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Abstract—We have experimentally measured the energy stored and the heat generated in flashlamp-pumped Nd:YAG and six different commercially available Nd-doped phosphate glasses. We find that the normalized heating parameter \( \chi \), defined as the heat deposited per unit stored energy, is 1.5-2 times the value expected from the known spectroscopy of the Nd ions in these hosts and the emission spectrum of Xenon flashlamps. We discuss the heat sources in Nd-doped glasses. Using a theoretical model, we calculate the influence of Nd concentration, flashlamp pulse length, and current density on \( \chi \), and we point out the effects of \( \chi \) on practical laser designs.

Introduction

ADVANCED Nd laser applications which require increasingly higher average output power necessitate operating near the stress-fracture limit, i.e., a regime in which output power is limited by the possibility of material fracture arising from thermally induced stresses in the laser medium [1], [2]. It is essential, therefore, to quantify the heat load that the laser medium must accommodate. In a series of systematic experiments, we have found large variations in the heat generation accompanying flashlamp pumping of various types of Nd-doped phosphate glass and Nd:YAG. Since the heating of laser media severely limits their performance, this finding can have significant practical design consequences. In this context, the best way to evaluate a candidate material is to quantify its normalized heating parameter \( \chi \), which is defined as the heat generated per unit stored energy at 1 \( \mu \)m. This parameter is relatively independent of the particular pumping geometry used, and it applies to all laser designs utilizing flashlamp pumping.

Until now, it was implicitly assumed that \( \chi \) was the same for similar laser hosts. From the known Nd absorption spectrum and branching ratios and the Xenon flashlamp emission spectrum, \( \chi \) can be computed to be between 0.5 and 2, depending on the particular experimental conditions [2]. Only for one type of glass has the value of \( \chi \) been inferred from experimental measurements [3] to be 1.8; in this previous work, the amount of heat in an LHG-5 glass slab was deduced by comparing experimentally measured depolarization to the predictions of a thermal model for a zig-zag slab. In our experiments, where we have used nine different identically sized rods in the same laser head, we have experimentally measured both the stored energy and the heat deposited; we find that \( \chi \) can be larger than the theoretically calculated value by as much as a factor of 2, depending on the host material. These results point out that \( \chi \) should be included in defining a figure of merit for Nd laser materials; previous attempts at defining a practical figure of merit have emphasized only thermomechanical properties [1], [2]. Moreover, our results indicate that laser performance might be improved once the source of excess heating is identified and eliminated.

The following section describes the experiments and presents the results. Then we discuss the implication of these results, and we suggest possible sources of the excess heat in some glass types.

Experimental Approach

The determination of \( \chi \) requires the measurement of two parameters: the upper laser level stored energy, and the heat deposited in the laser medium during the optical pumping process. In the present study, the stored energy was calculated from small-signal gain measurements, while an interferometric calorimeter was used to determine the heat deposition by measuring the thermally induced optical path length changes of the laser rod under test. In addition to Nd:YAG, we tested a total of eight samples representing six different types of commercially available Nd-doped phosphate glass, including Q-88 and Q-98 from Kigre Inc., LHG-5 and LHG-8 from Hoya Optics, Inc., and LG-750 and LG-760 from Schott Glass Technologies, Inc. Six of the glass samples had 3 weight percent Nd doping, and two samples had 6 weight percent doping. All samples were 4.6 cm long and 0.43 cm in diameter with fine-ground barrels.

In order that meaningful comparisons could be made, we used the same flashlamp and pump cavity for all samples. The rod was pumped by a 0.3 cm bore, 3 cm arc length Xenon flashlamp. The cavity walls were coated with electrodeposited gold, and parts of the surface were covered with packed barium sulfate powder. The use of a
Xenon flashlamp with a Cerium-doped quartz envelope minimized the UV emission below 400 nm. A 0.7 mm thick samarium-doped glass tube around the rod further filtered out the UV since this glass had the same UV cutoff wavelength as the phosphate glasses used. Water could be passed between the rod and this tube to cool the rod; the water also filtered out IR wavelengths longer than 1.4 μm. A pulse-forming network (PFN) provided ~200 μs long flashlamp current pulses (measured at the 10 percent points), which are shorter than the fluorescence lifetime (285–350 μs) of the Nd: glass samples used.

