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Measurement of the figure of merit of indigenously developed Nd-doped phosphate laser glass rods for use in high power lasers

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Abstract. High energy, high power (HEHP) Nd:glass laser systems are used for inertial confinement fusion and equation of state (EOS) studies of materials at high temperature and pressure. A program has been undertaken for the indigenous development of Nd-doped phosphate laser glass rods and discs for HEHP lasers. In this paper, we report the characterization of the Nd-doped phosphate laser glass rods produced under this program and compare the indigenously developed laser glass to LHG-8 laser glass of M/s Hoya, Japan. We experimentally measured the values of the stimulated emission cross-section (σ) and coefficient of intensity-dependent refractive index (n_2) and hence the figure of merit $F = \sigma/n_2$ of the indigenous phosphate laser glass rods. This value of figure of merit is found comparable to the reported value of identically doped Nd:glass rods.

Keywords. High power Nd:glass laser; figure of merit; stimulated emission cross-section; coefficient of intensity-dependent refractive index; Nd-doped phosphate laser glass; Abbe number.

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1. Introduction

High energy, high power (HEHP) Nd:glass laser systems [1] are used for studying inertial confinement fusion and equation of state (EOS) of materials at high temperature and pressure. These lasers are based on a master oscillator power amplifier (MOPA) architecture wherein the laser beam is sequentially relayed and spatially filtered to reduce the effects of phase distortions occurring because of self-focussing of the laser beam due to its high intensity (~1–4 GW/cm^2). An important factor involved in the design of such laser systems is the choice of the laser glass as the amplifying medium. The third-generation

Nd:glass laser systems like National Ignition Facility (NIF), USA [2] use Nd-doped phosphate glass rods and discs as the amplifying medium because their stimulated emission cross-section (σ) is moderately high and hence suitable (because of low amplified spontaneous emission and parasitic oscillations losses) and the coefficient of intensity-dependent refractive index (n_2) is lower than that of Nd-doped silicate glasses [3]. The figure of merit $F= \sigma/n_2$ of a laser glass is an important parameter that is used in differentiation of various laser glasses from the point of view of their use in HEHP lasers. Phosphate-based laser glasses have: (a) wide transmission range in the visible/near IR region required for pumping with xenon flash lamps, (b) low n_2, (c) suitable σ. Also, the spectroscopic and physical properties of these glasses can be tailored by varying the composition. A program has been undertaken for developing Nd-doped phosphate laser glasses (equivalent to LHG-8 glass of M/s Hoya, Japan) under a project in Central Glass and Ceramic Research Institute (CGCRI), Kolkata, with the participation of RRCAT, Indore and BARC, Mumbai. In this paper, we report the characterization of the Nd-doped phosphate laser glass rods produced under this program, and the values of the parameters σ and n_2 and hence the figure of merit of the phosphate laser glass.

2. Measurement of n_2 of the laser glass

Phosphate glass equivalent to LHG-8 has a typical composition [3] of 56% P_2O_5–12.5% Al_2O_3–16% K_2O–14.5% BaO–Nd_2O_3(1–3 wt%). The glass was melted in a silica crucible using the metaphosphates of aluminum, barium and potassium and Nd_2O_3 as the raw materials using 'Dry route' of melting [3]. The glass 'freit' obtained by melting the raw material was further homogenized in a bottom pouring platinum crucible, and the glass was cast using bottom pouring technique in pre-heated moulds. The cast glass was first annealed and further fine annealed [3]. The fine annealed glass was turned and optically polished into a laser glass rod and was further coated with antireflection (AR) coating.

The measurements of the electronic contribution to the nonlinear refractive index n_2 for a linearly polarized light at Na D line ($\lambda_d = 587.6$ nm) of the laser glass was performed by using Boling's method [4]. According to the Boling's formula (mentioned below), n_2 is a function of the refractive index n_d at Na D line wavelength and the Abbe number (v_d). The Abbe number is a measure of the dispersion in the visible region and is given by

$$v_{d=} (n_d - 1)/(n_F - n_C)\,, \tag{1}$$

where n_F and n_C are the refractive indices measured at $\lambda_F = 486.1$ nm and $\lambda_C = 656.3$ nm respectively. Using this, the n_2 is given by Boling's formula as

