Research on gain characteristics in a solid-state heat-capacity laser

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Based on the laser rate equations in a typical four-level system, we research the temperature-dependent gain characteristics of a solid-state heat-capacity laser (SSHCL) involving the small-signal gain coefficient and the gain distribution's uniformity. The influences of doping concentration of active ions and initial operating temperature on the small-signal gain coefficient are discussed for Nd-doped glass heat-capacity laser. Furthermore, the gain distributions of a slab laser gain medium operating in SSHCL mode are discussed.

OCIS codes: 000.4430, 140.3430, 140.3530.

It is well known that waste heat deposited in the lasing medium limits the amplification of the output power in high-average-power solid-state lasers. Thermal induced effects, which include thermally induced stress, thermal focusing, and depolarization, seriously degrade quality of the wave front. By so far, scientists have researched lots of methods to control the thermal effects, among these approaches, operating the lasing medium in a heat-capacity mode is a new and effective way. Solid-state heat-capacity laser (SSHCL), in which the waste heat produced during the lasing procedure is reserved in gain medium with simultaneous cooling absented, has attracted many scientists to explore its special features as soon as the concept of SSHCL was firstly originated by Lawrence Livemore National Laboratory (LLNL) in 1995[1].

In the last few years, this technology has been proved to be scalable to very high average output power with good beam quality. The flash-lamp pumped Nd:glass laser with average power of 10 kW at repetition frequency of 20 Hz was first reported by Rotter[2]. The laser diode array pumped neodymium-doped gadolinium gallium garnet (Nd:GGG) heat-capacity laser with average power of 30 kW with 200-Hz repetition rate was proposed later by Hecht[3]. The latest report is that 67 kW of average power with five Nd:YAG transparent ceramic slabs for short fire durations was achieved by LLNL in March, 2006[4]. It is the improvement in laser beam quality, system compactness and feasibility to be scale-amplified that makes its bright application future in directed-energy technologies.

During the excitation period of a SSHCL, the absence of cooling leads to waste heat accumulated in the laser gain medium, then the output energy of SSHCL will be influenced by the continuously increased temperature of lasing medium. In this paper, based on the rate equations in a typical four-level system, we basically discuss several factors contributing to the gain characteristics of some neodymium-doped laser materials operating in the heat-capacity mode when taking temperature-dependence cross section into account.

When constructing a high-power laser facility, the prior theoretical predictions of laser performance are essential to laser design. Based on the fundamental theory of laser, we know that the dynamic behavior of a laser can be described with reasonable precision by a set of coupled rate equations. Considering the four-level laser system, which is characteristic of Nd^{3+} ions doped in glass or crystalline host materials, is shown in Fig. 1[5].

Note that when operating in simultaneously cooling mode, the laser gain medium preserves a quasi-thermal equilibrium state. In this situation, the population distributions in all laser levels follow the Boltzmann distribution and in an ideal four-level system the populations in terminal level E_1 can be neglected. While for a SSHCL, the temperature of laser gain medium increases continuously to a large range which is about 150 °C to the Nd-doped mediums. Then n_1 cannot be omitted since the populations in each energy level is changed with the lasing time. In order to simplify the computation, n_0 in a four-level system can be approximated to the total ions in the medium. Furthermore, it is assumed that the transition from the pump band into the upper laser level occurs very rapidly. Therefore the population of the pump band is negligible, i. e., $n_3 \approx 0$, with this assumption the laser rate equations in a typical four-level system operating in heat-capacity mode are[5,6]:

$$\frac{\mathrm{d}n_2}{\mathrm{d}t} = W_\mathrm{p} n_0 - (n_2\sigma_{21} - n_1\sigma_{12})Nc - \frac{n_2}{\tau_\mathrm{f}}, \quad (1)$$

$$n_1 = n_\mathrm{tot} \exp(-\frac{\Delta E}{kT}), \quad (2)$$

$$n_\mathrm{tot} = n_0 + n_1 + n_2, \quad (3)$$

$$\frac{\mathrm{d}N}{\mathrm{d}t} = (n_2\sigma_{21} - n_1\sigma_{12})Nc\frac{l}{L} - \frac{N}{\tau_\mathrm{R}}, \quad (4)$$

where N is the summation of photon number density, n_2 is the upper laser level population, n_1 is the lower laser level population, n_0 is the ground-state population, W_p is the pump rate, n_tot is the total number of active ions per unit volume of laser medium, c is the speed of light, τ_f is the fluorescence lifetime, σ_{21} is stimulated emission cross section, σ_{12} is stimulated absorption cross section, L is the length of cavity, l is the length of gain medium

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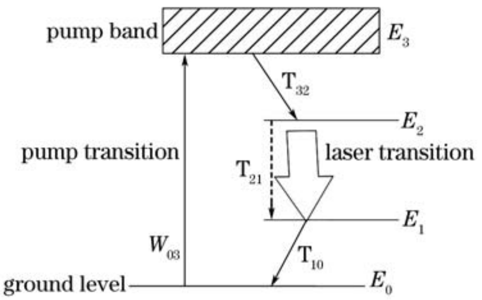

Fig. 1. Simplified four-level system diagram.

and $\tau_{\rm R}$ is the average lifetime of photons in resonant cavity which is described as

$$\tau_{\rm R} = \frac{2L}{c(\delta - \lg R)}, \tag{5}$$

where δ is the round-trip loss per pass, R is the reflectivity of output mirror.

