# Optical Spectroscopy of $Nd^{3+}$ Centres in the Glass with $3CaO\text{-}Ga_2O_3\text{-}3GeO_2$ Composition

B. Padlyak[1, 2], O. Vlokh[1], W. Ryba-Romanowski[3] and R. Lisiecki[3]

[1]Institute of Physical Optics, 23 Dragomanov St., 79005 Lviv, Ukraine
[2]Department of Physics, Kazimierz Wielki University of Bydgoszcz, 11 Weyssenhoff Sq., 85-072 Bydgoszcz, Poland, e-mail: fizbp@ukw.edu.pl
[3]Institute of Low Temperatures and Structure Research, Polish Academy of Sciences, 2 Okólna St., 50-422 Wrocław, Poland

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## Abstract

Optical absorption and luminescence spectra of Nd-doped glasses (0.2 and 1.0 wt. % of $Nd_2O_3$) with $3CaO\text{-}Ga_2O_3\text{-}3GeO_2$ (or $Ca_3Ga_2Ge_3O_{12}$ garnet) compositions are for the first time investigated in the temperature range of 4.2 ÷ 300 K. EPR and optical spectroscopies have shown that the neodymium impurity is incorporated into the glass network exclusively as $Nd^{3+}$ ions (the electron configuration $4f^3$ and the free-ion ground state $^4I_{9/2}$). All the transitions of $Nd^{3+}$ ions observed in the optical spectra are identified. The optical spectra of $Nd^{3+}$ are analyzed with the standard Judd–Ofelt theory. The oscillator strengths, the intensity parameters $\Omega_2$, $\Omega_4$ and $\Omega_6$, the radiative emission probabilities, branching ratios and the radiative lifetime for $Nd^{3+}$ ions in the glass with $3CaO\text{-}Ga_2O_3\text{-}3GeO_2$ composition are thus calculated. The luminescence kinetics of $Nd^{3+}$ centres for $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition at the room temperature could be satisfactorily described by exponential decay with the lifetimes 342 and 290 μs for the samples containing respectively 0.2 and 1.0 wt. % of $Nd_2O_3$. The incorporation peculiarities, spectroscopic parameters and the local structure of luminescence $Nd^{3+}$ centres in the glass with $3CaO\text{-}Ga_2O_3\text{-}3GeO_2$ composition are compared with those of the corresponding $Ca_3Ga_2Ge_3O_{12}$ garnet crystal.

**Keywords**: germanate glasses, $Nd^{3+}$ ion, optical absorption, emission, decay kinetics

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## 1. Introduction

Glasses and crystals doped with $Nd^{3+}$ ions are still attractive as active media for intense solid-state lasers. This fact gives rise to extensive spectroscopic studies of different $Nd^{3+}$-doped materials, especially neodymium laser glasses [1,2] and garnet crystals [3-6]. Traditional laser garnets such as YAG:$Nd^{3+}$ [3] and GSGG:$Cr^{3+}$, $Nd^{3+}$ [7] are characterized by good spectroscopic and lasing properties, though their synthesis is very difficult and expensive, since these crystals have too high melting temperatures (1960°C and 1850°C, respectively). Subsequent laser garnets such as $Ca_3(Nb,Ga)_2Ga_3O_{12}$:$Nd^{3+}$ [8], $Ca_3Ga_2G_3O_{12}$:$Nd^{3+}$ (CGGG:$Nd^{3+}$) [9,10] and $Ca_3Sc_2Ge_3O_{12}$:$Nd^{3+}$ (CaSGG:$Nd^{3+}$) [11] have been synthesized later on. These multi-cationic garnets are characterized by compositionally (or substitutionally) disordered structure and relatively low melting temperatures falling into 1450°C ÷ 1460°C region. So, structural disordering of $Ca_3(Nb,Ga)_2Ga_3O_{12}$ crystal is related to statistical filling by Nb and Ga atoms of the octahedral sites, thus leading to optical multi-sites of $Nd^{3+}$. At the same time, structural disordering of $Ca_3Sc_2Ge_3O_{12}$:$Nd^{3+}$ and $Ca_3Ga_2G_3O_{12}$:$Nd^{3+}$ crystals is caused by compensation redistribution of $Ga^{3+}$ and $Ge^{4+}$ cations at octahedral and tetrahedral sites of the garnet structure, occurring due to heterovalent $Nd^{3+} \rightarrow Ca^{2+}$ substitution. This compensation

redistribution yields in creating anti-site defects of the types of $Ga^{3+}_{(d)}$ ($Ga^{3+}$ in tetrahedral (d) sites) and $Ge^{4+}_{[a]}$ ($Ge^{4+}$ in octahedral [a] sites) [12,13] and forming several $Nd^{3+}$ centres in dodecahedral {c} sites with different local cationic environments.