$$n_2 = K(n_d - 1)\,(n_d^2{+}2)^2(v_d)^{-1}\left[1.517 + (n_d^2 + 2)\,(n_d + 1)\,v_d/6n_d\right]^{-1/2}, \tag{2}$$

where the constant $K = 68 \times 10^{-13}$ esu for the phosphate glass [3]. The measurements of the refractive indices were done using an ellipsometer (SOPRA, GS-5) by determining the Brewster angle (θ_B) for each of the wavelengths. The Brewster angle of incidence was determined by varying the angle of incidence of linearly polarized light and measuring the reflected light passing through an analyser in the ellipsometer. To get precise values for the Brewster angle of incidence, the intensity of the reflected light was expressed as a 12th-order polynomial of angle of incidence and the graph was plotted around the Brewster angle of incidence for three wavelengths. Figure 1 shows the angle-dependent reflectivity of the sample at the three wavelengths. The Brewster angles were determined to be 57.02°, 56.94° and 56.88° for the wavelengths 486.1 nm, 587.6 nm and 656.3 nm respectively. Thus, by knowing Brewster angle, the refractive index can be calculated at different wavelengths using the relation $n = \tan\theta_B$. The refractive indices were found to be $n_F = 1.5409$, $n_d = 1.5363$ and $n_C = 1.5328$, and the corresponding Abbe number was found to be $\upsilon_d = 66.13$. The non-linear refractive index coefficient (γ) was found to be 3.18×10^{-20} m^2/W. The n_2 value of the glass matches well with the n_2 values calculated by Boling's formula of phosphate glass LHG-8.

3. Measurement of the stimulated emission cross-section

The stimulated emission cross-section σ was measured by the process of amplification in a glass rod of 10 mm diameter and 150 mm length (l) which was optically machined from a slab supplied by CGCRI. The glass rod was loaded in an amplifier cavity with four xenon flash lamps for pumping the glass rod, powered by a critically damped pulsed power supply [5]. Schematic diagram of the gain measurement set-up is shown in figure 2. The gain (G) and the gain coefficient (g) of a gain medium of unit length at different input fluences (E) of the pump laser is given by [6]

$$G = \exp(gl)\,, \tag{3}$$

where

$$g = g_0/(1 + E/E_s)\,.$$

In this equation, $E_s = h\upsilon/\sigma$ is the saturation energy density of the laser medium and g_0 is the small signal gain coefficient [6]. The gain coefficient at different input fluences was measured at the same input electrical energy of 2.45 kJ. The gain was measured at different input fluences (E) and the variation of $1/g$ was plotted as a function of E and is shown in figure 3. It is a linear function, as expected from eq. (3). Knowing the slope and intercept from the above graph, the values of E_s and the gain coefficient g_0 have been

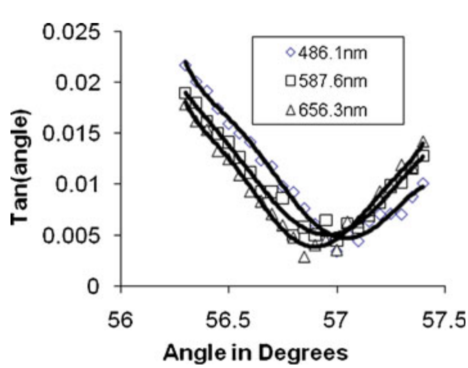

Figure 1. Angle-dependent reflectivity at the three wavelengths for phosphate glass.

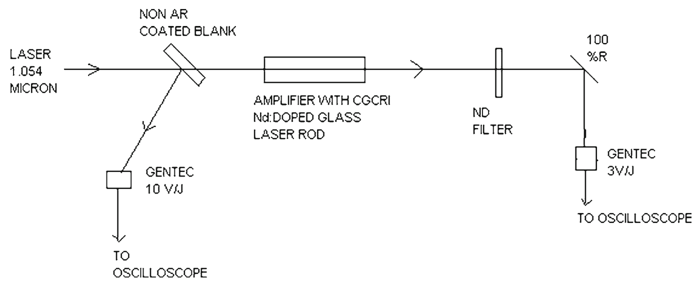

Figure 2. Schematic diagram of the gain measurement set-up.

determined. The value of E_s was found to be 4.04 J/cm^2 and the value of σ was found to be 4.65×10^{-20} cm^2.

