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Luminescent and thermo-optical properties of Nd\textsuperscript{3+}-doped yttrium aluminoborate laser glasses

C. N. Santos,\textsuperscript{1,2,a} D. Mohr,\textsuperscript{3} W. F. Silva,\textsuperscript{4} A. S. S. de Camargo,\textsuperscript{1,3} H. Eckert,\textsuperscript{3} M. S. Li,\textsuperscript{1} M. V. D. Vermelho,\textsuperscript{4} A. C. Hernandes,\textsuperscript{1} A. Ibanez,\textsuperscript{2} and C. Jacinto\textsuperscript{4,b}

\textsuperscript{1}Instituto de Física de São Carlos, Universidade de São Paulo, CEP 13560-960, São Carlos, São Paulo, Brazil
\textsuperscript{2}Institut de Physique, Université de Lyon, Université jean Monnet, École Nationale Supérieure des Télécommunications de Lyon, CNRS, 46 avenue Charles de Gaulle, 69342 Lyon Cedex 07, France
\textsuperscript{3}Institut für Physikalische Chemie, Westfälische Wilhelms-Universität Münster, Corrensstrasse 30, D-48149 Münster, Germany
\textsuperscript{4}Instituto de Física de São Carlos, Universidade de São Paulo, CEP 13560-960, São Carlos, São Paulo, Brazil

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In this work we performed a thorough spectroscopic and thermo-optical investigation of yttrium aluminoborate glasses doped with neodymium ions. A set of samples, prepared by the conventional melt-quenching technique and with Nd\textsubscript{2}O\textsubscript{3} concentrations varying from 0.1 to 0.75 mol \%, were characterized by ground state absorption, photoluminescence, excited state lifetime measurements, and thermal lens technique. For the neodymium emission at 1064 nm (\textsuperscript{4}F\textsubscript{3/2} \rightarrow \textsuperscript{4}I\textsubscript{11/2} transition), no significant luminescence concentration quenching was observed and the experimental lifetime values ranged around 70 \(\mu\)s. The obtained values of thermal conductivity and diffusivity of approximately 10.3 \times 10^{-3} \text{W/cm K} and 4.0 \times 10^{-3} \text{cm}^2/s, respectively, are comparable to those of commercial laser glasses. Moreover, the fluorescence quantum efficiency of the glasses, calculated using the Judd–Ofelt formalism and luminescence decay, lies in the range from 0.28 to 0.32, larger than the typical values obtained for Nd\textsuperscript{3+} doped YAl\textsubscript{3}(BO\textsubscript{3})\textsubscript{4} crystals. © 2009 American Institute of Physics. [DOI: 10.1063/1.3176503]

I. INTRODUCTION

YAB\textsubscript{4} (YAB) is a nonlinear optical crystal with excellent chemical and physical properties.\textsuperscript{1,2} When doped with Nd\textsuperscript{3+} and/or Yb\textsuperscript{3+}, it becomes a promising system for infrared lasers,\textsuperscript{3,4} self-frequency doubling,\textsuperscript{4-6} or self-sum frequency mixing lasers.\textsuperscript{7-9} These potential applications are of great interest since nowadays systems with bifunctional laser materials can be efficiently pumped by low cost and high power diode lasers.\textsuperscript{5} Nevertheless, YAB is an incongruently melting solid and can only be grown using flux techniques. Therefore, its processing is very expensive and the crystals can only be obtained in small sizes. These unfavorable characteristics add to unsatisfactory homogeneity during growth process, restricting its practical applications.\textsuperscript{1,2,4} In order to overcome such difficulties, rare-earth doped yttrium aluminoborate glasses, in the ternary system Y\textsubscript{2}O\textsubscript{3}–Al\textsubscript{2}O\textsubscript{3}–B\textsubscript{2}O\textsubscript{3} (YAB), are good alternatives for obtaining low cost materials with good laser properties and easy shaping. Although the YAB crystal has been extensively investigated,\textsuperscript{1,4-6,8,9} the properties of the glassy counterpart have been much less explored. Chakraborty et al.\textsuperscript{10} were the first to obtain the ternary glass diagram. They found that YAB glasses melted between 1100 and 1550 °C cannot be formed when yttria or alumina concentrations are less than 10 mol \%, while compositions containing less than 65 mol \% boron oxide were outside the immiscibility gap and homogeneity. Homogeneous glasses containing up to 25 mol \% yttria and 35 mol \% alumina have been prepared between 1300 and 1570 °C by Rutz et al.\textsuperscript{11} More recently, Rocherullé and co-workers\textsuperscript{12,13} obtained transparent and homogeneous glasses for a boron oxide content in the range from 35 to 65 mol \% by melting the former oxides between 1600 and 1800 °C under nitrogen atmosphere. As a general feature, YAB glasses are nonhygroscopic and present high chemical stability due to the presence of aluminum glass forming ions.\textsuperscript{11,14}