Studies of various optical properties of $Nd^{3+}$ ions in disordered crystals, in particular resolution and reliable identification of non-equivalent luminescence centres with different local environment on the basis of spectroscopic methods, are essential for complete understanding of their laser properties, since the laser effect is possible when the $Nd^{3+}$ ions are located in specific sites [14,15]. One can notice that the $Nd^{3+}$-doped glasses, garnets and the other compositionally disordered crystals are also promising materials for the solid-state lasers with laser emitting diode (LED) pumping [1,16-20].

$Nd^{3+}$-doped compounds of $CaO$-$Ga_2O_3$-$GeO_2$ system, which can be obtained in both crystalline and glassy (or vitreous) states, also represent promising materials for the LED-pumped lasers. Three stable crystalline forms exist in the ternary oxide $CaO$-$Ga_2O_3$-$GeO_2$ system: $Ca_3Ga_2Ge_3O_{12}$ (ordered garnet structure, the space group *Ia3d*), $Ca_3Ga_2Ge_4O_{14}$ (compositionally-disordered Ca-gallogermanate structure, the space group *P321*) and $Ca_2Ga_2GeO_7$ (gelenite structure, the space group $P\bar{4}2_1m$) [21,22]. There are also the corresponding glassy (or vitreous) forms with stoichiometric compositions similar to those of the crystals [23].

The optical, luminescence and laser properties of CGGG:$Nd^{3+}$ garnet crystals have been described in detail in the works [9,10,24-26]. The Stark energy levels of $Nd^{3+}$ in the CGGG crystal have been identified in the assumption of local symmetry $D_2$ and some relevant spectroscopic parameters for the laser applications (the radiative lifetime, branching ratios and the quantum efficiency for emitting $^4F_{3/2}$ level) have been estimated in [24], using the Judd-Ofelt theory. The six non-equivalent $Nd^{3+}$ centres in dodecahedral {c} sites of the CGGG:$Nd^{3+}$ garnet have been observed with the laser-excited site-selective spectroscopy [25]. Furthermore, the authors [25] have discussed the nature and local structure of the observed non-equivalent $Nd^{3+}$ centres in terms of possible charge compensating defects and have suggested formation of $Nd^{3+}$-$Nd^{3+}$ pairs. The structural peculiarities of compositionally disordered $Nd^{3+}$-doped $Ca_3Ga_2Ge_4O_{14}$ and $Sr_3Ga_2Ge_4O_{14}$ crystals have been considered in the study [27]. Besides, the absorption and luminescence characteristics and the stimulated emission parameters of $Nd^{3+}$ ions in $Ca_3Ga_2Ge_4O_{14}$ and $Sr_3Ga_2Ge_4O_{14}$ crystals have been investigated, the luminescence intensity parameters of $Nd^{3+}$ centres have been analyzed and the cross-sections of the induced transitions at the wavelengths of lasing channels $^4F_{3/2} \rightarrow {}^4I_{11/2}$ and $^4F_{3/2} \rightarrow {}^4I_{13/2}$ have been determined.

At the present time, the glasses with $Ca_3Ga_2Ge_3O_{12}$ (or $3CaO$-$Ga_2O_3$-$3GeO_2$) garnet compositions doped with Nd have been successfully obtained. Some preliminary results for the optical spectroscopy of $Nd^{3+}$ centres in the glass with the garnet composition $Ca_3Ga_2Ge_3O_{12}$ have been reported in [28]. In this paper we present and analyze the optical spectra and the luminescence kinetics of impurity $Nd^{3+}$ centres in the glass characterized with $3CaO$-$Ga_2O_3$-$3GeO_2$ composition. The obtained optical spectra, decay kinetics and the laser parameters of $Nd^{3+}$ centres in the glass with the garnet composition are also compared with the corresponding data obtained for the laser garnet $Ca_3Ga_2Ge_3O_{12}$.

## 2. Experimental details

### 2.1. Characteristics of samples under investigation

Nd-doped glasses of high chemical purity and optical quality with $3CaO$-$Ga_2O_3$-$3GeO_2$ composition were obtained in corundum crucibles with the aid of high-temperature

synthesis performed according to [23]. The Nd impurity was added to the glass as $Nd_2O_3$ oxide in the amounts of 0.2 and 1.0 wt. %. The colour of thus obtained Nd-doped glasses varied, depending on the Nd content, from almost uncoloured ($Nd_2O_3$ content 0.2 wt. %) to lightly blue (the content 1.0 wt. %). Chemical composition of the samples was controlled by X-ray microanalysis technique, using "Camebax" apparatus. Samples for the optical measurements were polished to the approximate size of $6\times3\times2$ $mm^3$. Samples for the electron paramagnetic resonance (EPR) studies were cut to the approximate size of $4\times2\times2$ $mm^3$.

The synthesized Nd-doped glasses with $3CaO\text{-}Ga_2O_3\text{-}3GeO_2$ composition show typical glassy-like X-ray structure factor, which is quite similar to that of undoped glass of the same composition [29]. Structural investigations of the undoped and rare-earth doped glasses with $3CaO\text{-}Ga_2O_3\text{-}3GeO_2$ composition based on EXAFS (Extended X-ray Absorption Fine Structure) technique show that incorporation of $Nd^{3+}$ and the other rare-earth ions changes the local structure only around Ga atoms (i.e., the short-range order of Ga), whereas the short-range order of Ge is almost independent of rare-earth doping and remains similar to that characteristic for the undoped glass of the same composition [30,31]. Preliminary results of EXAFS studies for the local environment (the coordination to oxygen) for $Nd^{3+}$ and the other rare-earth impurity ions have been reported in [32] and the analysis of the obtained EXAFS spectra is now in progress.

