Influence of the thermal effect on stability of the output in a heat capacity laser

Xinying Jiang (蒋新颖), Xiaodong Yuan (袁晓东), Haiwu Yu (於海武), Meijian Xu (徐美健), Dingxiang Cao (曹丁象), and Wentao Duan (段文涛)

Research Center of Laser Fusion, China Academy of Engineering Physics, Mianyang 621900

The stability of the output of a heat capacity laser was measured. The output power dropped rapidly with the increase of lasting time. The result showed that the rise of the average temperature of laser medium was not the main reason, while the non-uniform distribution of the temperature was the main reason which resulted in depolarization and maladjustment of resonant cavity.

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In recent years, solid-state lasers have made significant progress in the thermal management, the laser beam quality and efficiency. The emergence of the heat capacity laser allows us to get both high average power and high beam quality beam, so it becomes new highlight of research of high-power solid-state laser technology at present rapidly[1−3]. However, the operating mode of heat capacity may bring some unique technical problems for heat capacity laser itself, because the internal waste heat of the laser medium will accumulate continuously. Therefore its thermal effect is a dynamic change process, which results in the output-power change. According to the characteristics of waste heat accumulating persistently in laser medium when working on the mode of heat capacity, an unsteady-state thermodynamic model was established based on a practical distribution of gain in the laser medium. Furthermore a theoretical model of the optical transmission was established to study the optical distortion which resulted from the dynamic thermal effect. The theoretical analysis and experimental result both showed that Boltzmann distribution of particle number on lower laser level was not the main reason for the rapid decline of output power with time under the existing experimental conditions, while the main reason was the thermal effect which results in depolarization and maladjustment of resonant cavity.

We used eight $60 \times 30 \times 6$ (mm) Nd:YAG disks. The pumping system was composed of 12 flash lamps and divided into 4 groups. The output energy with a pump duration of 1 ms and repetition frequency of 20 Hz was measured at different lasting time. The result is listed in Table 1. The average power of the heat capacity laser dropped rapidly. For example after 5 seconds, it dropped by 17%.

Table 1. Output Energy and Power of the Heat Capacity Laser at Different Lasting Time

Lasting Time (s)	Total Energy (J)	Average Power (W)
1	88	88
2	167	83.5
3	235	78
4	305	76
5	367	73

Nd:YAG laser is a typical four-level system which can be expressed by rate equations as[4]

$$\frac{\mathrm{d}n_2}{\mathrm{d}t} = W_\mathrm{p} n_0 - \left(n_2 - \frac{f_2}{f_1} n_1\right) \sigma\phi c - \frac{n_2}{\tau_{21} - \tau_{20}}, \quad (1)$$

$$\frac{\mathrm{d}n_1}{\mathrm{d}t} = \left(n_2 - \frac{f_2}{f_2} n_1\right) \sigma\phi c + \frac{n_2}{\tau_{21}} - \frac{n_1}{\tau_{10}}, \quad (2)$$

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

In an ideal four-level system the terminal level relaxes infinitely fast to the ground level. Suppose the lose of laser cavity in a single trip is δ, the threshold of population inversion under normal temperature is

$$n_{2t} \approx \Delta n = \frac{\delta}{\sigma_{21} l}. \quad (4)$$

When the temperature rises, the Boltzmann distribution results in

$$n_1 = n_0 \exp(-E_\mathrm{LL}/kT). \quad (5)$$

We can phenomenologically express the threshold of population inversion as

$$n_{2t} = \Delta n + \frac{f_2}{f_1} n_1. \quad (6)$$

Then the threshold pump power is

$$P_\mathrm{th} = \frac{h\nu_\mathrm{p} V}{\eta_\mathrm{F}\tau_\mathrm{s}} n_{2t} = \frac{h\nu_\mathrm{p} V}{\eta_\mathrm{F}\tau_\mathrm{s}} \left[\frac{\delta}{\sigma_{21} l} + \frac{f_2}{f_2} n_0 \exp\left(\frac{-E_\mathrm{LL}}{kT}\right)\right]. \quad (7)$$