Another important disadvantage of YAB crystals is the heat generation. For instance, Jaque et al.\textsuperscript{15} showed a decrease both in the emitted infrared laser power at 1.06 \(\mu\)m and in the second harmonic generation, relating this performance deterioration to heating effects.\textsuperscript{16,17}

In this work we have prepared and characterized neodymium-doped YAB glasses with boron oxide content of 60 mol \%, by the melt-quenching technique. This composition was chosen due to its lower melting temperature while maintaining high glass forming ability. The trend toward crystallization increases with the Y\textsubscript{2}O\textsubscript{3} content.\textsuperscript{11} Ground state absorption, photoluminescence, excited state lifetime measurements, and the thermal lens (TL) technique were used to evaluate the optical and thermo-optical properties of this very promising material.

II. EXPERIMENTAL PROCEDURE

Glass samples, with molar composition of \(x\text{Nd}_2\text{O}_3-(20-x)\text{Y}_2\text{O}_3-20\text{Al}_2\text{O}_3-60\text{B}_2\text{O}_3\), where 0 \(\leq x \leq 0.75\) mol \% (hereafter referred to as Nd\textsubscript{x}), were prepared by the conventional melt-quenching technique, as previously described.\textsuperscript{18} Differential thermal analysis measurements were done with a
Netzsch STA 409 analyzer. For the undoped glass composition (called YAlB20 hereafter), the glass transition and crystallization temperatures were determined as 711 and 812 °C, respectively, indicating that this glass presents good thermal stability against crystallization ($\Delta T_g-T_m=101$ °C). The density of the YAlB20 glass was measured using the Archimedes method. An average density $3.23 \pm 0.01$ g/cm$^3$ was obtained for a set of ten measurements. The refractive index (at 589.7 nm) was measured by the prism method, and the obtained value for the YAlB20 glass was 1.659. A Cary 17 UV-vis-NIR (Varian) spectrophotometer was used to measure ground state optical absorption spectra of the doped samples over the wavelength range from 250 to 950 nm. Room-temperature fluorescence spectra were recorded using a diode laser at 810 nm as the excitation source. The fluorescence signal was dispersed in a 64 cm single-grating monochromator with a resolution of 0.1 nm, amplified by a lock-in, and detected by either photodetectors (Si, Ge, and PbS) or a S-20 uncooled photomultiplier tube. The $^4F_{3/2}$ level lifetime values were obtained from the 1064 nm emission decay curves using a Ge detector with rise time of $<3$ µs, very similar to the cut-off time of modulation. The TL experiments were carried out using an Argon laser (514.5 nm) as excitation source and a HeNe laser (632.8 nm) as probe beam.