### 2.2. Experimental methods and equipment

The X-band EPR spectra of Nd-doped glasses were detected at liquid-helium temperatures, using commercial RADIOPAN SE/X-2544 (Poznań, Poland) radio frequency spectrometer with 100 kHz magnetic field modulation.

The optical absorption spectra were measured at both the room and liquid-nitrogen temperatures on Carl Zeiss Jena (Specord M-40 model) spectrophotometer. The photoluminescence spectra were obtained in the temperature range 4.2 ÷ 300 K with the equipment built at the Institute of Low Temperatures and Structure Research of the Polish Academy of Sciences (Wrocław, Poland). The luminescence spectra were excited with ionic Ar laser operating at $\lambda$ = 514.5 nm. They were recorded at the room temperature with a scanning monochromator Dongwoo (DM 711 model), which had 750 mm focal length and was equipped with InGaAs detector. Finally, low-temperature emission spectra were obtained with 1 m double grating monochromator and detected using a photomultiplier with S-1 spectral response.

Luminescence decay curves were recorded with a digital oscilloscope Tektronix (TDS 3052 model). The excitation was provided by a Continuum Surelite I Optical Parametric Oscillator (OPO) pumped by a third harmonic of YAG:$Nd^{3+}$ laser ($\lambda$ = 355 nm). The samples for low-temperature measurements were mounted into a continuous-flow liquid-helium cryostat Oxford (CF 2104 model) equipped with a temperature controller.

## 3. Experimental results and discussion

### 3.1. Optical absorption and luminescence spectra

The impurity of Nd in the oxide crystals and glasses could manifest itself as $Nd^{3+}$ ($4f^3$, $^4I_{9/2}$) or $Nd^{2+}$ ($4f^4$, $^5I_4$) ions, with different characteristic EPR and optical spectra. Only the EPR spectrum of $Nd^{3+}$ was observed at liquid-helium temperatures in the Nd-doped glass with $3CaO\text{-}Ga_2O_3\text{-}3GeO_2$ composition. This result certifies that the Nd impurity is incorporated into the glass network of $CaO\text{-}Ga_2O_3\text{-}GeO_2$ as $Nd^{3+}$ ions.

The undoped glasses of $CaO\text{-}Ga_2O_3\text{-}GeO_2$ system are transparent in the UV region down to 280÷300 nm and are characterized by high transparency in the IR spectral range (see also [23]). At the room and liquid-nitrogen

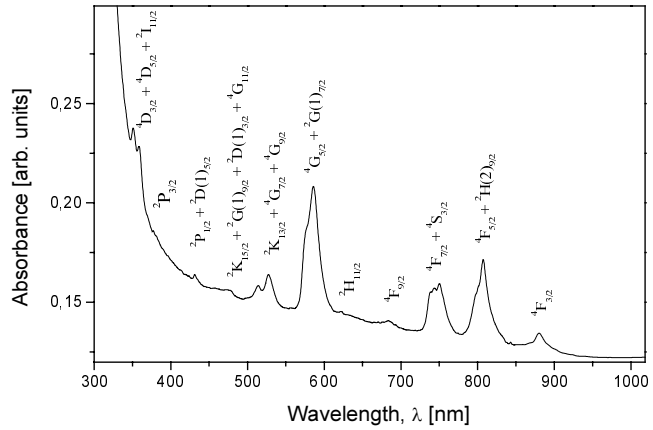


**Fig. 1.** Optical absorption spectra recorded at T = 293 K for $Nd^{3+}$ centres in the glasses with $Ca_3Ga_2Ge_3O_{12}$:Nd composition containing 1.0 wt. % of $Nd_2O_3$.

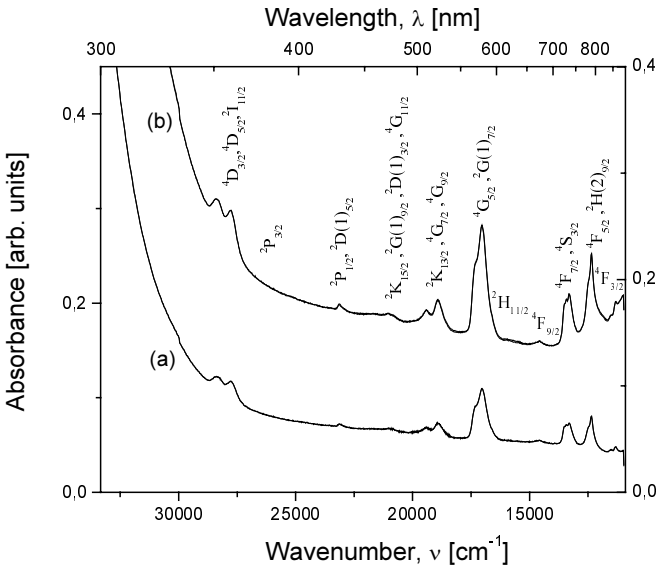


**Fig. 2.** Optical absorption spectra recorded at T = 293 K (a) and T = 85 K (b) for $Nd^{3+}$ centres in the glasses with $Ca_3Ga_2Ge_3O_{12}$:Nd composition containing 0.2 wt. % of $Nd_2O_3$.

