\lambda_{lum}$ , nm	$\nu_{lum}$ , $\text{cm}^{-1}$	$\Delta\nu$ , $\text{cm}^{-1}$	$\lambda_{lum}$ , nm	$\nu_{lum}$ , $\text{cm}^{-1}$	$\Delta\nu$ , $\text{cm}^{-1}$	$\lambda_{lum}$ , nm	$\nu_{lum}$ , $\text{cm}^{-1}$	$\Delta\nu$ , $\text{cm}^{-1}$			
$\text{La}_{0.98}\text{Nd}_{0.02}\text{InO}_3$	889	11248	210	890	11236	198	889	11248	210	${}^4F_{3/2} \rightarrow {}^4I_{9/2}$		
	906	11038		906	11038		906	11038				
	1070	9346	112	1070	9346	112	1070	9346	112		${}^4F_{3/2} \rightarrow {}^4I_{11/2}$	
	1083	9234		1083	9234		1083	9234				
	1351	7402	108	1349	7413	108	1349	7413	108			${}^4F_{3/2} \rightarrow {}^4I_{13/2}$
	1371	7294		1369	7305		1369	7305				
$\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$	890	11236	198	891	11223	185	888	11261	223	${}^4F_{3/2} \rightarrow {}^4I_{9/2}$		
	906	11038		906	11038		906	11038				
	1070	9346	112	1070	9346	112	1069	9355	113		${}^4F_{3/2} \rightarrow {}^4I_{11/2}$	
	1083	9234		1083	9234		1082	9242				
	1352	7396	102	1349	7413	114	1349	7413	108			${}^4F_{3/2} \rightarrow {}^4I_{13/2}$
	1371	7294		1370	7299		1369	7305				
$\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$	887	11274	236	891	11223	185	889	11249	211	${}^4F_{3/2} \rightarrow {}^4I_{9/2}$		
	906	11038		906	11038		906	11038				
	1071	9337	103	1070	9346	104	1069	9355	121		${}^4F_{3/2} \rightarrow {}^4I_{11/2}$	
	1083	9234		1082	9242		1083	9234				
	1352	7396	97	1349	7413	104	1349	7413	108			${}^4F_{3/2} \rightarrow {}^4I_{13/2}$
	1370	7299		1368	7309		1369	7305				

practically independent of the concentration of  $\text{Nd}^{3+}$  ions and wavelength of the exciting radiation. The largest splitting value is observed for  ${}^4I_{9/2}$  multiplet ( $\Delta\nu = 185\text{--}223 \text{ cm}^{-1}$ ), and the smallest value of  $\Delta\nu$  ( $102\text{--}114 \text{ cm}^{-1}$ ) is demonstrated by the  ${}^4I_{13/2}$  multiplet. The value of the Stark splitting for  ${}^4I_{11/2}$  multiplet insignificantly differs from the  $\Delta\nu$  value for the  ${}^4I_{13/2}$  multiplet. Figure 3a shows an excitation spectrum ( $\lambda_{mon} = 900 \text{ nm}$ ) for a  $\text{LaIn}_{0.99}\text{Cr}_{0.01}\text{O}_3$  solid solution, in which 1% of the  $\text{In}^{3+}$  ions are replaced by  $\text{Cr}^{3+}$  ions. Figure 3b shows an excitation spectrum ( $\lambda_{mon} = 1080 \text{ nm}$ ) for a  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$  solid solution, in which 0.5% of the  $\text{In}^{3+}$  ions are replaced by the  $\text{Cr}^{3+}$  ions. In the wavelength intervals of 240–360, 420–580, and 620–800 nm, the excitation spectrum of the  $\text{LaIn}_{0.99}\text{Cr}_{0.01}\text{O}_3$  solid solution (Fig. 3a) contains three intense bands whose FWHMs are 52, 79, and 128 nm, respectively (Table 2). A comparison of the excitation spectra for solid solutions  $\text{LaIn}_{0.99}\text{Cr}_{0.01}\text{O}_3$  (Fig. 3a),  $\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$  (Fig. 1a, curve 3), and  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$  (Fig. 3b) shows that the width of the excitation bands for of  $\text{LaIn}_{0.99}\text{Cr}_{0.01}\text{O}_3$

solid solution is substantially larger than for  $\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$  and  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$  solid solutions (Table 2). Besides, the number of bands in the excitation spectra for  $\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$  and  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$  solid solutions, which contain  $\text{Nd}^{3+}$  ions, is larger than for the spectrum of the  $\text{LaIn}_{0.99}\text{Cr}_{0.01}\text{O}_3$  solid solution, in which the neodymium ions are absent. In the excitation spectra of the  $\text{LaIn}_{0.99}\text{Cr}_{0.01}\text{O}_3$  solid solution in the wavelength intervals of 420–580 and 620–800 nm one broad band is observed (Fig. 3a). For solid solutions  $\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$  (Fig. 1a, curve 3) and  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$  (Fig. 3b) the presence of several bands in the wavelength intervals of 420–580 and 620–800 nm is characteristic. In this case, the bands of the  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$  solid solution (Fig. 3b) are more blurred than the bands of  $\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$  (Fig. 1a, curve 3), in which the  $\text{Cr}^{3+}$  ions are absent. This is associated with the fact that in the wavelength interval of 420–550 nm the bands of  $\text{Nd}^{3+}$  ions in the  $\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$  solid solution ( $\lambda_{max} = 479, 531 \text{ nm}$ ) and  $\text{Cr}^{3+}$  ions in the



**Fig. 4.** PL band of the  $\text{LaIn}_{0.99}\text{Cr}_{0.01}\text{O}_3$  solid solution at  $\lambda_{\text{exc}} = 445$  nm (1, a) and excitation band of the  $\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$  solid solution at  $\lambda_{\text{mon}} = 1080$  nm (2, a); PL spectra of the  $\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$  (1) and  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$  solid solutions (2) at  $\lambda_{\text{exc}} = 490$  nm (b).



