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Research and development of neodymium phosphate laser glass for high power laser application

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ABSTRACT

Neodymium phosphate laser glass is a key optical element for high-power laser facility. In this work, the latest research and development of neodymium phosphate laser glass at the Shanghai Institute of Optics and Fine Mechanics (SIOM), China, is addressed. Neodymium phosphate laser glasses, N31, N41, NAP2, and NAP4, for high peak power and high average power applications have been developed. The properties of these glasses are presented and compared to those of other commercial neodymium phosphate laser glass from the Schott and Hoya companies and the Vavilov State Optical Institute (GOI), Russia. Continuous melting and edge cladding are the two key fabrication techniques that are used for the mass production of neodymium phosphate laser glass slabs. These techniques for the fabrication of large-aperture N31 neodymium phosphate laser glass slabs with low stress birefringence and residual reflectivity have been developed by us The effect of acid etching on the microstructure, optical transmission, and mechanical properties of NAP2 glass is also discussed.

1. Introduction

Phosphate glass is used as a matrix for Nd^{3+} ions because it has medium phonon energy, high solubility to rare earth ions, a high damage threshold, a lower nonlinear refractive index, and superior spectroscopic properties compared to a silicate glass matrix. In addition, phosphate laser glasses have better solubility to platinum inclusion which is very important to prevent the laser damage in high power laser application. More than 50 years have passed since the discovery of Nd:phosphate laser glass in the early 1960s [1,2]. Today, Nd:phosphate laser glass continues to play an important role in inertial confinement fusion, laser processing, and as a pumping source for ultrafast laser systems [3–5]. As a result, new kinds of neodymium phosphate laser glass and new melting technologies for their mass production have been developed over the last two decades [6–8].

In general, high-power neodymium phosphate laser glasses are classified into two on the basis of their applications [6,9,10]: high-peak-power laser applications and high-average-power laser applications. For high peak power laser applications, neodymium laser glasses with high gain, low nonlinear refractive index, low attenuation at laser wavelength, excellent optical homogeneity, and large damage threshold are required. Thousands of large-aperture phosphate laser glasses have been successfully applied in at the National Ignition Facility (NIF) in the United States [11,12]. In China, N31 Nd:phosphate laser glass was developed at the Shanghai Institute of Optics and Fine Mechanics in the 1990s, and it has been applied in Shen Guang series of high power laser facilities in China for more than ten years [13–15]. More recently, three new kinds of Nd:phosphate laser glass N41, NAP2, and NAP4 were developed for high power laser applications, and continuous melting technology for large aperture N31 laser glass has been explored at the Shanghai Institute of Optics and Fine Mechanics (SIOM), China [7,16–18]. In this paper, we present the composition, main properties, and fabrication techniques of Nd:phosphate laser glass developed at SIOM, China.

2. Compositions and properties of high peak power neodymium phosphate laser glass

The figure of merit for high peak power Nd:phosphate laser

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glass is given in Eq. (1).

$$FOM_{laser} = \frac{\Delta\lambda_{abs}(\tau_0 Q)\sigma_{em}\eta_{ex}}{n_2} \quad (1)$$

where $\Delta\lambda_{abs}$ is the absorption bandwidth, σ_{em} is the peak stimulated emission cross section, η_{ex} is the energy extraction efficiency, n_2 is the nonlinear refractive index, Q is the concentration quenching factor, and τ_0 is the fluorescent lifetime at zero Nd^{3+} ion concentration.

For high peak power laser application, the most important goal is to achieve a high peak stimulated emission cross section and high energy extraction efficiency. The second is to control its nonlinear refractive index [19]. There have been many reports on the study of neodymium phosphate laser glass compositions [20–24], and it is well known that high peak power Nd:phosphate laser glass is usually a kind of metaphosphate glass. The main composition of Nd:phosphate laser glass is P_2O_5–Al_2O_3–M_2O–MO [25]. M_2O can be K_2O or a mixture of alkali oxides. MO can be an alkaline oxide or a mixture of alkaline oxides. Al_2O_3 is used to improve the chemical durability and control the thermal expansion coefficient of Nd:phosphate laser glass. The peak stimulated emission cross section of Nd:phosphate laser glass is sensitive to glass composition. A small cationic field strength is favored to achieve a large stimulated emission cross section of Nd^{3+} ions in phosphate glass. The Al_2O_3 content usually decreases the stimulated emission cross section of Nd^{3+} ions but it enhances the chemical durability of the phosphate glass. In one study, the stimulated emission cross section increased with increasing P_2O_5 content from 45 to 70 mol% P_2O_5 [25]. In order to achieve small n_2 values, components such as K_2O and MgO are preferred. Designing the composition of high peak power Nd:phosphate glass requires a balance between laser parameters and fabrication parameters. Since 1990, two kinds of high peak power Nd:phosphate laser glasses N31 and N41 have been developed. The glass composition of N31 is (58–62)P_2O_5–(8–12)Al_2O_3–(12–16)K_2O–(8–12)BaO– (1–2)Re_2O_3 (in mol%, Re_2O_3 indicates the total amount of rare earth elements). The glass composition of N41 is (58–62)P_2O_5–(6–10)Al_2O_3–(20–25)K_2O–(8–12)MgO–(1–2)Re_2O_3 (in mol%, Re_2O_3 indicates the total amount of rare earth elements). N41 glass has a relatively smaller n_2 value and a higher stimulated emission cross section as compared to N31 glass. However, the thermal expansion coefficient of the N41 glass is larger than that of the N31 glass, which increases the risk of cracking during fabrication [18].