III. RESULTS AND DISCUSSION

A. Optical absorption and Judd–Ofelt (JO) analysis

The optical absorption coefficient spectra of three Nd$^{3+}$-doped glasses are presented in Fig. 1. The absorption bands are attributed to Nd$^{3+}$ transitions from the ground state $^4I_{9/2}$ to the various excited states numbered in the figure. The assignment of these bands is given in Table I. The Nd$^3+$ glasses present higher transparency in the UV region when compared to other borate glasses, with a maximum absorption edge at 240 nm (for Nd01). This result is consistent with that observed for rare-earth doped YAB crystals, whose absorption edges vary between $\sim 200$ and 300 nm, depending on the doping level. As the glass matrix lacks long range order, the Stark structure of the absorption transitions is poorly resolved due to an inhomogeneous broadening.

In order to evaluate the potential of a rare-earth doped material for laser applications, the radiative properties of the luminescent ion in the host matrix must be determined. These properties can be predicted from the optical absorption spectra, using the JO formalism. The JO theory can be successfully used to estimate the strength of the forced electric-dipole transitions of rare-earth ions. In this work, nine absorption bands were used for determination of the experimental oscillator strengths ($f_{\text{exp}}$), whose values are shown in Table I together with the values of calculated oscillator strengths ($f_{\text{calc}}$). The phenomenological intensity parameters $\Omega_2$, $\Omega_4$, and $\Omega_6$ are obtained by solving a system of equations in which $f_{\text{exp}}$ is equaled to $f_{\text{calc}}$. Their values are presented in Table II for the samples studied in this work and for a Nd$^{3+}$ doped YAl$_3$(BO$_3$)$_4$ (NYAB) crystal with comparable Nd concentration. Within errors of the JO calculations, the values are in good agreement between the glasses and the NYAB crystal.

B. Photoluminescence and excited state lifetimes

The photoluminescence spectra of Nd:YAlB glasses are presented in Fig. 2. The three main peaks centered at 895, 1059, and 1325 nm are assigned to the transitions $^4I_{9/2} \rightarrow ^4I_{11/2}$, $^4F_{3/2} \rightarrow ^4I_{11/2}$, and $^4F_{3/2} \rightarrow ^4I_{13/2}$, respectively. As it is expected for low doping levels, there are no observable changes in peak wavelengths and transitions line shapes. For

<table>
<thead>
<tr>
<th>Final excited state</th>
<th>$\bar{v}$ (cm$^{-1}$)</th>
<th>$f_{\text{exp}}$ (10$^{-6}$)</th>
<th>$f_{\text{calc}}$ (10$^{-6}$)</th>
<th>$f_{\text{cal}}$ (10$^{-6}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) $^4F_{3/2}$</td>
<td>11 441.65</td>
<td>3.1624</td>
<td>3.6268</td>
<td>2.0014</td>
</tr>
<tr>
<td>(2) $^4F_{5/2}$</td>
<td>12 468.83</td>
<td>7.5315</td>
<td>8.2038</td>
<td>8.5092</td>
</tr>
<tr>
<td>(3) $^4I_{11/2}$</td>
<td>13 513.51</td>
<td>7.5845</td>
<td>6.8928</td>
<td>8.4424</td>
</tr>
<tr>
<td>(4) $^4I_{13/2}$</td>
<td>14 727.54</td>
<td>0.1802</td>
<td>0.5950</td>
<td>1.3846</td>
</tr>
<tr>
<td>(5) $^4G_{5/2}$</td>
<td>17 211.70</td>
<td>20.696</td>
<td>20.644</td>
<td>20.652</td>
</tr>
<tr>
<td>(6) $^4G_{9/2}$</td>
<td>19 193.86</td>
<td>6.8721</td>
<td>7.3155</td>
<td>7.9942</td>
</tr>
<tr>
<td>(7) $^4G_{13/2}$</td>
<td>21 505.38</td>
<td>1.2957</td>
<td>1.7038</td>
<td>2.5576</td>
</tr>
<tr>
<td>(8) $^2D_{5/2}$</td>
<td>23 364.49</td>
<td>0.2210</td>
<td>1.0904</td>
<td>1.0111</td>
</tr>
<tr>
<td>(9) $^2D_{9/2}$</td>
<td>28 248.59</td>
<td>19.696</td>
<td>19.304</td>
<td>16.947</td>
</tr>
</tbody>
</table>

