Energy storage and heat deposition in Cr,Yb,Er co-doped phosphate glass

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Received February 13, 2006

Energy storage and heat deposition in Cr,Yb,Er co-doped phosphate glass were reported. A model based on rate equations was used to determine the energy storage from the free-oscillating output energy characteristics. The heat deposition was calculated by measuring the temperature rise of the glass rod. The results provided important information for the glass operating in Q-switched mode, and also for calculating the temperature profiles and cooling requirements of the glass under single shot and repetitive pulsed conditions.

OCIS codes: 350.6830, 140.6810.

Erbium doped glass laser provides a useful coherent source in the spectral range near 1.5 μm, which is relatively safe for the human eye and convenient in many applications[1], such as lidar and range measurements, fiber-optic communication, and laser surgery. In spite of the considerable progress in the development of InGaAs laser diode pump sources, Xe flashlamp will continue to be used as pump sources of Er:glass lasers because of their high reliability and low cost, and also the simplicity of design of such systems[2,3]. Furthermore Alekseev *et al.* have demonstrated that flashlamp pumped Er:glass is also capable of continuous-wave (CW) lasing[4]. Since about half the flashlamp radiation energy is emitted in the visible and near infrared (IR) ranges, a second sensitizer Cr^{3+} is introduced into Yb-Er laser glasses to utilize this energy[2−6]. By doping a suitable amount of Cr_2O_3 into the glass, the laser slope efficiency can be increased about 100% and the laser threshold can be decreased about 20%. Kigre Inc. has developed QE-7 and QE-7S Cr,Yb,Er co-doped phosphate glasses[5]. Russian Academy of Sciences has also developed LGS-kh Cr,Yb,Er co-doped phosphate glass[6]. The spectroscopy properties of Cr14-05 Cr,Yb,Er co-doped phosphate glass developed and synthesized in our lab have been reported earlier, and the results showed that the spectroscopy parameters of Cr14-05 glass are similar to those of QE-7S glass[7].

But Cr_2O_3 doping also brings side effects. The heat deposition induced by Cr_2O_3 doping causes a larger temperature increase in the glass, which will enhance thermal effects[8]. For example, thermal lensing changes the laser mode dynamically, which affects the output energy and beam quality[9]. The temperature drop from the rod center to its side surface produces mechanical stresses in the rod, which will cause the destruction of the rod above the glass stress threshold[4]. An important parameter for laser operation is the heating parameter η defined as the ratio of the generated heat and the energy stored in the inverted laser population during pumping[10]. The heat deposition can be calculated by measuring the temperature rise of the glass rod. Lukac *et al.* introduced an indirect technique and a model based on rate equations for determining energy storage in three-level laser materials by measuring output energy characteristics of the laser operating in free-oscillating mode, and achieved a good agreement (with 10% experimental error) between the measured and predicted inversions when applying the model to Er:glass[5]. Compared with the method that needs to measure the laser thresholds for several mirror reflectivities, this method overcomes the difficulties connected with the nonlinear relationship between the mirror reflectivity and the threshold energy in three-level laser materials. Energy storage is also an important parameter for the glass operating in Q-switched mode. In this letter, we report on measurements of energy storage and heat deposition for Cr14-05 glass.

The detailed synthesizing process of the glass based upon $65P_2O_5$-$12.5K_2O$-$10Al_2O_3$-$5La_2O_3$-$2.4CeO_2$-$0.05Cr_2O_3$-$5Yb_2O_3$-$0.05Er_2O_3$ was introduced in Refs. [11] and [12]. The activator concentrations in the glass are 1.5×10^{21} /cm^3 (Yb^{3+}), 1.3×10^{19} /cm^3 (Er^{3+}), and 1.2×10^{19} /cm^3 (Cr^{3+}), respectively. The energy storage was determined from the free-oscillating output energy characteristics[5]. In the laser experiment, a cylinder 3×50 (mm) glass rod was pumped by a 3-mm bore Xe flashlamp with a 50-mm arc length. The rod was placed in a 75-mm-long silver-coated single-lamp ellipse reflector with a minor axis of 24 mm and a major axis of 28 mm. The resonator length was 230 mm, with the output mirror reflectivity 85%. The temperature rises of the glass rod following isolated flashlamp pulses were measured with a thermocouple thermometer. The room temperature was 20 °C.

Assuming that all of the Er^{3+} ions are in either upper laser level $^4I_{13/2}$ or ground level $^4I_{15/2}$, with corresponding population densities n_2 and n_1, then the rate equations of Er^{3+} ions can be written as

$$\frac{\partial n}{\partial t} = -2cn\phi\sigma + W_{\mathrm{p}}(n_0 - n), \tag{1}$$

$$\frac{\partial \phi}{\partial t} = cn\phi\sigma - \frac{\phi}{\tau_{\mathrm{d}}}, \tag{2}$$

where ϕ is the photon density at the laser frequency ν,

$n = n_2 - n_1$ is the population inversion per unit laser resonator volume, σ is the stimulated emission cross section, n_0 is the Er^{3+} ions per unit laser resonator volume ($n_0 = n_1 + n_2$), c is the speed of light, and τ_d is the decay time of photon, the parameter W_p describes the pump rate (s^{-1}) from the ground to the upper laser level of Er^{3+} ions. The exact time variation of pumping is not essential to the model where the pumping process is described by the total pump pulse area A defined as the integral of the pump rate over the pump pulse duration[5],

$$A = \int W_p dt. \tag{3}$$

It is assumed that for a particular pumping configuration the pump pulse area depends only on the input energy [$A = A(E_{in})$]. For simplification, the pump pulse is approximated with a square pulse of duration T and constant amplitude W_0 (i.e., $A = W_0 T$).