When the population inversion is established, gain coefficient g is expressed as

$$g = n_2\sigma_{21}(T) - n_1\sigma_{12}(T) \tag{6}$$

where σ_{21} and σ_{12} are dependent on the temperature of laser medium. For Nd-doped glass, they are described as[7]

$$\sigma_{12}(T) = \frac{\sigma_{21}(T)\exp[b(T_0 - T)]}{2.26}, \tag{7}$$

$$\sigma_{21}(T) = \sigma_{21}(T_0)\exp[b'(T_0 - T)]. \tag{8}$$

As far as a continuous-wave oscillator is concerned, which a stable cavity is adopted, $\mathrm{d}n_2/\mathrm{d}t$=0. It can be derived from Eqs. (1)−(3) that under the condition that pump power is lower than population-inversion threshold small-signal gain coefficient g_0 is presented as

$$g_0 = \tau_{\rm f} W_{\rm p} n_0 \sigma_{21}(T) - n_1\sigma_{12}(T). \tag{9}$$

There is also alternative formula expressing small-signal gain coefficient: when the pump irradiance is far lower than the saturation flux, gain coefficient is independent of the pump irradiance, and then the small-signal gain coefficient can be expressed in terms of absorbed pump power[5]:

$$g_0 = \frac{\eta_{\rm Q}\eta_{\rm S}\eta_{\rm B}P_{\rm ab}}{I_{\rm S}V}, \tag{10}$$

where $\eta_{\rm Q}$ is the quantum efficiency, $\eta_{\rm S}$ is the Stokes factor, $\eta_{\rm B}$ is the beam overlap efficiency, $I_{\rm S}$ is the saturation flux, V is the effective pump volume of laser gain medium, $P_{\rm ab}$ is the absorbed pump power which is given by

$$P_{\rm ab} = \eta_{\rm P}\eta_{\rm T}\eta_{\rm a}P_{\rm in}, \tag{11}$$

where $P_{\rm in}$ is the electrical input to the pump source, $\eta_{\rm P}$ is diode slope efficiency, $\eta_{\rm T}$ is the transfer efficiency, and $\eta_{\rm a}$ is the absorption efficiency.

Under the condition that $\mathrm{d}N/\mathrm{d}t \geq 0$, the radiation fields in the resonant cavity is enhanced to a intensive stimulated one. The absorbed pump power at threshold which could maintain the system oscillating is

$$P_{\rm pt} = \frac{h\nu V\delta}{\sigma_{21}\tau_{\rm f}\eta_{\rm q}l}. \tag{12}$$

Using the formulas described above, we discuss the gain characteristics of several Nd-doped laser mediums operating in heat-capacity mode, including Nd-doped glass, which will be mainly researched, and Nd-doped YAG. The detailed parameters of Nd-doped glass are taken from Refs. [1,5,7]. The mentioned doping concentration in Nd-doped glass ranges from 1 to 5 wt.-%. Parameters of Nd-doped YAG are taken from Ref. [5].

The influence of laser medium temperature on small-signal gain coefficient is investigated firstly. As we know that the heat-capacity mode of operation is intermediate between single pulse and steady-state operation. During lasing process, the temperature of laser gain medium increases with the lasing time and the laser runs within the limit of the heat capacity of lasing material. Due to temperature dependencie of the cross section, the laser gain will vary with running time also. The value of small-signal gain coefficient could reflect the increasing speed of photon density in optical resonator before the pump intensity reaches the oscillating irradiance at threshold. Therefore, in the case of initial temperature at 273 K, the temperature's influences on gain within 150 K range are researched. Calculation results are shown in Fig. 2 when pump rate is 30 Hz. It can be seen that small-signal gain coefficient will decrease with increasing temperature in lasing medium. With 100-K temperature rise, there will be 12% decrease in g_0. This will cause a corresponding drop on output energy which is consistent with some reported experimental results in tendency[8]. And under the condition that other parameters are uniform, higher pump rate can achieve higher gain.