**Fig. 5.** PL of the  $\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$  (1) and  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$  (2) solid solutions at  $\lambda_{\text{exc}} = 358$  (a), 532 (b), and 585 nm (c).

$\text{LaIn}_{0.99}\text{Cr}_{0.01}\text{O}_3$  solid solution ( $\lambda_{\text{max}} = 494$  nm) are partially overlapped, forming a broad band with two maxima at 486 and 527 nm (Fig. 3b, Table 2) in the excitation spectra of the  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$  solid solution. The PL spectrum of the  $\text{LaIn}_{0.99}\text{Cr}_{0.01}\text{O}_3$  solid solution (Fig. 4a, curve 1) in the wavelength interval of 700–1100 nm contains only one blurred PL band, with which the excitation band of the  $\text{Nd}^{3+}$  ions having two maxima at  $\lambda = 753$  and 811 nm in the  $\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$  solid solution (Fig. 4a, curve 2) is overlapped. Hence, for a pair of ions  $\text{Nd}^{3+}$  and  $\text{Cr}^{3+}$ , which are introduced into various cationic sublattices

of the crystal lattice of lanthanum indate  $\text{LaInO}_3$ , the basic condition of sensibilization with the  $\text{Cr}^{3+}$  ions of the PL of  $\text{Nd}^{3+}$  ions is fulfilled. According to this condition, the PL band of the sensitizer should overlap the band of activator absorption. In this respect, the specific number of  $\text{Cr}^{3+}$  ions introduced into the crystalline lattice of the  $\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$  solid solution can act as a sensitizer of the PL of the  $\text{Nd}^{3+}$  ions. It can be seen from Fig. 4b that an introduction of 0.5% of  $\text{Cr}^{3+}$  ions into a sublattice of  $\text{In}^{3+}$  ions of the  $\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$  solid solution leads to a substantial increase in the intensity of all the PL bands ( $\lambda_{\text{exc}} = 490$  nm)

of the  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$  solid solution (curve 2) compared to the  $\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$  solid solution (curve 1). This indicates that the energy absorbed by the  $\text{Cr}^{3+}$  ions by the excitation of the  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$  solid solution by a light of wavelength  $\lambda_{\text{exc}} = 490$  nm is transferred to the  $\text{Nd}^{3+}$  ions; i.e., the  $\text{Cr}^{3+}$  ions are the sensitizers of the PL of  $\text{Nd}^{3+}$  ions. When the  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$  solid solution is excited by a light with wavelengths smaller or greater than the wavelength of the maximum absorption of the  $\text{Cr}^{3+}$  ions (494 nm, Fig. 3a), the value of the energy absorbed by the  $\text{Cr}^{3+}$  ions decreases; hence, the efficiency of the energy transfer to the  $\text{Nd}^{3+}$  ions decreases. In this respect, as can be seen from Fig. 5, excitation by a light with wavelengths of  $\lambda_{\text{exc}}$  equal to 358 nm (a), 532 nm (b), and 585 nm (c) (curves 2) of the  $\text{La}_{0.95}\text{Nd}_{0.05}\text{In}_{0.995}\text{Cr}_{0.005}\text{O}_3$  solid solution leads to a decrease in the intensity of the PL bands located in the wavelength intervals of 1040–1100 and 1350–1370 nm compared to the intensity of the bands of the  $\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$  solid solution (curves 1). In this case, the intensity of the PL band in the wavelength interval of 850–950 nm also decreases, albeit, to a lesser degree.

## CONCLUSIONS

In all the PL spectra of the  $\text{La}_{1-x}\text{Nd}_x\text{InO}_3$  solid solutions ( $x = 0.007, 0.02, 0.05$ ) radiation bands in the IR region are present with wavelengths of 850–950, 1040–1100, and 1350–1370 nm. The presence of two closely located maxima in each PL band of  $\text{Nd}^{3+}$  ions made it possible to calculate the value of the Stark splitting of the  ${}^4I_{9/2}$ ,  ${}^4I_{11/2}$ , and  ${}^4I_{13/2}$  multiplets for the basic  ${}^4I$  term by the crystalline field of the orthorhombically distorted perovskite structure. The largest splitting value is observed for the  ${}^4I_{9/2}$  multiplet ( $\Delta\nu = 185\text{--}223\text{ cm}^{-1}$ ), while the smallest one ( $\Delta\nu = 102\text{--}114\text{ cm}^{-1}$ ) has the  ${}^4I_{13/2}$  multiplet. The intensity of the corresponding PL bands of the  $\text{La}_{1-x}\text{Nd}_x\text{InO}_3$  solid solution with  $x = 0.007$  is substantially smaller than that for solid solutions with  $x = 0.02$  and  $0.05$  whose intensity differs insignificantly. It is found that the replacement of 0.5% of the  $\text{In}^{3+}$  ions in the  $\text{La}_{0.95}\text{Nd}_{0.05}\text{InO}_3$  by  $\text{Cr}^{3+}$  ions leads to a substantial increase in the intensity of all the PL bands under the excitation by a light with the wavelength of  $\lambda_{\text{exc}} = 490$  nm, while under the excitation by a light with the wavelengths of 358, 532, and 585 nm, the intensities of the PL bands decrease, and the decrease is larger the larger the difference of the excitation wavelength from the wavelength corresponding to the maximum of the absorption of the  $\text{Cr}^{3+}$  ions.

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