Q-switched Nd: YLF and Nd: YAG lasers were employed as probes to measure the small-signal gain in the Nd: glass and Nd: YAG samples, respectively. The Nd: YLF laser operated at a wavelength of 1.054 μm, which matches the peak fluorescence wavelength of the Nd-doped phosphate glasses. Probe pulses were adjusted in time to coincide with the instant that the gain reached a maximum in the test rod. The probe fluence, even following amplification, was always less than two percent of the saturation fluence, thereby guaranteeing operation in the small-signal regime. Thus, the ratio of the output and input pulse energies accurately gave the small-signal gain \( G \). The energy stored in the rod \( E_{st} \) is obtained from \( G \) using the relation

\[
E_{st} = \frac{hν}{α} A \ln G = \frac{hν}{K} A \int_0^L N(z) \, dz
\]

where \( hν \) is the photon energy, \( α \) is the stimulated emission cross section of the particular sample, \( A \) is the rod cross-sectional area, \( L \) is the length of the rod, and \( N(z) \) is the inversion density at the position \( z \) along the rod axis. The factor \( k \) accounts for the fact that, in general, only a fraction of the total upper laser level population is in the correct \(^4F_{3/2}\) sublevel to participate in the stimulated emission; for Nd: YAG at room temperature, \( k = 40 \) percent, while for Nd: glass, \( k = 100 \) percent. We assumed that the gain was uniform over the rod cross section. Since we did not observe any appreciable difference in gain when we probed either the central 1.5 mm of the rod or the whole cross section, the assumption of a radially uniform energy deposition is reasonable.

Table I presents the measured values of the energy storage efficiency \( η_{st} \) which we define as the ratio of energy stored in the rod to the electrical energy stored in the PFN. We obtained good agreement (within 15 percent) between the values of \( η_{st} \) deduced from the small-signal gain measurements and laser threshold measurements which were done separately.

The heat deposited in the test rod during flashlamp pumping was deduced from the observed temperature rise of the uncooled rod following the flashlamp pulse. The rod temperature rise was obtained by measuring the shift of the interference fringes which were created by partially reflecting an HeNe laser off the two polished rod end faces. One advantage of this method is that unavoidable pumping nonuniformities that arise along the length of the rod due to the finite lengths of the flashlamp and rod are averaged out in the same way as the small-signal gain measurement averages out longitudinal stored energy nonuniformities. Thus, the experimental value of \( χ \) is not affected by pumping nonuniformities along the length of the rod.

Fig. 1(a) shows a schematic of the experimental apparatus used to quantify the fringe shifts. An HeNe laser is aligned to pass through the slightly tilted laser rod. The reflections from the two rod end faces create a set of linear fringes with a spacing which can be adjusted to a convenient value by varying the angle between the HeNe laser beam and the rod axis. The magnified fringe pattern is swept across a 1 mm diameter silicon photodiode using a scanning mirror. This arrangement allows the fringe pattern to be displayed on an oscilloscope for accurate quantitative measurement. The PFN voltage is adjusted so that a rapid burst of \( m \) consecutive flashlamp pulses (burst length is \( ≲ 1 \) s) induces one complete fringe shift. Fig. 1(b) shows the output of the detector for \( m = 3 \). Following the third pulse, the shifted trace coincides with initial trace, indicating one complete fringe shift. To improve the accuracy, we typically repeated this procedure for various values of \( m \) between 1 and 5.

The heat deposited into the rod \( H \) can be obtained using the relation

\[
H = (ρAC_p) \int_0^L ΔT(z) \, dz
\]
where \( \rho \) and \( C_p \) are the density and heat capacity, respectively, of the particular glass tested and \( \Delta T(z) \) is the temperature change induced by the flashlamp pulse at the position \( z \) in the rod. The temperature change required to produce one fringe shift can be found using the following equation:

\[
2 \left( n \alpha + \frac{dn}{dT} \right) \int_0^L \Delta T(z) \, dz = \lambda \quad (3)
\]

where \( n \), \( dn/dT \), and \( \alpha \) are the refractive index, thermooptic, and thermal expansion coefficients of the glass, respectively, and \( \lambda \) is the HeNe wavelength of 633 nm. Combining (2) and (3) yields

\[
H = \left( \rho A C_p \right) \frac{\lambda}{2(dn/dT + n \alpha)} \quad (4)
\]

The heat generation efficiency \( \eta_H \) is defined as

\[
\eta_H = \frac{H}{m E_a} \quad (5)
\]

where \( E_a \) is the energy stored in the PFN capacitor.

