# Heat distortion influence on laser output with different cooling conditions

**Jindong Li (李劲东), Mingxiu Guo (郭明秀), Wenqiang Fu (付文强), Qiquan Hu (胡企铨), and Xiangchun Shi (施翔春)**

*Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800*

A laser diode (LD) stack pumped solid-state laser (DPL) with different cooling conditions was reported. The thermal lens was calculated and compared under different cooling conditions. The influence of the thermal lens effect on the output energy fluctuation of the DPL was studied. The LD stacks peak power was 12 kW with 1-kHz repetition frequency and 20% duty ratio. In the examination with nothing to cool the solid-state heat capacity laser (SSHCL), the output power was 1 J at the beginning, after 1 s it fell down to 50%, and with the water cooling the output power hardly fell down.

*OCIS codes:* 140.0140, 140.3410, 140.4780.

Laser diode (LD) pumped solid-state lasers are useful in a wide variety of fields, such as materials processing, spectroscopy, remote sensing, due to its simple structure, high efficiency, long life. Because of thermal lens and stresses[1−4] the traditional symmetric rod lasers have power limitations and distortion of the laser beam. Lawrence Livermore National Laboratory (LLNL) has first brought forward the concept of solid-state heat capacity laser (SSHCL). It is a good way to get high power and good laser beam. The difference between the SSHCL and the tradition laser system is that at the working time the laser material does not be cooled, after the temperature of the laser material becomes enough high to stop work and cool down. Under that condition the laser material does not become steady-state and makes the output instable[5]. The thermal effects which occur in the laser material are thermal lens and thermal stress-induced birefringence. The thermal lens make the laser material become a nonideal lens. With the thermal effects accumulating the thermal lens focus becomes shorter than the resonator length, which makes the resonator become unstable[2,6]. To get steady output, one must optimize the resonator parameter. Many researches have been done for the optimization only after the laser material becomes steady-state. To get steady output laser system the influence of the thermal effects on the output energy should be studied. Theory calculation and research have been reported before the laser material becomes steady-state at the SSHCL and water cooling in this paper.

By equation of thermal conductivity and the stress/strain relationships we can get the transient temperature and stress/strain distribution, and by the photoelastic effects the modification of index due to the temperature changing and the stress induced isknown, so the thermal lens focus dependent on time could be figured out. In the experiment we observe the output variety in one second at SSHCL and water cooling condition.

The laser material is Nd:YAG with the dimension of $57 \times 40 \times 4$ (mm) in the $z$, $x$, $y$ directions as shown in Fig. 1. The pump beam is focused as small as $15 \times 57$ (mm) in profile size with average power 2.4 kW, and the working time lasts 1 s.

The temperature distribution in medium is governed by[7]

$$pc\frac{\partial T(x,y,z)}{\partial t} = k(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}) + q_v, \quad (1)$$

$$T(x,y,z;0) = 300, \quad (2)$$

$$-k\frac{\partial T}{\partial n} = h_c(T - T_{\text{out}}), \quad (3)$$

where $p$ is the mass density, $c$ is the specific heat capacity, $k$ is the thermal conductivity, $T$ is the temperature, $q_v$ is the thermal power per unit volume. From the equations, one can get the transient temperature of one second. Figures 2(a) and (b) show the laser material temperature distributions of SSHCL and water cooling at one second, respectively. The temperature distributions in the laser slabs of SSHCL and water cooling along the $x$ axis are shown in Figs. 3(a) and (b), respectively. The temperature of water cooling is lower than that of SSHCL due to the surface heat transfer. From Fig. 2(a) we know the middle temperature is higher than the edge one because the pump power is compressed by lens to increase the power density and the temperature gradient in this direction is maximum, so the thermal lens focus of $x$ direction has more influence than that of the $y$ direction.

The temperature distributions in the laser slabs of SSHCL and water cooling along the $y$ axis are shown in Figs. 4(a) and (b). Because of the thickness of YAG being only 4 mm and the good thermal conductivity of it the temperature gradient in this direction is lower than that in the $x$ direction, so this direction is ignored.

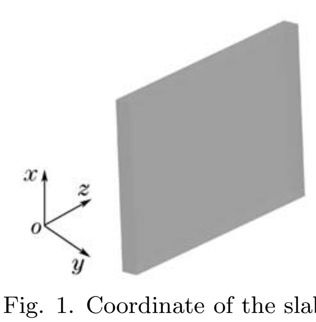


Fig. 1. Coordinate of the slab.

 

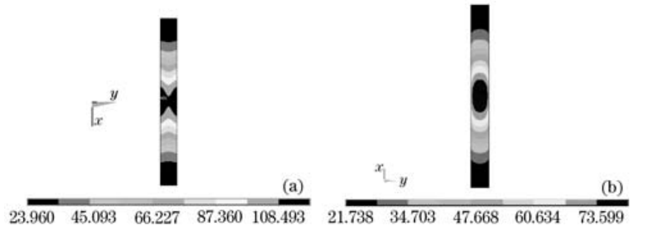


Fig. 2. Temperature distributions of (a) SSHCL and (b) water cooling at one second.