the main emission at 1059 nm, the effective bandwidth was calculated as \( \Delta \lambda_{\text{eff}} = \left( \frac{I(\lambda) \, d\lambda}{I(\lambda_{\text{peak}})} \right) \), where \( I(\lambda) \) is the emission intensity for the wavelength \( \lambda \) and \( I(\lambda_{\text{peak}}) \) is the intensity at the wavelength peak. The calculated \( \Delta \lambda_{\text{eff}} \), about 40 nm, are higher than those of commercial laser phosphate glasses such as Schott LG 770 (25.4 nm) and Kigre Q-88 (21.9 nm),\(^{26}\) which is an advantageous characteristic for broadband diode pumping. Heavy metal borate glasses containing PbO or Bi2O3 have been investigated for large bandwidth applications\(^1\),\(^2\) and are presented in Table III along with those reported for the NYAB crystal.\(^{32}\)

Concerning the photoluminescence spectra in Fig. 2, once the transitions energy and the \( \Omega _{4} \) intensity parameters are known, they can be used to evaluate the radiative transition rates \( A_{\text{rad}} \) and the branching ratios \( \beta_{\text{rad}} \). The results are presented in Table III along with those reported for the NYAB crystal.\(^{32,33}\)

The lifetime values of level \( ^{4}F_{5/2} \) were also determined experimentally from the first decay \( (e^{-1}) \) of the luminescence intensity \( I_{\text{lum}}(t) \) and, for comparison, as an effective lifetime \( \tau_{\text{eff}} = \frac{\int I_{\text{lum}}(t) \, dt}{I_{\text{lum}}(0)} \). No appreciable difference, within \( \pm 3\% \), was observed in values obtained through both methods. By using the radiative lifetime value \( \tau_{\text{rad}} \), calculated using \( A_{\text{rad}} \), and the experimental values \( \tau_{\text{exp}} \), the fluorescence quantum efficiency of the glasses was calculated according to \( \eta = \frac{\tau_{\text{exp}}}{\tau_{\text{rad}}} \). Table III summarizes the results for the doped glasses Nd035 and Nd075 and for the NYAB crystal.\(^{32}\) For samples doped with up to 0.35% a maximum \( \eta = 0.30 \) was obtained, with a slight decrease to 0.28, which is actually within experimental error, when the concentration is raised to 0.75%. These values are comparable to those of the stoichiometric NdAl3(BO3)4 crystal\(^{30,31}\) and \( \approx 40\% \) higher than that of the NYAB crystal (Table III).\(^{32,33}\) An overall analysis could seem that these values are too low when compared to those of other Nd3+-doped phosphate and silicate glasses and corresponding crystals. However, the reason for lower \( \eta \) values in borates lies in their intrinsic high maximum phonon energy \( (\sim 1350 \text{ cm}^{-1}) \), which favors multiphonon relaxations. Nevertheless, the higher \( \eta \) of the Nd:YAB glasses, as compared to the NYAB crystal, is an important factor in favoring the former for practical applications.

### C. Thermo-optical properties

As the heating effects are critical features of YAB crystals, we decided to use the TL technique to quantify the thermo-optical properties and heat generation of our glassy system. The TL effect is caused by the deposition of heat via nonradiative decay processes after absorption of excitation energy by the sample. In this situation, a transverse temperature gradient is established, producing a lenslike optical element, which is analyzed in terms of the temperature coefficient of the optical path length change \( (dL/dT) \). In the dual...

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**TABLE II.** Phenomenological JO intensity parameters for Nd\(_{x}\) glasses. The values corresponding to a NYAB crystal (Ref. 32) are included for comparison.