Of course, the rod must not be actively cooled during these measurements. The observed conductive heat transfer time from the rod to its surroundings is 15–18 s. This time is much longer than our measurement time (0.2–1 s) which is limited by the sweep time of the scanning mirror (0.2 s) and the time interval between pulses (0.3 s). Nevertheless, a small (<5 percent) correction for this heat loss is made to the measured values of \( H \) and \( \eta_H \). Experimental values of \( \eta_{st} \) and \( \eta_H \) required to less than 10 percent, with uncertainties primarily arising from the difficulty in determining exactly one fringe shift. We estimate that systematic errors in measured values of \( \eta_H \) and \( \eta_{st} \) due to radially nonuniform pumping are less than 20 percent, based on the observation that measured values of \( G \) did not change appreciably as the probe beam diameter was increased. Since the same technique was used for all samples, this error would not change the relative values of \( \chi \) among different samples, even if it did affect the absolute values. Of course, our results implicitly carry any errors or uncertainties in the reported values of several material parameters used, such as \( dn/dT \), \( C_p \), and \( \alpha \). Although \( \eta_{st} \) and \( \eta_H \) are not very sensitive to errors in these parameters, there seems to be a ~10–15 percent discrepancy between some of the parameter values as reported by Lawrence Livermore National Laboratory [10] and the respective suppliers. In all cases, we used the values provided by the glass suppliers.

With stronger pumping, a systematic decrease of 10–15 percent in \( \eta_{st} \) and a less than 5 percent decrease in \( \eta_H \) was observed as the stored energy density \( \epsilon_a \) increased from 0.25 to 0.4 J/cm\(^3\). The resultant small (5–10 percent) increase in \( \chi \) is within our ±12 percent experimental uncertainty. Tabulated values of \( \eta_{st} \), \( \eta_H \), and \( \chi \) are for \( \epsilon_a = 0.25 \) J/cm\(^3\). As we discuss later, such small changes in \( \chi \) with \( \epsilon_a \) can arise from the increased flashlamp current density (from 3 to 7 kA/cm\(^2\)). During our measurements, we noticed that as the flashlamp aged, measured values of \( \eta_{st} \) and \( \eta_H \) both decreased by approximately 30 percent, but \( \chi \) stayed the same within the ±12 percent experimental accuracy.

For one of the samples (LHG-8), we remeasured \( \eta_{st} \) and \( \eta_H \) without water (only air) between the glass rod and the Sm:YAG glass tube. This configuration differs from the previous one in several aspects: 1) it modifies the optical path of pump light, 2) it removes the IR filtering effects of the water, and 3) it almost eliminates any heat loss from the rod to the surrounding medium following a flashlamp pulse. We obtained \( \eta_{st} = 1.8 \) percent, \( \eta_H = 4.5 \) percent, and thus \( \chi = 2.5 \). \( \chi \) is the same within our experimental accuracy of 12 percent, although \( \eta_{st} \) and \( \eta_H \) are both larger in this case than the corresponding values obtained with...


water surrounding the rod. Thus, we attribute the increase in $\eta_H$ and $\eta_H$ to better coupling of the flashlamp light to the rod. This comparison indicates that 1) filtering of IR ($\lambda > 1.4 \mu m$) pump light by water is not important, and 2) heat loss from the rod to the surrounding water within our measurement time was indeed very small.

Finally, we must allow that there may be variations from sample to sample since we measured only one sample for each laser host. For example, when we used a different, but similar, pump cavity to measure $\eta_H$ and $\eta_H$ for a 3 percent Nd-doped Q-98 glass sample which was manufactured prior to 1980 and was 7.5 cm long and 0.63 cm in diameter, we obtained a larger value of $\chi = 3.8 \pm 0.4$. Therefore, a more exhaustive study on a large number of samples is needed to determine the extent of variations among samples from the same glass type and doping.