Below threshold, the photon density ϕ is very small, and the stimulated emission term in Eq. (1) can be ignored. It is assumed that initially all ions are in the ground state, and therefore $n(t = 0) = -n_0$. The inversion density n after the onset of a pump pulse therefore changes in time as

$$n(t) = n_0[1 - 2\exp(-W_0 t)]. \tag{4}$$

The threshold inversion density $n_t = 1/(c\sigma\tau_d) = \gamma/(c\sigma t_R) = \gamma/(2l\sigma)$, where l is the length of the resonator, and t_R is the round trip time in cavity. From Eq. (4), the threshold n_t is reached in a time t_t when the pump area equals the threshold area A_t,

$$A_t = W_0 t_t = -\ln(\frac{n_0 - n_t}{2n_0}) = -\ln\left[\frac{1}{2}\left(1 - \frac{\gamma}{G_0}\right)\right], \tag{5}$$

$G_0 = 2l\sigma n_0$ represents the maximum small signal gain for the case when all Er^{3+} ions are in the excited state. The round trip photon loss γ can be subdivided into $\gamma = \gamma_1 + \gamma_2$, where γ_1 represents the fraction of photons emitted as laser, and γ_2 represents incidental losses. In a resonator where one of the mirrors is totally reflecting, and the output mirror has reflectivity R, the output losses are $\gamma_1 = -\ln(R)$. When the total pump pulse area A exceeds the threshold area A_t, the difference $A - A_t$ is used up for laser oscillation. During laser oscillation (for time $t_t \leq t \leq T$), Eq. (1) becomes

$$\frac{\partial n}{\partial t} = -2cn_t\phi\sigma + W_p(n_0 - n_t) = 0. \tag{6}$$

In Eq. (6) a constant population inversion density n_t and a constant photon density ϕ are assumed. In reality, the output consists of a series of random spikes. The parameters n_t and ϕ must therefore be considered as average values for the whole laser pulse length. Since $\partial\phi/\partial t = 0$, it follows from Eq. (2) that the output energy

$$E_{out} = Vh\nu\frac{\gamma_1}{\gamma}\int_{t_t}^{T}\left(\frac{\phi}{\tau_d}\right)dt = Vh\nu\frac{\gamma_1}{\gamma}\int_{t_t}^{T} cn_t\phi\sigma dt, \tag{7}$$

where h is Planck constant and V is the laser resonator volume. By combining Eqs. (6) and (7), the relation between output energy and pump area is obtained as

$$E_{out} = \frac{1}{2}Vh\nu\frac{\gamma_1}{\gamma}\int_{t_t}^{T} W_0(n_0 - n_t)dt$$
$$= \frac{1}{2}Vh\nu\frac{\gamma_1}{\gamma}(n_0 - n_t)[A(E_{in}) - A_t]. \tag{8}$$

The pump area $A(E_{in})$ is defined by Eq. (8) only for input energies above threshold. It is assumed that the measured output energy data points can be fitted to a sufficiently low order polynomial[5]

$$E_{out} = E(E_{in}) = a_0 + a_1 E_{in} + a_2 E_{in}^2 +, \cdots. \tag{9}$$

It is also assumed that this polynomial describes adequately the pump area below the threshold. The pump area can be obtained from

$$A(E_{in}) = \frac{E(E_{in})}{K} + A_t, \tag{10}$$

$$K = \frac{1}{2}Vh\nu\frac{\gamma_1}{\gamma}(n_0 - n_t). \tag{11}$$

In these expressions the total loss γ is an unknown parameter, and can be calculated from the zero-order term a_0 of the polynomial $E(E_{in})$. Namely, by inserting the polynomial of Eq. (9) into Eq. (8), we can get

$$a_0 = -KA_t = \frac{1}{2}Vh\nu n_0\frac{\gamma_1}{\gamma}\left(1 - \frac{\gamma}{G_0}\right)\ln\left[\frac{1}{2}\left(1 - \frac{\gamma}{G_0}\right)\right]. \tag{12}$$

From Eq. (11) we can see a_0 depends on the material and resonator properties, and is independent of the particular pumping conditions. Since the fit to the output energy data in a nonlinear regime brings larger error than a linear regime to the value of a_0, it is better to measure a_0 in a linear regime. We carried out the laser experiment with pulse duration of 2.3 ms, which makes laser operating in a linear regime.