The output power of the laser is

$$P_\mathrm{out} = \sigma_\mathrm{s} \left(P_\mathrm{in} - P_\mathrm{th}\right), \quad (8)$$

where σ_s is the slope efficiency of the laser under normal temperature. In an integrity last duration, the average temperature rising can be analyzed numerically. The expressions are

$$\begin{cases} \rho C \frac{\partial T(x,y,z)}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + q_v \\ T(x,y,z;0) = T_0 \\ -\kappa \frac{\partial T}{\partial \vec{n}}\Big|_{\sum i} = h_\mathrm{c}(T - T_\mathrm{gas}) \end{cases}, \quad (9)$$

where $\sum$ is the surface of laser slab, κ, ρ, c are respectively thermal conductivity coefficient, mass density, and heat capacity of the laser slab, h_c is the coefficient of heat transfer, q_v is heat production rate. Now we can deduce that the influence of thermal effect on the output

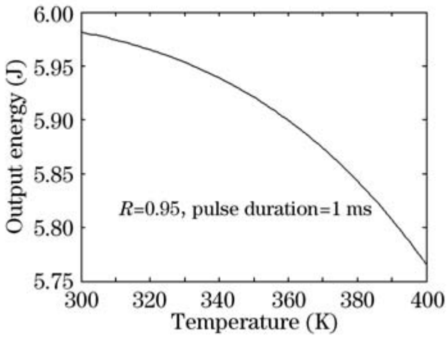

Fig. 1. Energy dropping caused by Boltzmann distribution of particle number as temperature rising.

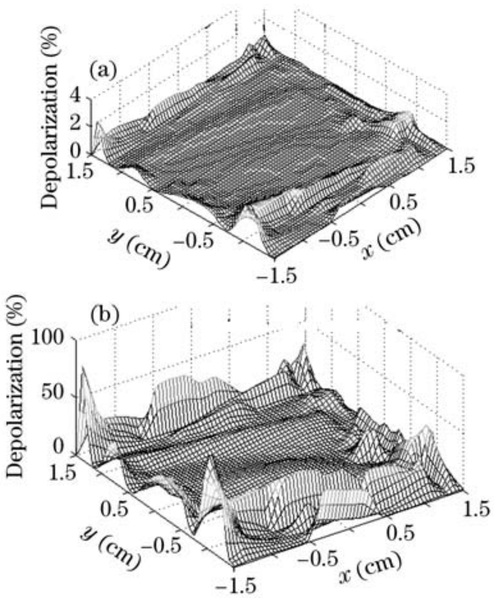

Fig. 2. Depolarization distribution of laser on the masking aperture at (a) 2 and (b) 5 seconds.

power has two aspects. One is the the threshold pump power, and the other is the loss δ caused by non-uniform temperature distribution. The temperature of the laser disks is non-uniform because the distribution of pumping light is not uniform on the surface of the disks and the absorption of the medium in the thickness dimension is also non-uniform. The non-uniform distribution of temperature can cause thermal stress which results in a depolarization.

When we only consider the average temperature rise, the loss δ is a constant, the Boltzmann distribution of particle number causes the threshold pump power rising, then the output energy/power dropping. This phenomenon was simulated. The result is shown in Fig. 1. As we can see, when ΔT of the slab is 50 K, the dropping rate of the laser energy is only 1%.

The thermal distribution causes depolarization. When the slabs were put in a Brewster angle, the dropping caused by depolarization is remarkable. The depolarizations at different time in a laser lasting periods were simulated. The outcome indicates that the losses of output power are 1.7% and 13.71% at 2 and 5 seconds, respectively. The distribution of loss is shown in Fig. 2. The average ΔT of the slab is only 45 K.

In conclusion, the influence of thermal effect is analyzed. The reason of the rapid decline of output power has two facets, one is the average temperature rising, the other is the non-uniform temperature distribution which causes depolarization. We found that the former is obviously less than the latter. To increase the stability of the output power of a heat capacity laser, we must try to avoid the thermal depolarization.

X. Jiang's e-mail address is noveltymm@126.com.

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