**DISCUSSION**

Since the energy storage is related to pump light absorption, which is very similar for the phosphate glasses studied, the energy storage efficiency should be the same for different glasses having the same Nd doping. Indeed, this is the case observed experimentally, with $\eta_H = 1.6 \pm 0.1$ percent as shown in Table I for the various 3 percent Nd-doped glasses. But the values of $\eta_H$ vary by a factor of 2 among the same glass samples. Before we discuss the sources that contribute to heat generation in Nd: glass, we would like to point out the impact of $\chi$ on the practical design of high average power Nd: glass amplifiers.

**Power-Handling Capability**

In the stress-fracture limit, the thermal power-handling capability of a solid-state host material is defined as [1], [2]

$$P = 12 \left( \frac{\kappa(1 - \nu)}{\alpha E r} \right) (L w \theta)$$

for a uniformly pumped slab of width $w$, thickness $\theta$, and length $L$. Here $\kappa$ is the thermal conductivity, $\alpha$ is the linear thermal expansion coefficient, $E$ is Young's modulus, $\nu$ is Poisson's ratio, and $\sigma_\rho$ is the stress-fracture limit of the solid. Therefore, the maximum amount of energy stored $E_{st}$ in such a slab, being pumped at pulse repetition rate $R$, is

$$E_{st} = \frac{P}{R \chi} \frac{1}{12} \left( \frac{\kappa(1 - \nu)}{\alpha E r} \right) (L w \theta) \frac{1}{\chi}.$$  

Thus, a glass which does not have the best thermomechanical properties might still handle large input pump powers if $\chi$ is small.

In situations when thermal stress fracture is not likely, another negative effect of a large $\chi$ is that for the same stored energy, larger amounts of heat must be dissipated in the glass, leading to higher operating temperatures within the glass and increased requirements for cooling. With Nd: glass, in contrast to Nd: YAG, a high operating temperature can substantially reduce the efficiency because of ground-state absorption. For example, at 360 K, absorption coefficients at 1.053 $\mu m$ due to the thermally populated lower laser level are 0.0068 and 0.0136 cm$^{-1}$ for 3 and 6 percent Nd doping, respectively [4, 5]. Considering that typical gain coefficients in Nd-doped phosphate glasses are $\sim 0.08-0.1$ cm$^{-1}$, thermal absorption leads to a more than 8.5-17 percent decrease in the energy that can be effectively extracted. In Nd: YAG, the relative effect of thermally induced absorption is smaller by 50-100 times for the following reasons: 1) the thermal conductivity is $\sim 20$ times larger than for phosphate glasses, so the temperature rise is $\sim 20$ times lower than glass for the same heat load; and 2) only one of the six Stark-split sublevels of the $I_{1/2}$ state can absorb the 1.064 $\mu m$ radiation.

Thus, we see that larger values of both $\chi$ and the Nd doping limit the power scalability due to increased absorption at 1 $\mu m$. As we shall show below, for the same glass type, larger Nd doping percentages increase $\chi$ as well; hence, highly doped Nd: glass should not be used in high average power laser systems.

**Heat Sources in Nd: Glass**

At this point, it is appropriate to review Nd: glass heat sources. Ideally, the only source of heat should be due to the quantum defect between the energies of the absorbed pump photon and the output laser photon. For this ideal case, $\chi$ can be estimated using the known absorption spectrum of Nd: glass and the emission spectrum of a Xenon flashlamp. However, there are other absorption processes which can heat the glass without contributing to pumping the $F_{3/2}$ level of the Nd ions: 1) UV absorption by the host glass if the flashlamp UV radiation ($\lambda < 400$ nm) is not filtered out, 2) absorption of IR radiation ($\lambda > 1.4 \mu m$) from the flashlamp by the Nd ion ($I_{9/2} \rightarrow I_{15/2}, I_{13/2}$), and 3) absorption by impurity atoms, which do not transfer their energy to Nd ions. In addition, impurities such as OH can quench the Nd $F_{3/2}$ level [6] and increase $\chi$, even if they do not directly absorb pump light.