Furthermore, Fig. 3 illustrates the small-signal gain coefficient variance with the Nd doping concentration in glass with pump rate of 30 Hz. Results show that higher doping concentration can achieve higher laser gain. Whereas, a so-called concentration quenching will occur if the material is excessively doped. On the other hand, the gain medium with lower doping concentration absorbs less pumping energy and thus the output energy is decreased, but it is helpful to weaken the stress in lasing medium[9]. Thus, the contradictions between the gain and stress should be balanced by adopting lower doping content with higher pump rate which is just one of merits in heat-capacity laser.

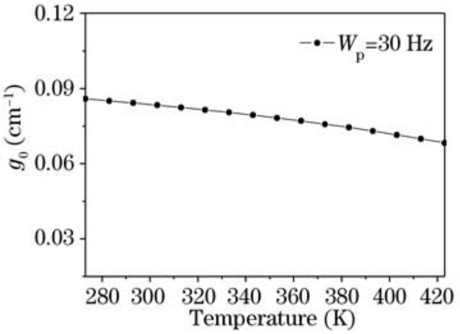

Fig. 2. Dependence of gain coefficient on temperature.

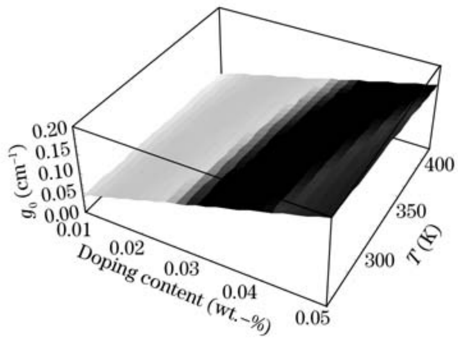

Fig. 3. Relationship between doping concentration and gain coefficient.

At the same time, the influence of different initial working temperatures on small-signal gain coefficient is simulated, as shown in Fig. 4. Typical start temperatures are 253, 273, and 293 K. Calculated results proved that lower initial working temperature makes higher gain. This can be explained from Eq. (2) that the population inversion is easy to be created in lower temperature because the populations in terminal laser level (N_1) will increase with the temperature.

Taken different lasing materials into account, according to Eqs. (10) and (11), the gain characteristics of several Nd-doped laser materials including Nd-doped glass, YAG are researched at the same input power and effective absorbing size. Since the energy-transfer efficiencies of them is different, even if under the same input conditions, the achieved gain is different. The numerical values for the various efficiencies are taken from Ref. [5]. From the calculations, it can be seen that under the situation we suppose that small-signal gain coefficient of Nd-doped YAG is four times higher than that of Nd-doped glass. This is interpreted by the fact that the system efficiency of Nd-doped YAG is a little higher than that of Nd-doped glass, besides, its saturation flux is much lower. SSHCLs' demand for high repetition frequency, also excludes Nd-doped glass from the alternative lasing material for a high average-power SSHCL.

From previous results of our research group[10,11], it is shown that due to the exponential decayed absorbed energy along the pump direction, the temperature distributions in laser mediums operating in heat-capacity mode are not uniform both in absorbing direction and in lasing time. With non-adiabatic boundary conditions or non-uniform pumping, the thermal distributions in the border will be more complex. This leads to non-uniform gain distributions in laser gain medium and thus fluctuate the output beam quality. The non uniformity of gain distributions can be improved by better pump beam distributions or adopting other methods to reduce the thermal gradient in laser gain medium. A composite crystal constituted by active ions doped body and un-doped edge is a novel approach to achieve this goal, as well as minish the parasitic oscillation.

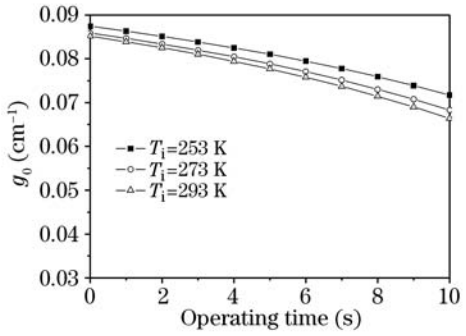

Fig. 4. Relationship between initial working temperature and gain coefficient.

In this paper, based on the rate equations in a typical four-level system, several factors contributing to the gain characteristics of some neodymium-doped laser materials operating in heat-capacity mode are discussed when taking temperature-dependence cross section into account. Results show that, as far as Nd-doped glass is concerned, small-signal gain coefficient will decrease with increasing temperature in lasing medium and in the case that pump rate is 30 Hz there will be 12% decrease in g_0 with 100 K temperature rise. Furthermore, higher doping concentration and lower initial working temperature can achieve higher laser gain. On the other hand, uniformity of gain distributions should be considered to improve the output beam quality. The results are helpful to comprehend the laser mediums' gain characteristics in heat-capacity mode and offer some references to the design of SSHCL.

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