<table>
<thead>
<tr>
<th>Material</th>
<th>( \Omega _{4} ) ( (10^{-20} \text{ cm}^{2}) )</th>
<th>( \Omega _{4} ) ( (10^{-20} \text{ cm}^{2}) )</th>
<th>( \Omega _{6} ) ( (10^{-20} \text{ cm}^{2}) )</th>
<th>rms(_{\text{error}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd075</td>
<td>3.27</td>
<td>6.38</td>
<td>5.34</td>
<td>6.32%</td>
</tr>
<tr>
<td>Nd035</td>
<td>2.66</td>
<td>7.47</td>
<td>4.20</td>
<td>5.32%</td>
</tr>
<tr>
<td>Nd(^{3+}):YALB ( (1.1 \times 10^{21} \text{ Nd}^{3+} \text{ ions/cm}^{3}) )</td>
<td>3.09</td>
<td>5.04</td>
<td>3.11</td>
<td>0.5 ( \times 10^{-20} )</td>
</tr>
</tbody>
</table>

---

**FIG. 2.** Fluorescence spectra for Nd\(_{x}\) glasses for some Nd\(^{3+}\) concentrations. Inset presents the integrated area as a function of Nd\(^{3+}\) concentration.
TABLE III. Radiative transition rates, branching ratios, radiative and experimental lifetimes, and fluorescence quantum efficiency values for Nd\textsuperscript{x} glasses and NYAB crystal (Ref. 32).

<table>
<thead>
<tr>
<th>Material</th>
<th>Transition</th>
<th>(A(I\rightarrow J')) (s(^{-1}))</th>
<th>(\theta)</th>
<th>(\tau_{\text{rad}}) ((\mu)s)</th>
<th>(\tau_{\text{exp}}) ((\mu)s)</th>
<th>(\eta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd035 ((1.25 \times 10^{20} \text{ Nd}^{14} \text{ ions/cm}^{3}))</td>
<td>(^4F_{3/2} \rightarrow ^4I_{9/2})</td>
<td>12 038</td>
<td>0.49</td>
<td>242</td>
<td>75</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>(-^4I_{1/2})</td>
<td>1 789</td>
<td>0.43 &amp;</td>
<td></td>
<td>&amp;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(-^4I_{3/2})</td>
<td>272</td>
<td>0.07 &amp;</td>
<td></td>
<td>&amp;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(-^4I_{5/2})</td>
<td>16</td>
<td>0.01 &amp;</td>
<td></td>
<td>&amp;</td>
<td></td>
</tr>
<tr>
<td>Nd075 ((2.64 \times 10^{20} \text{ Nd}^{14} \text{ ions/cm}^{3}))</td>
<td>(^4F_{3/2} \rightarrow ^4I_{9/2})</td>
<td>1 848</td>
<td>0.44</td>
<td>238</td>
<td>67</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>(-^4I_{1/2})</td>
<td>1 989</td>
<td>0.47 &amp;</td>
<td></td>
<td>&amp;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(-^4I_{3/2})</td>
<td>358</td>
<td>0.08 &amp;</td>
<td></td>
<td>&amp;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(-^4I_{5/2})</td>
<td>20</td>
<td>0.01 &amp;</td>
<td></td>
<td>&amp;</td>
<td></td>
</tr>
<tr>
<td>Nd:YAl(_3)(BO(_4))(_x) ((1.1 \times 10^{20} \text{ Nd}^{14} \text{ ions/cm}^{3}))</td>
<td>(^4F_{3/2} \rightarrow ^4I_{9/2})</td>
<td>1 637</td>
<td>0.49</td>
<td>302</td>
<td>53</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>(-^4I_{1/2})</td>
<td>1 430</td>
<td>0.43 &amp;</td>
<td></td>
<td>&amp;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(-^4I_{3/2})</td>
<td>235</td>
<td>0.07 &amp;</td>
<td></td>
<td>&amp;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(-^4I_{5/2})</td>
<td>12</td>
<td>0.005 &amp;</td>
<td></td>
<td>&amp;</td>
<td></td>
</tr>
</tbody>
</table>

beam mode-mismatched TL configuration\(^{29,34}\) the propagation of a probe laser beam through this lenslike region results in a variation in its on-axis intensity, which can be calculated using diffraction integral theory.\(^{35}\)