By appropriate design of the laser head, heat sources 1) and 2) can be eliminated. Moreover, commercially available high-purity Nd: glass should not have impurities that would contribute appreciable absorption. When we examined the absorption spectra of the Nd: glass samples, we did not see any absorption peaks that could not be attributed to Nd. From the measured fluorescence lifetimes and absorption coefficients [6] at 2.2 $\mu m$, we determined that quenching of the $F_{3/2}$ level by OH reduces the fluorescence lifetime by less than 5 percent in our glass samples. However, we did observe a baseline absorption $\beta_b = 2-3$ percent/cm within the 390-410 nm region, which is free of Nd absorption peaks. This residual absorption is most probably intrinsic to the glass host and is due to the tail of the UV absorption edge. Indeed, 1-3 percent/cm absorption in the 390-450 nm region is observed in many undoped phosphate glasses [7]. We did not see any correlation between $\beta_b$ and $\eta_H$. Therefore,
whatever the source of this residual absorption might be, it is not the cause of the differences in $\eta_d$ that we observe among different Nd: glass samples. As we discuss in the next section, some of the observed variations in $\eta_d$ (and $\chi$) can be explained by variations in the quantum efficiency of the different glass types and dopings.

**Calculation of $\chi$**

The emission spectrum of Xenon flashlamps can be modeled quite accurately [8], [9] given the lamp current density and diameter. The Nd absorption spectrum $\beta(\lambda)$ for different glass types has been carefully measured [10]. Using this information, and assuming a uniformly illuminated Nd: glass slab with a thickness extending from $y = 0$ to $\infty$, we can calculate the energy storage density available as 1.054 $\mu$m photons $\epsilon_d(y, t)$ and the heat generation density $h(y)$ [8]:

$$\frac{d}{dt} \epsilon_d(y, t) = \frac{\epsilon_d(y, t)}{\tau} + \int d\lambda I(\lambda, J(t)) \cdot K(\lambda, t) e^{-\gamma_0(\lambda)} \beta(\lambda) \eta(\lambda) \frac{\lambda}{\lambda_0} \tag{8}$$

$$h(y, t = \infty) = h_0(y) + \int_0^\infty dt [q_1(y, t) + q_2(y, t)]. \tag{9}$$

The time integral is performed over the flashlamp pulse of duration $T$; the integral over wavelength extends over the 350–900 nm region of the Nd pump bands; $I(\lambda, J(t))$ $d\lambda$ represents the light intensity emitted by the flashlamp into the wavelength interval between $\lambda$ and $(\lambda + d\lambda)$ at time $t$ with current density $J(t)$; $K(\lambda, t)$ represents how the reflectors in the laser head modify the flashlamp spectrum [8]; $\lambda_0$ is 1.054 $\mu$m for Nd-doped phosphate glass; $\tau$ is the fluorescence lifetime; and $\eta(\lambda)$ is the quantum efficiency (i.e., the probability that the Nd ion absorbing a photon at wavelength $\lambda$ will eventually relax to the $^4F_{3/2}$ state). The functions $h_0$, $q_1$, $q_2$ are defined as

$$h_0(y) = r \epsilon_d(y, t = T) = \int_T^\infty dt \frac{r}{\tau} \epsilon_d(y, t) \tag{10}$$

$$q_1(y, t) = \frac{r}{\tau} \epsilon_d(y, t) \tag{11}$$

$$q_2(y, t) = \int d\lambda K(\lambda, J(t)) K(\lambda, t) e^{-\gamma_0(\lambda)} \beta(\lambda) [f_1 + f_2] \tag{12}$$

with $f_1 = 1 - \eta(\lambda)$, $f_2 = \eta(\lambda) (1 - \lambda/\lambda_1)$. The product $r \epsilon_d$ represents the fraction of the energy stored in the $^4F_{3/2}$ state that is converted to heat as a result of fluorescence decay where

$$r = \frac{1}{h c/\lambda_0} (E_{11/2} B_{11/2} + E_{13/2} B_{13/2} + E_{15/2} B_{15/2}) \tag{13}$$

with $E$, $B$ being the energy and fluorescence branching ratios [10], respectively, of the $I_{11/2}$, $I_{13/2}$, and $I_{15/2}$ states of the Nd ion in the phosphate glass. $f_1$ is the probability that an Nd ion will directly relax to the ground state after absorbing a pump photon; $f_2$ is the fraction of the absorbed pump energy that is dissipated as heat as the Nd ion relaxes to the $^4F_{3/2}$ state. $h c/\lambda_1$ is the energy of the $^4F_{3/2}$ state.