Once $A(E_{in})$ is known, it is possible to calculate inversion density. The maximum normalized inversion density $N = n/n_0$ that can be achieved with a flashlamp pulse of energy E_{in} is obtained from

$$N = 1 - 2\exp[-A(E_{in})]. \tag{13}$$

This situation corresponds to the inversion population pumping during ΔT measurements which in our experiment were carried out without resonator mirrors. The maximum energy stored in the inverted population E_{st} during a flashlamp pulse can be calculated from $E_{st} = Vh\nu n_0(N + 1)/2$.

The free-oscillating output energy characteristics are shown in Fig. 1. The linear fit gives $a_0 = -72.3$ mJ. By using the values $V = 1.63$ cm^3, $h\nu = 1.30 \times 10^{-16}$ mJ, $n_0 = 0.282 \times 10^{19}$ /cm^3, $\gamma_1 = 0.163$, $\sigma = 7.40 \times 10^{-21}$ cm^2, and $G_0 = 0.960$, the total loss was calculated to be $\gamma = 0.469$. Then we can get $K = 52.8$ mJ and $A_t = 1.36$ from Eqs. (11) and (5), respectively.

The pump area calculated from Eq. (10) and the maximum normalized inversion density calculated from Eq. (13) are shown in Fig. 2. The dashed line represents the normalized threshold inversion density of $N_t = 0.489$.

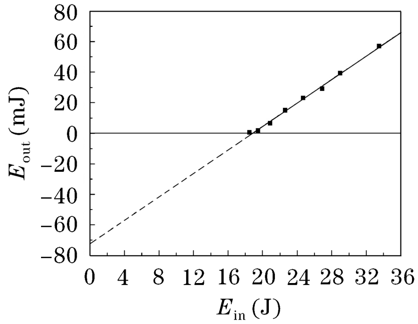

Fig. 1. Free-oscillating output energy versus input energy.

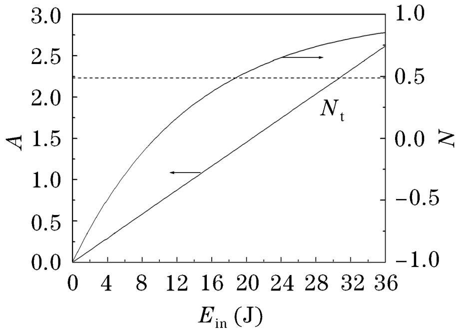

Fig. 2. Pump area and normalized inversion density versus input energy.

The energy value of the intersectional point of the threshold inversion density line and the maximum normalized inversion density curve represents the threshold energy.

Temperature rises ΔT following isolated flashlamp pulses with duration of 2.3 ms are shown in Fig. 3. Full line represents least-square second-order polynomial fit to the data points. The heat deposition Q in the rod is given by

$$Q = \Delta T C \rho V', \tag{14}$$

where C is the specific heat, ρ is the density of the glass, and V' is the rod volume. The heating parameter η defined as the ratio of the generated heat and the energy stored in the inverted population during pumping is calculated from[10]

$$\eta = \frac{Q}{E_{\mathrm{st}}} = \frac{2\Delta T C \rho V'}{V h\nu n_0 (N+1)} = \frac{2C\rho}{h\nu n_0'} \cdot \frac{\Delta T}{(N+1)}, \tag{15}$$

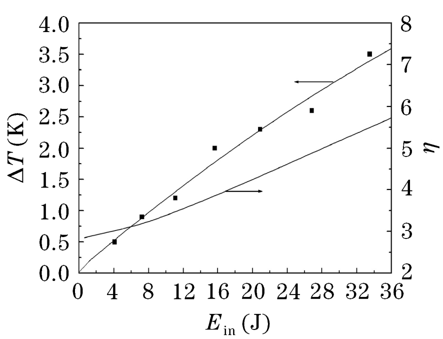

Fig. 3. Temperature rises and heating parameters versus input energy with pump pulse duration of 2.3 ms.

Table 1. Temperature Rises and Heating Parameters of Cr,Yb,Er Co-Doped Phosphate Glasses at Input Energy of 27 J

Glass	Cr14-05	QE-7S[5]	QE-7[5]
Temperature Rise (K)	2.6	2.6	3.2
Heating Parameter	6.2	5.8	8.5

where n_0' is the Er^{3+} ions concentration in the glass. A variation of the calculated heating parameter with the input energy is also shown in Fig. 3. The values $\rho = 3.11$ g/cm^3 and $C = 0.8$ J/(g·K)[13] were used. The increase of the heating parameters with the input energy can be attributed mostly to the saturation of the upper laser level. The temperature rises and heating parameters of Cr14-05 glass, Kigre QE-7S glass and QE-7 glass at input energy of 27 J under similar testing conditions are listed in Table 1. From Table 1 we can see the temperature rise and heating parameter of Cr14-05 glass are close to Kigre QE-7S glass and less than QE-7 glass.

In conclusion, energy storage and heat deposition in Cr14-05 glass were measured. The results provided important information for the glass operating in Q-switched mode and for calculating the temperature profiles and cooling requirements of the glass under various single shot and repetitive pulsed conditions.

This work was supported by the International Cooperation Project of Shanghai Municipal Science and Technology Commission under Grant No. 05S207103. L. Chen's e-mail address is leon@mail.siom.ac.cn.

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