temperatures, the optical absorption spectrum of Nd-doped glasses with $3CaO\text{-}Ga_2O_3\text{-}3GeO_2$ composition in the region of 340 ÷ 1000 nm (10000 ÷ 30000 $cm^{-1}$) consists of a number of absorption bands with weakly resolved structures (see Fig. 1 and 2). The observed absorption spectrum belongs to $Nd^{3+}$ ions. The linewidth and the resolution of the absorption bands of $Nd^{3+}$ at the room and liquid-nitrogen temperatures are quite similar (cf. the spectra a and b in Fig. 2), thus evidencing inhomogeneous broadening associated with disordering of the glass structure. As a consequence, some of the observed complex and weakly resolved $Nd^{3+}$ bands can be assigned only to groups of absorption transitions, as shown in Fig. 1 and 2. In accordance with the energy level diagram for $Nd^{3+}$ and the literature data [33,34], all of the observed absorption bands (Fig. 1 and 2) have been assigned to appropriate electronic $f - f$ transitions from the ground $^4I_{9/2}$ state to the following terms of the excited states: ($^4D_{3/2}$, $^4D_{5/2}$, $^2I_{11/2}$), $^2P_{3/2}$, ($^2P_{1/2}$, $^2D(1)_{5/2}$), ($^2K_{15/2}$, $^2G(1)_{9/2}$, $^2D(1)_{3/2}$, $^4G_{11/2}$), ($^2K_{13/2}$, $^4G_{7/2}$, $^4G_{9/2}$), ($^4G_{5/2}$, $^2G(1)_{7/2}$), $^4H_{11/2}$, $^4F_{9/2}$, ($^4F_{7/2}$, $^4S_{3/2}$), ($^4F_{5/2}$, $^2H(2)_{9/2}$) and $^4F_{3/2}$ (see Fig. 1 and 2). None band characteristic for $Nd^{2+}$ ions has been observed in the optical absorption spectra. This again testifies that the Nd impurity is incorporated into the $3CaO\text{-}Ga_2O_3\text{-}3GeO_2$ glass network exclusively as $Nd^{3+}$ ions.

Several weakly resolved or unresolved bands are observed at room temperature in the luminescence excitation spectrum of $Nd^{3+}$ ions for the glass with $3CaO\text{-}Ga_2O_3\text{-}3GeO_2$ composition (see Fig. 3). These bands show a good cor-

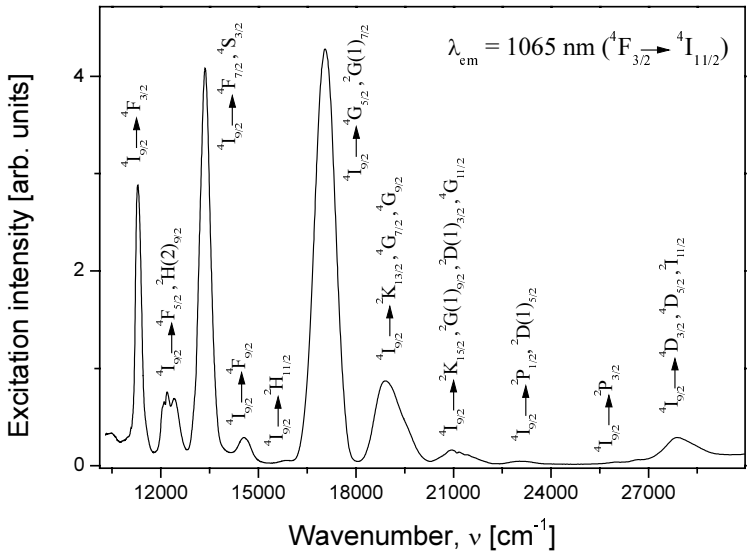


**Fig. 3.** Luminescence excitation spectra recorded at T = 293 K for $Nd^{3+}$ centres in the glass with $Ca_3Ga_2Ge_3O_{12}$:Nd composition containing 1.0 wt. % of $Nd_2O_3$.