In practice, accurately calculating $\epsilon_d$ and $h$ using (8) and (9) is not possible due to a lack of detailed information on $K(\lambda, t)$ and $\eta(\lambda)$. Hence, we have made several simplifying assumptions and used the equations to assess how $\chi = h(y)/\epsilon_d(y, y)$ might be affected by different design or material parameters, such as the lamp pulsewidth, current density, and Nd concentration. First, we explored the sensitivity of the calculations represented by (8) and (9) to the precise formulation of $K(\lambda, t)$. Employing the particular $K(\lambda, t)$ used in [8], calculated values of $\chi$ were only 5–7 percent larger than the results obtained using a constant value of $K(\lambda, t)$. Because of this insensitivity to $K(\lambda, t)$, we have simply used a constant value in the calculations of $\chi$ reported here. Second, we attempted to choose a realistic expression for absolute quantum efficiency. Brecher et al. [11] have shown that the relative quantum efficiency $\eta(\lambda)$ varies from 100 to 75 percent as the excitation wavelength is scanned across the 430 nm absorption band of the Nd: glass. However, the wavelength dependence and absolute value of $\eta(\lambda)$ are not known for the other excitation bands. Thus, we used an average value of $\eta$ independent of wavelength:

$$\eta = \tau(d)/\tau(d \to 0) - \delta \tag{14}$$

where $d$ is the Nd doping concentration and $\tau(d)$ is the fluorescence lifetime at the concentration $d$. This equation accounts for the decrease in the quantum efficiency due to Nd concentration quenching of the $^4F_{3/2}$ state, and $\delta$ allows for the possibility that the maximum value of $\eta$ may not be 1. Because there are no data on which to base the estimate of $\delta$, we used $\delta = 0$ in our calculations rather than choose an arbitrary value. Since it is well documented that the fluorescence decay in Nd: glass is not a simple exponential [10], [12], [13], there is 5–10 percent uncertainty in defining an exact value of $\tau(d)$. However, consistent with the approximations leading to (14) and within the accuracy of our calculations, such minute details are unimportant.

Within the limitations of the above assumptions and approximations, the dependence of $\chi$ on maximum flashlamp current density $J$, normalized current pulse duration $T/\tau$, and the quantum efficiency $\eta$ are shown in Figs. 2, 3, and 4 where we approximated the actual current pulse with a half sine wave of 200 $\mu$s total duration. Calculated values of $\chi$ depend very weakly on the slab thickness $y$; $\chi$ varies only 5–10 percent across a 3 percent Nd-doped 1 cm thick glass slab, while $\epsilon_d(y)$ and $h(y)$ decrease by a factor of $\sim 5$.

We see from Figs. 2 and 3 that $\chi$ is rather insensitive to $J$ and $T/\tau$ as long as $T/\tau \leq 0.6$. On the other hand, $\chi$ increases very rapidly as $\eta$ decreases, even if the fluorescence lifetime does not change. As was mentioned above, higher Nd doping in glasses leads to larger $T/\tau$ and smaller
Fig. 2. Calculated normalized heating parameter versus maximum current density in a 0.3 cm bore Xenon flashlamp with a 200 µs half-sinewave current pulse. A fluorescence lifetime and average quantum efficiency of 330 µs and 0.87, respectively, were used in the calculations.

Fig. 3. Calculated normalized heating parameter versus normalized pulse duration for a 3 percent-doped Nd :glass with a 330 µs fluorescence lifetime. A half-sinewave current pulse was assumed.