Table 1 compares various physical and spectroscopic properties of INLG-25 glass developed indigenously with that of LHG-8 glass of M/s Hoya, Japan, like the linewidth $\Delta\lambda$, the emission peak wavelength λ, the refractive index n and the fluorescence lifetime τ from $^4F_{3/2}$ to $^4I_{11/2}$ level. The OH^- bond content in the indigenously melted glass is slightly higher as indicated by the absorption coefficient of 3.86 at ~3000 cm^{-1}. This leads to slightly higher non-radiative decay of population because the third overtone of OH^- bond absorption overlaps with the wavelength of lasing transition. In addition to this, the lifetime of the $^4F_{3/2}$ level decreases as the doping density of the Nd atoms in the glass increases [7]. The table has listed the lifetime of ~350 μs for the low-doped LHG-8 glass, whereas the fluorescence lifetime of ~298 μs was observed for the INLG-25 glass. Assuming that there is no radiative coupling from $^4F_{3/2}$ to any level other than $^4I_{11/2}$, the value of peak σ at wavelength λ can be calculated from the values of various parameters mentioned in table 1 using the following relation:

$$\sigma = \frac{\lambda^4}{8\pi c n^2 \Delta\lambda\tau}. \tag{4}$$

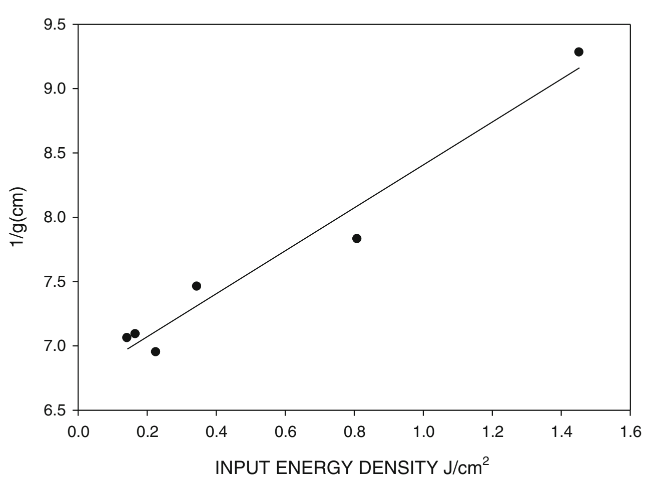

Figure 3. Variation of the gain coefficient with input energy fluence.

Table 1. Comparison of properties of indigenous glass INLG-25 with LHG-8 glass of Hoya.

Parameters	Values for LHG-8 glass	Values for INLG-25
Physical and optical properties		
Nd_2O_3 concentration (wt%)	3.03	3.00
Nd^{3+} concentration ($\times 10^{20}$ ions/cm^3)	3.074	3.026
Density (g/cm^3)	2.78	2.8179
Refractive index, n_d	1.529	1.5301
Abbe number (υ_d)	66.5	66.13
Non-linear refractive index coefficient γ ($\times 10^{-20}$ m^2/W)	3.08	3.18
Stimulated emission cross-section (10^{-20} cm^2)	3.6	4.65 (4.41)
Spectroscopic properties		
Fluorescence peak (nm)	1053	1053
Fluorescence half line width (nm)	27	26.5
Fluorescence lifetime (μs) (low doping of Nd)	350	298 (3 wt%)
Attenuation coefficient at 1053 nm (cm^{-1})	0.001	0.0018
Absorption coefficient at 3000 cm^{-1} (α^{OH-1})	3.0	3.86

σ was theoretically calculated to be 4.41×10^{-20} cm^2, which is presented in parentheses in table 1. This matches well with the value of σ measured experimentally by the method of amplification (4.65×10^{-20} cm^2). The value of σ calculated for low doping of Nd atoms that has $\tau = 350$ μs matches well with the value mentioned in table 1 for LHG-8 glass. The figure of merit for the INLG-25 Nd:phosphate laser glass is 1.46×10^{-4} W.

4. Conclusion

The calculated and measured values of stimulated emission cross-section matched well and the value of n_2 matched to within ~5% of the reported values [3]. The figure of merit for the Nd:phosphate laser glass was found to be comparable to the reported value [7].

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