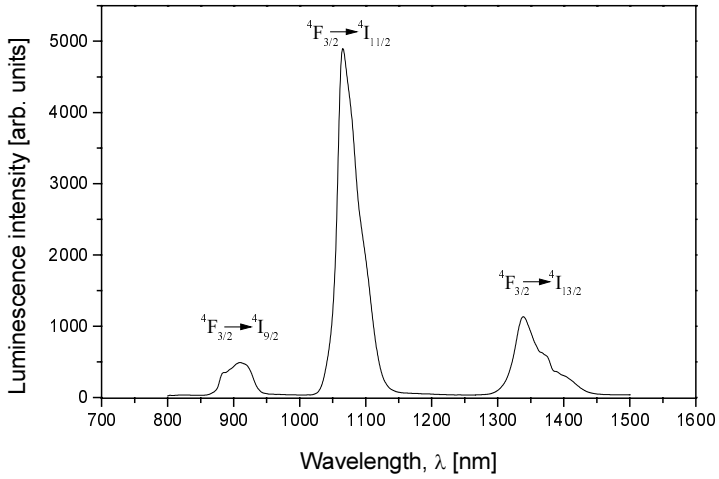


**Fig. 4.** Luminescence spectrum of $Nd^{3+}$ centres in the glass with $Ca_3Ga_2Ge_3O_{12}$:Nd composition containing 1.0 wt. % of $Nd_2O_3$ recorded at T = 293 K under the excitation with Ar laser.

relation with the optical absorption transitions (see Fig. 1 and 2).

The emission spectrum of $Nd^{3+}$ has been measured at the room temperature in the spectral region of 800 ÷ 1500 nm, using the excitation into the absorption band corresponds to $^4I_{9/2} \rightarrow (^2K_{13/2}, {}^4G_{7/2}, {}^4G_{9/2})$ transitions (see Figs. 1-3). performed with Ar laser ($\lambda_{exc}$ = 514.5 nm). The observed luminescence spectrum of $Nd^{3+}$ ions consists of three well-known characteristic bands that correspond to the following transitions: $^4F_{3/2} \rightarrow {}^4I_{9/2}$ ($\lambda_{max}$ = 910 nm), $^4F_{3/2} \rightarrow {}^4I_{11/2}$ ($\lambda_{max}$ = 1065 nm) and $^4F_{3/2} \rightarrow {}^4I_{13/2}$ ($\lambda_{max}$ = 1339 nm) (see Fig. 4). No better resolution of $^4F_{3/2} \rightarrow {}^4I_{13/2}$ and $^4F_{3/2} \rightarrow {}^4I_{11/2}$ $Nd^{3+}$ emission bands is observed at the liquid-helium temperatures (Fig. 5). This also confirms inhomogeneous broadening of the spectral lines caused by disordering of the glass structure.

The optical absorption and luminescence spectra of $Nd^{3+}$ ions in the glasses of $CaO\text{-}Ga_2O_3\text{-}GeO_2$ system observed at 4.2 ÷ 300 K are almost independent of basic glass composition and temperature. They are quite similar to the optical spectra typical for the other $Nd^{3+}$-doped oxide glasses [35-37] and compositionally disordered crystals with the $Ca_3Ga_2Ge_4O_{14}$ composition [27].

One can notice that the intrinsic luminescence is not observed under the UV excitation of Nd-doped glass with the garnet composition for the case of 1.0 wt. % content of $Nd_2O_3$, whereas a broad intrinsic emission band

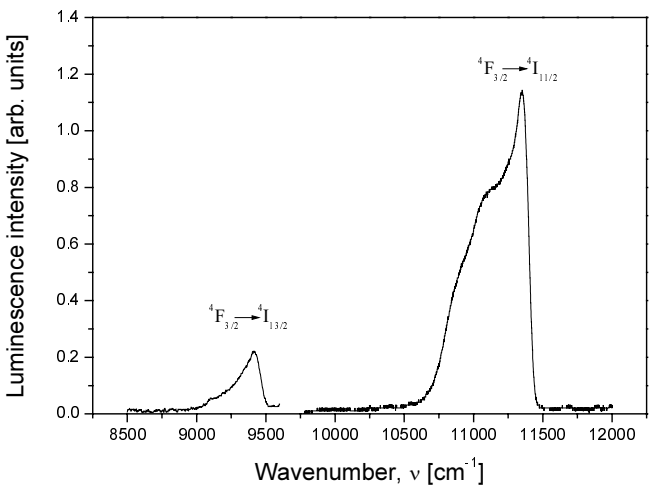


**Fig. 5.** Luminescence spectrum of $Nd^{3+}$ centres in the glass with $Ca_3Ga_2Ge_3O_{12}$:Nd composition containing 1.0 wt. % of $Nd_2O_3$ recorded at T = 10 K under the excitation with Ar laser.

characteristic for the undoped and weakly doped glasses of $CaO\text{-}Ga_2O_3\text{-}GeO_2$ system [38] is observed under the excitation at $\lambda_{exc} = 296$ nm in the glass doped with 0.2 wt. % of $Nd_2O_3$.