The temporal evolution of the TL signal depends on the characteristic TL signal time \(t_c\), which is related to the thermal diffusivity \((D)\) by \(D = w_c^2/4t_c\), and this one relates to the thermal conductivity \((K)\) by \(K = \rho c D\), where \(\rho\) is the sample density and \(c\) is its specific heat. The TL transient signal amplitude \(\theta\) is approximately the phase difference of the probe beam at \(r = 0\) and \(r = \sqrt{2w_c}\) induced by TL, and it is given by

\[
\theta = -\frac{P_{\text{abs}}}{K\lambda p} \frac{ds}{dT},
\]

where \(\lambda_p\) is the probe beam wavelength, \(P_{\text{abs}}\) is the absorbed pump power, and \(\varphi\) is the fraction of absorbed energy converted into heat, which is also called absolute nonradiative quantum efficiency or fractional thermal loading. More details about the TL technique can be obtained in previous literatures.\(^{17,26,34}\) In the present work, it is interesting to redefine Eq. (1) as a normalized phase shift

\[
\Theta = -\frac{\theta}{P_{\text{abs}}} = B\varphi,
\]

where \(B = (K\lambda_p)^{-1}ds/dT\) is a constant that depends only on the host matrix characteristics and on the probe beam wavelength. This is an important factor that relates the ratio of \(ds/dT\) (desirable to be near zero for “athermal” systems) with \(K\) (desirable to be as large as possible to avoid thermal damages in the samples). Thus, it is desirable that \(B\) be close to zero.\(^{29,36}\)

Figure 3 shows a typical TL transient signal for the sample doped with 0.75%. The excitation and transmitted powers for this transient were 90 and 62 mW, respectively. The fitting of the experimental curve using the TL equation,\(^{29}\) which is represented as a solid line in Fig. 3, yields \(t_c\) and \(\theta\) parameters. These parameters were obtained as a function of the excitation power \(P_e\), as shown in Fig. 4, for all the studied samples. In agreement with Eq. (1), a linear dependence was observed without any sign of saturation or any deviation from this behavior, indicating the validity of the TL equation.\(^{29}\) From the linear fitting, the parameter \(\theta/P_e\) was calculated, and this result will be discussed later on. Table IV summarizes the values obtained for thermal properties \(\theta/P_e, \Theta, D,\) and \(K\). In order to obtain the thermal conductivity, the specific heats were approximated.

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**FIG. 3.** TL transient signal of the Nd075 glass with \(P_e = 90\) mW and \(\lambda_{\text{exc}} = 514.5\) nm. The solid line corresponds to the fit using the TL equation from which \(\theta = -(115.7 \pm 0.4) \times 10^{-3}\) rad and \(t_c = (1.03 \pm 0.01)\) ms were obtained.

**FIG. 4.** (Color online) TL phase shift \(\theta\) as a function of the excitation power \(P_e\) and Nd\textsuperscript{x} concentration for the Nd\textsuperscript{x} glasses.
from the Dulong–Petit relation. The $c=0.804$ J/g K value was found for all samples within 2% of accuracy. In fact, the values of $D$ and $K$ are very similar to those of various glasses, such as fluorides and silicates, and about twice as large as that of amorphous phosphates. As it can be seen in Table IV, the $D$ and $K$ values are the same for the undoped and Nd$^{3+}$ doped glasses, indicating the low Nd$^{3+}$ concentrations levels, i.e., the Nd$^{3+}$ ions act neither as network modifiers nor network formers, only as dopants/impurities.

For a more complete characterization of the samples, it is necessary to determine the nonradiative quantum efficiency ($\varphi$) and the $ds/dT$ coefficient. In this sense, it is important to note that a main common feature of Nd$^{3+}$ doped materials, independently of the excitation wavelength, is that all emission bands originate from the $^4F_{3/2}$ metastable state. In other words, the relationship between $\varphi$ [see Eq. (1)] and $\eta$ has a simple form, being given by $\varphi=1-\eta(\nu_{em})\nu_{exc}^{-1}$, where $(\nu_{em})$ and $\nu_{exc}$ are the average emission and excitation energies, respectively.