Table 1 lists the main properties of the N31 and N41 glass developed at SIOM, along with those of two commercial laser glasses, LHG-8 from Hoya and LG-770 from Schott. For comparison, the properties of KGSS-0180 glass from Russia are also given. The peak stimulated emission cross section of the N31 glass is larger than that of the LHG-8 glass. However, it has a relatively larger n_2 value as compared to those of LHG-8 and LG-770. The LG-770 glass has the lowest n_2 value among all the glass listed in Table 1. The peak stimulated emission cross sections of the LG-770 and N41 glass are also the largest.

The most important property of neodymium laser glass is a small signal gain coefficient, given in Eq. (2).

$$g = [\sigma(\lambda)N^* - \alpha] \quad (2)$$

where $\sigma(\lambda)$ is the emission cross section at wavelength λ. For Nd:phosphate glass, the maximum emission cross section in the near-infrared region occurs at 1053 nm. N^* is the Nd^{3+} inversion density at the $^4F_{3/2}$ state. It is determined by the fluorescent lifetime, the Nd^{3+} doping concentration, and the fluorescence effective bandwidth of this state. α is the attenuation at laser wavelength. In order to obtain a high gain coefficient, a high stimulated emission cross section, long fluorescent lifetime, and smaller attenuation are preferred.

Table 1
Main parameters of neodymium phosphate laser glass for high peak power lasers from Hoya [25], Schott [25], Russia (GOI) [26,27], and SIOM [28].

Parameters	N31	N41	LHG-8	LG-770	KGSS-0180
$\sigma/10^{-20}cm^2$	3.8	3.9	3.6	3.9	3.6
$\tau_{rad}/\mu s$	348	351	365	351	360
$\Delta\lambda_{eff}/nm$	25.6	25.5	26.5	25.4	
[a]$d/g/cm^3$	2.84	2.60	2.83	2.59	2.83
[a]n_d	1.540	1.510	1.5296	1.5067	1.532
n_{1053nm}	1.535	1.500	1.5201	1.4991	
Abbe number	65.7	67.5	66.5	68.4	
$n_2/10^{-13}$ esu	1.18	1.04	1.12	1.01	1.1
$T_g/°C$	445	465	485	460	460
$\alpha/10^{-7}/K$ (20–100 °C)	115	118	115	116	116
$dn/dT/10^{-7}/K$	−43	−56	−53	−47	−40
$dS/dT/10^{-7}/K$	14	4	6	11	
k/W/m K	0.56	0.56	0.58	0.57	
E/GPa	56.4	49.7	50.0	47	59

[a] Parameters that may vary with Nd_2O_3 concentration in glass.

Fig. 1 shows the small signal gain coefficients of N31 and N41 glass rods ϕ20 × 360 mm in size. The Nd^{3+} ion concentration of the two glasses is 1.22×10^{20} cm^{-3}. The fluorescent lifetimes of the N31 and N41 glass are 360 μs and 370 μs, respectively. It is clearly seen that the N41 glass has a larger gain coefficient than the N31 glass at the same pumping voltage. From the data shown in Table 1 and Fig. 1, it is apparent that the gain coefficient of laser glass is mainly determined by the stimulated emission cross section and fluorescent lifetime.

In order to achieve optimal gain properties and energy extraction efficiency from neodymium phosphate laser glass for inertial confinement fusion (ICF) lasers, the stimulated emission cross section at the emission peak wavelength is limited to 3.5 to 4.0 × 10^{-20} cm^2. To suppress the damage from self-focusing because of the optical nonlinear effect at high-energy fluence, the n_2 value of the neodymium phosphate laser glass should be controlled to be as low as possible. From Table 1, the n_2 value is below 1.2 × 10^{-13} esu for all high peak power Nd:phosphate glasses.

3. Composition and properties of high average power neodymium phosphate laser glass

The figure of merit for high average power Nd:phosphate laser

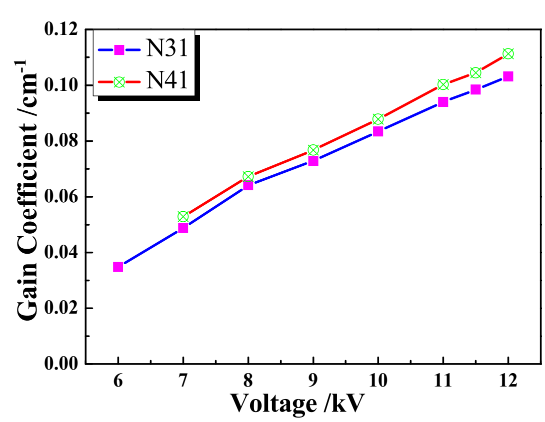

Fig. 1. Gain coefficients of N31 and N41 glass rods ϕ20 × 360 mm in size under various xenon lamp pumping voltages.

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