### 3.2. Luminescence kinetics and Judd-Ofelt analysis of $Nd^{3+}$ centres in glass

The luminescence decay curves for $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition of $Nd^{3+}$ centres in the glass with $3CaO\text{-}Ga_2O_3\text{-}3GeO_2$ composition obtained under the excitation with a third harmonic of YAG:$Nd^{3+}$ laser ($\lambda_{exc}$ = 355 nm) at the room temperature are presented in Fig. 6. The observed decay curves may be satisfactorily described using a single-exponential law, with the lifetimes $\tau$ = 342 and $\tau$ =290 μs obtained for the samples containing respectively 0.2 and 1.0 wt. % of $Nd_2O_3$. A lower lifetime value for the glass sample doped with 1.0 wt. % of $Nd_2O_3$, when compare with the corresponding parameter typical for the sample doped with 0.2 wt. % of $Nd_2O_3$, may evidence for the saturation effect.

The temperature dependences of the luminescence lifetime for $Nd^{3+}$ centres in the glass with $Ca_3Ga_2Ge_3O_{12}$ garnet composition are depicted in Fig. 7. Small increase in the $Nd^{3+}$ luminescence lifetime is observed with increasing temperature for the glass sample containing 0.2 wt.% of $Nd_2O_3$ (see Fig. 7a), whereas the lifetime for the sample doped with 1.0 wt. % of $Nd_2O_3$ practically does not change in the entire range (4.2 ÷ 300 K – see Fig. 7b).

The transition energies and the relative intensities of the absorption lines for $Nd^{3+}$ ions in the glasses with $3CaO\text{-}Ga_2O_3\text{-}3GeO_2$ composition are close to those measured for the other $Nd^{3+}$-doped oxide glasses [35-37] and so they could be analyzed on the basis of the *Judd-Ofelt* theory [39,40]. Using a standard program for the *Judd–Ofelt* calculations, the oscillator strengths and the intensity parameters ($\Omega_2$, $\Omega_4$ and $\Omega_6$) are obtained for $Nd^{3+}$ centres in the glass with the garnet composition (see Table 1).

For a comparison, we also present in Table 1 the oscillator strengths, which are calculated from the energies of experimental absorption transitions of $Nd^{3+}$ ions in the glass, together with the *Judd-Ofelt* intensity parameters ($\Omega_2$, $\Omega_4$ and $\Omega_6$) of $Nd^{3+}$ ions for the crystal with $Ca_3Ga_2Ge_3O_{12}$ garnet composition. As seen from Table 1, the differences between the theoretical ($f_{theor}$) and experimental ($f_{exp}$) oscillator strengths are negligible for all of the observed $Nd^{3+}$ absorption transitions in the glass with the garnet compositions. Besides, an essential difference takes place between the *Judd-Ofelt* intensity parameters for the glass and crystal with $Ca_3Ga_2Ge_3O_{12}$ garnet composition, especially for the case of $\Omega_2$ and $\Omega_6$ parameters.

Using the $\Omega_2$, $\Omega_4$ and $\Omega_6$ parameters obtained above, on the basis of standard relations [24] we have calculated the electro-dipole radiative emission probabilities $W_r$, the branching ratios ($\beta$) for $^4F_{3/2} \rightarrow {}^4I_{9/2}$, $^4F_{3/2} \rightarrow {}^4I_{11/2}$, $^4F_{3/2} \rightarrow {}^4I_{13/2}$ and $^4F_{3/2} \rightarrow {}^4I_{15/2}$ transitions and the radiative lifetime ($\tau_{rad}$) for $^4F_{3/2}$ level of

$Nd^{3+}$ ions in the glass with the garnet composition.

The spectroscopic parameters of $Nd^{3+}$ centres obtained for the glass with the garnet composition and relevant for the laser applications ($W_r$, $\beta$ and $\tau_{rad}$) are presented in Table 2, where the corresponding laser parameters of $Ca_3Ga_2Ge_3O_{12}$:$Nd^{3+}$ garnet crystal are also gathered for a comparison. One can see from Table 2 that the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ channel is characterized by the highest branching ratio and so it can be used for the laser generation.

## 4. Conclusions

On the basis of both the results and analysis presented in this work we conclude the following:

1. The neodymium impurity is incorporated into the $3CaO\text{-}Ga_2O_3\text{-}3GeO_2$ glass network exclusively as $Nd^{3+}$ ($4f^3$, $^4I_{9/2}$) ions, since no characteristic optical and EPR spectra of $Nd^{2+}$ ($4f^4$, $^4I_5$) ions have been detected.
2. The optical spectra of $Nd^{3+}$ ions in the glasses with $3CaO\text{-}Ga_2O_3\text{-}3GeO_2$ composition are quite similar to the spectra of $Nd^{3+}$ observed in the other oxide glasses and compositionally-disordered crystals. They are characterized by inhomogeneous broadening of spectral lines. The UV, visible and IR transitions of $Nd^{3+}$ ions observed in the optical absorption, emission and the luminescence excitation spectra are identified.
3. The luminescence kinetics of $Nd^{3+}$ centres for the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition observed at the room temperature is satisfactorily described in terms of exponential decay with