The TL technique is well known for its high sensitivity and accuracy with respect to the determination of $\eta$. Equation (2) allows $\eta$ to be obtained through $\Theta$ if $B$ and $(\nu_{em})$ are previously known. The parameter $(\nu_{em})$ can be easily determined from standard emission measurements, but the parameter $B$ is usually unknown. One way to overcome this drawback is to determine $B$ for an undoped sample, which usually presents negligible luminescence intensity. Under these conditions, $\eta=0$ and $\varphi=1$, so it can be used as reference. Then, by measuring the TL signal for doped ($\Theta_d$) and undoped ($\Theta_{und}$) samples, $\varphi_d$ and then $\eta_d$ are obtained through the relation $\Theta_d/\Theta_{und}=\varphi_d=1-\eta_d(\nu_{em})\nu_{exc}^{-1}$. As a matter of fact, it should be noted that undoped samples usually present very low optical absorption, so it is difficult to determine $P_{abs}$ accurately. In fact, this was the problem faced in the present study (note in Table IV the absence of $\Theta$ for the undoped YAI20 sample). Although there are other TL approaches to obtain $\eta$ and $B$ as multiwavelength and normalized lifetimes methods, for instance, in this work $\eta$ was obtained by means of the JO formalism and fluorescence decay measurements. Knowing $\eta$, the calculation of $\varphi$ is then straightforward as the absorbed pump power for doped samples is easily obtained from the incident and output powers. Thus, knowing $\varphi$ and $P_{abs}$, $B$ can be evaluated from Eq. (2), and thus $ds/dT$ is accessible as well. Table IV presents the $ds/dT$ values for all studied samples, which can be considered identical within the error margin, about 10%.

<table>
<thead>
<tr>
<th>Glass sample</th>
<th>$L$ (mm)</th>
<th>$-\theta/P_e$ (W$^{-1}$)</th>
<th>$\Theta=-\theta/P_{abs}$ (W$^{-1}$)</th>
<th>$D$ (10$^{-3}$ cm$^2$/s)</th>
<th>$K$ (10$^{-3}$ W/cm K)</th>
<th>$ds/dT$ (10$^{-6}$ K$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YAI20</td>
<td>3.0</td>
<td>1.84 x 10$^{-2}$</td>
<td>...</td>
<td>4.0 ± 0.3</td>
<td>10.3 ± 0.8</td>
<td>...</td>
</tr>
<tr>
<td>Nd01</td>
<td>2.0</td>
<td>2.45 x 10$^{-1}$</td>
<td>8.29</td>
<td>4.0 ± 0.1</td>
<td>10.3 ± 0.3</td>
<td>6.4</td>
</tr>
<tr>
<td>Nd02</td>
<td>2.0</td>
<td>4.90 x 10$^{-1}$</td>
<td>8.42</td>
<td>4.1 ± 0.1</td>
<td>10.6 ± 0.3</td>
<td>6.6</td>
</tr>
<tr>
<td>Nd035</td>
<td>2.0</td>
<td>8.40 x 10$^{-1}$</td>
<td>8.83</td>
<td>4.3 ± 0.2</td>
<td>11.1 ± 0.5</td>
<td>7.3</td>
</tr>
<tr>
<td>Nd050</td>
<td>2.0</td>
<td>1.23</td>
<td>8.94</td>
<td>4.1 ± 0.1</td>
<td>10.6 ± 0.3</td>
<td>7.0</td>
</tr>
<tr>
<td>Nd075</td>
<td>2.0</td>
<td>1.90</td>
<td>9.47</td>
<td>4.0 ± 0.3</td>
<td>10.3 ± 0.8</td>
<td>7.2</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td>4.1 ± 0.3</td>
<td>10.6 ± 0.8</td>
<td>6.9 ± 0.9</td>
</tr>
</tbody>
</table>

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