Fig. 4. Calculated normalized heating parameter versus quantum efficiency for an Nd :glass with a 330 µs fluorescence lifetime. A half-sinewave lamp current pulse having a 200 µs duration was assumed, producing 3 kA/cm² maximum current density in a 0.3 cm bore Xenon flashlamp.

TABLE II

<table>
<thead>
<tr>
<th>Class Type</th>
<th>Nd Doping, w (weight %)</th>
<th>τ(d) (µsec)</th>
<th>η</th>
<th>calculated</th>
<th>measured</th>
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<tr>
<td>Q-88</td>
<td>3</td>
<td>280</td>
<td>0.85</td>
<td>1.3</td>
<td>2.35</td>
</tr>
<tr>
<td>Q-98</td>
<td>3</td>
<td>350</td>
<td>0.86</td>
<td>1.2</td>
<td>2.85</td>
</tr>
<tr>
<td>LRG-8</td>
<td>3</td>
<td>360</td>
<td>0.88</td>
<td>1.1</td>
<td>2.4</td>
</tr>
<tr>
<td>LRG-5</td>
<td>3</td>
<td>290</td>
<td>0.88</td>
<td>1.2</td>
<td>2.2</td>
</tr>
<tr>
<td>LRG-760</td>
<td>3</td>
<td>330</td>
<td>0.85</td>
<td>1.2</td>
<td>2.25</td>
</tr>
<tr>
<td>LRG-760</td>
<td>3</td>
<td>335</td>
<td>0.93</td>
<td>1.0</td>
<td>1.8</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>calculated</td>
<td>measured</td>
</tr>
</tbody>
</table>

* Value calculated using (14), with δ = 0.

η; therefore, we expect χ to increase with doping. These predictions are in qualitative agreement with the results shown in Table I.

In Table II, we compare measured and calculated values of χ. No attempt was made to calculate χ for Nd : YAG since the absorption spectrum β(λ) is difficult to represent accurately. Nevertheless, one would intuitively expect χ to have a value similar to that of Nd : glass. For the Nd : glass calculations, we used η computed from (14) employing our measured values of τ(d) and published values [10] of τ(d → 0). We find that the calculated value of χ is always less than the measured value, indicating that certainly other processes contribute to glass heating during flashlamp pumping. We determined that the excess heat is not caused by leakage of the UV radiation through the Sm-doped glass tube. When we repeated our measurements for one of the samples using a flashlamp with a clear quartz envelope, which increases the amount of UV emission, we measured the same value of χ. The geometric difference between our model, which assumes a uniformly illuminated slab, and the experiments, which were done with rods, should not be the source of a large discrepancy between the calculated and measured values. In any event, such a systematic error would have been the same for all samples. Another likely reason for the discrepancy may be that our estimates of the average value of η(λ) shown in Table II [and the assumption that δ = 0 in (14)] are optimistic. Indeed, if one arbitrarily chooses δ = 0.23, much better agreement is obtained between the...
calculated and measured values of $\chi$ for many of the samples [except LG-760 and LGH-5 (6 percent Nd)].

**CONCLUSION**

We have shown that there are significant variations among different glass types in the normalized heating parameter $\chi$. In some glass types, $\chi$ is $\sim 2$ times larger than the expected value. We have pointed out the adverse effects of large values of $\chi$ on the power-handling capability of any laser medium and on the thermally induced ground state absorption in Nd:glass. Our data and analysis indicate that although highly doped Nd:glass leads to more efficient utilization of flashlamp emission, heat generation increases relatively faster than energy storage efficiency. Therefore, from an overall thermal viewpoint, highly doped Nd:glass is not the best choice for high average power laser systems.

Apart from the expected increase in $\chi$ with increasing Nd doping, there seems to be an additional process, yet to be identified, that leads to larger values of $\chi$ in some of the samples. We have tested one sample of each laser host, and we realize that there may be variation from one glass melt to another, even among the same glass type. Therefore, as a part of a long-term systematic study in collaboration with glass manufacturers, it would be desirable to carry out these measurements for many samples, identify the source(s) of excess heat, and possibly eliminate them. If values of $\chi$ can be reduced for glasses with the best thermomechanical properties, improved performance will be possible from high average power Nd:glass lasers.

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