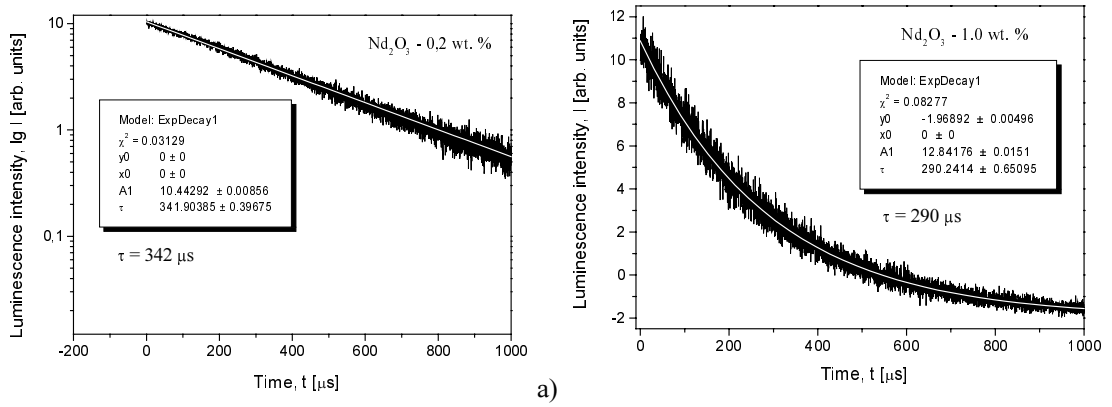


**Fig. 6.** Luminescence decay curves for $Nd^{3+}$ centres ($^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition, $\lambda_{max}$ = 1065 nm) recorded at T = 293 K in the glass with $Ca_3Ga_2Ge_3O_{12}$:Nd composition containing 0.2 wt. % (a) and 1.0 wt. % (b) of $Nd_2O_3$. Noisy curves correspond to the experiment and white lines to the results of single-exponential fit.

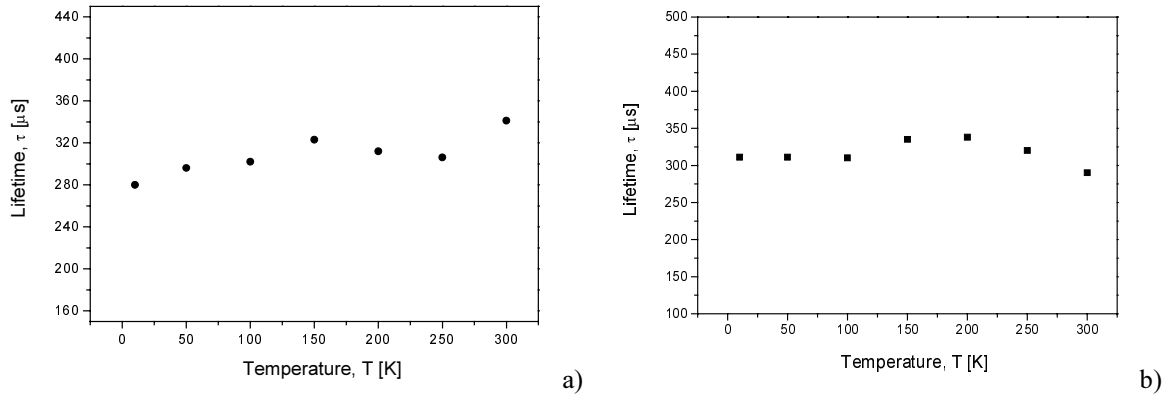


**Fig. 7.** Temperature dependences of luminescence lifetime obtained for $Nd^{3+}$ centres in the glass with $Ca_3Ga_2Ge_3O_{12}$:Nd composition containing 0.2 wt. % (a) and 1.0 wt. % (b) of $Nd_2O_3$.

Table 1. Results of the Judd-Ofelt analysis for $Nd^{3+}$ centres in the glass with $Ca_3Ga_2Ge_3O_{12}$:Nd garnet composition.

| Absorption transition $^4I_{9/2} \rightarrow$ | Energy, [$cm^{-1}$] | Experimental oscillator strength $f_{exp}$ | Theoretical oscillator strength $f_{theor}$ | The difference $\lvert f_{exp} - f_{theor} \rvert$ |
|---|---|---|---|---|
| $^4F_{3/2}$ | 11284 | $8.20 \times 10^{-7}$ | $9.32 \times 10^{-7}$ | $1.12 \times 10^{-7}$ |
| $^4F_{5/2} + {}^2H(2)_{9/2}$ | 12344 | $4.97 \times 10^{-6}$ | $4.70 \times 10^{-6}$ | $2.75 \times 10^{-7}$ |
| $^4F_{7/2} + {}^4S_{3/2}$ | 13387 | $4.06 \times 10^{-6}$ | $4.06 \times 10^{-6}$ | 0.00 |
| $^4F_{9/2}$ | 14625 | $4.06 \times 10^{-7}$ | $3.09 \times 10^{-7}$ | $0.97 \times 10^{-7}$ |
| $^4G_{5/2} + {}^2G(1)_{7/2}$ | 17164 | $1.58 \times 10^{-5}$ | $1.58 \times 10^{-5}$ | 0.00 |
| $^2K_{13/2} + {}^4G_{7/2} + {}^4G_{9/2}$ | 19252 | $4.22 \times 10^{-6}$ | $4.47 \times 10^{-6}$ | $2.47 \times 10^{-7}$ |
| $^2K_{15/2} + {}^2G(1)_{9/2} + {}^2D(1)_{3/2} + {}^4G_{11/2}$ | 21380 | $8.32 \times 10^{-7}$ | $9.62 \times 10^{-7}$ | $1.31 \times 10^{-7}$ |
| $^2P_{1/2} + {}^2D(1)_{5/2}$ | 23290 | $6.35 \times 10^{-7}$ | $5.93 \times 10^{-7}$ | $0.42 \times 10^{-7}$ |
| $^2P_{3/2}$ | 26203 | $2.76 \times 10^{-7}$ | $2.16 \times 10^{-7}$ | $0.60 \times 10^{-7}$ |
| $^4D_{3/2} + {}^4D_{5/2} + {}^2I_{11/2}$ | 28048 | $5.62 \times 10^{-6}$ | $5.62 \times 10^{-6}$ | 0.00 |
| Judd-Ofelt intensity parameter $\Omega$, [$cm^2$] | $\Omega_2 = 2.29 \times 10^{-20}$; $\Omega_4 = 2.98 \times 10^{-20}$; $\Omega_6 = 1.85 \times 10^{-20}$ ($\Omega_2 = 0.98 \times 10^{-20}$; $\Omega_4 = 3.96 \times 10^{-20}$; $\Omega_6 = 5.94 \times 10^{-20}$)* | | | |

* For a comparison, the calculated Judd-Ofelt intensity parameters for $Nd^{3+}$ centres in the laser crystal with $Ca_3Ga_2Ge_3O_{12}$ garnet composition [24] are given in parentheses.

the lifetimes 342 and 290 μs determined for the garnet-composition samples containing respectively 0.2 and 1.0 wt. % of $Nd_2O_3$.

4. The optical spectra of $Nd^{3+}$ are successfully analyzed and described in framework of the *Judd-Ofelt* theory. The oscillator strengths, the *Judd-Ofelt* intensity parameters ($\Omega_2$, $\Omega_4$ and $\Omega_6$), the radiative emission probabilities, branching ratios and the radiative lifetime for $Nd^{3+}$ centres are calculated for the glass with $3CaO\text{-}Ga_2O_3\text{-}3GeO_2$ composition.
5. The calculated spectroscopic and laser parameters are compared to the corresponding data obtained earlier for the laser garnet $Ca_3Ga_2Ge_3O_{12}$:$Nd^{3+}$. The analysis of the optical spectra shows that the glasses of $CaO\text{-}Ga_2O_3\text{-}GeO_2$ system activated with $Nd^{3+}$ ions are promising materials for the LED-pumped lasers that operate in the IR range (the emission wavelength $\lambda_{em}$ =1065 nm and the emission channel $F_{3/2} \rightarrow {}^4I_{11/2}$).
6. Basing on the presented results and the analysis of the referenced data, we could suggest that the coordination number (the first oxygen coordination sphere) of $Nd^{3+}$

Table 2. Calculated probabilities of spontaneous electro-dipole transitions ($W_r$), branching ratios ($\beta$) and radiative lifetime ($\tau_{rad}$) for the emission of $Nd^{3+}$ centres from $^4F_{3/2}$ level occurring in the glass with garnet $Ca_3Ga_2Ge_3O_{12}$ composition.

| Emission transition $^4F_{3/2} \rightarrow$ | Transition energy [$cm^{-1}$] | Parameter $W_r$ [$s^{-1}$] | Parameter $\beta$ |
|---|---|---|---|
| $^4I_{9/2}$ | 11284 | 721.16 (1904.88) | 0.3307 (0.3937) |
| $^4I_{11/2}$ | 9170 | 1242.62 (2400.71) | 0.5699 (0.4962) |
| $^4I_{13/2}$ | 7186 | 209.46 (508.10) | 0.0961 (0.1050) |
| $^4I_{15/2}$ | 5136 | 7.25 (24.18) | 0.0033 (0.0050) |
| | | $\sum W_r = 2180.49\ s^{-1}$<br>$\tau_{rad}$ ($^4F_{3/2}$) = 459 ms<br>($\tau_{rad}$ ($^4F_{3/2}$) = 206.7 ms) | |

In parentheses we give for comparison the calculated probabilities of spontaneous electro-dipole transitions ($W_r$), the branching ratios ($\beta$) and the radiative lifetime ($\tau_{rad}$) for the emission of $Nd^{3+}$ centres from $^4F_{3/2}$ level occurring in the laser crystal of garnet $Ca_3Ga_2Ge_3O_{12}$ composition [24].

luminescence centres in the glasses and crystals with the garnet $Ca_3Ga_2Ge_3O_{12}$ composition is the same and it equals to eight. However, the latter result needs further confirmation by means of the EXAFS spectroscopy.

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