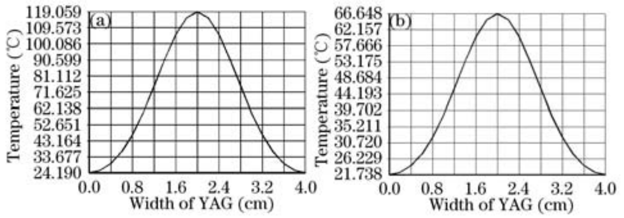


Fig. 3. Temperature distributions in the laser slab along the $x$ axis of (a) SSHCL and (b) water cooling at one second.

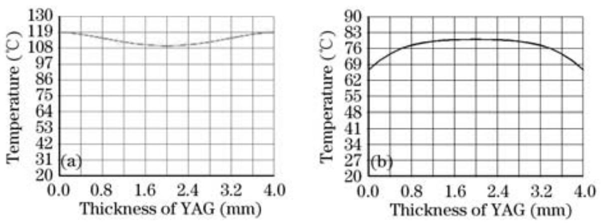


Fig. 4. Temperature distributions in the laser slab along the $y$ axis of (a) SSHCL and (b) water cooling at one second.

The non-uniform temperature distribution induce thermal stress in the laser material. We can get the stress and strain by[8]

$$\sigma_{xx} = 0,\ \sigma_{yy} = \frac{E\alpha}{(1-\nu)} T'(x),\ \sigma_{zz} = \sigma_{yy}, \tag{4}$$

where $\sigma_{xx}$, $\sigma_{yy}$, and $\sigma_{zz}$ are the stresses of $x$, $y$, $z$ directions, $E$ is Young's modulus, $\alpha$ is the thermal expansion coefficient, $T'(x)$ is the temperature.

Equations (3) and (4) uniquely determine the stress distribution. Figures 5(a) and (b) show the stress distributions in the laser slabs of SSCHL water cooled at one second, respectively.

The stress distributions in the laser slabs of SSCHL and water cooling along the $x$ axis are shown in Figs. 6(a) and (b), respectively. From Fig. 6(a) we can see

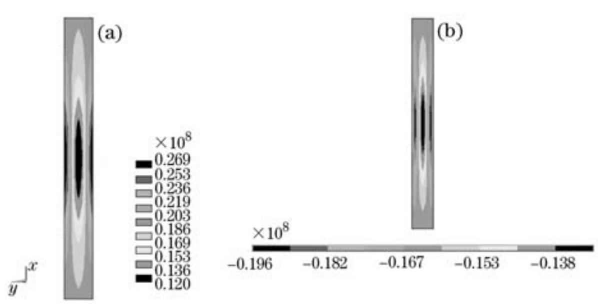


Fig. 5. Stress distribution in the laser slabs of (a) SSCHL and (b) water cooling at one second.

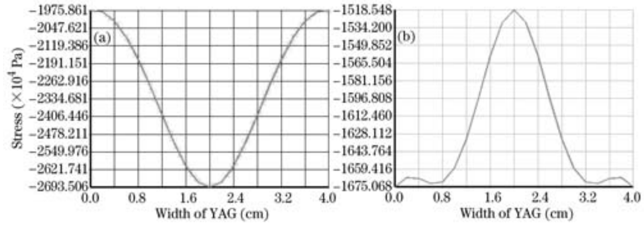


Fig. 6. Stress distribution in the laser slabs of (a) SSCHL and (b) water cooling along the $x$ axis at one second.

that there is compression stress at the material surface. The maximum compression of 269 kg/cm$^2$ is only 15% of the tensile strength of Nd:YAG of $1800-2100$ kg/cm$^2$.

The temperature and stress induced effects on refraction index depend on[8,9]

$$\begin{aligned} n_{xx} &= n + \frac{\mathrm{d}n}{\mathrm{d}T} T'(x) + B_{\perp}\sigma_{zz} + B_{//}\sigma_{xx}, \\ n_{yy} &= n + \frac{\mathrm{d}n}{\mathrm{d}T} T'(x) + B_{\perp}(\sigma_{zz} + \sigma_{xx}), \\ B_{\perp} &= 0.34 \times 10^{12}/\mathrm{Pa}, \\ B_{//} &= -0.91 \times 10^{12}/\mathrm{Pa}, \end{aligned} \tag{5}$$

where $n$ is the refraction index, $n_{xx}$ is refraction index of $x$ direction, $n_{yy}$ is refraction index of $y$ direction, $\frac{\mathrm{d}n}{\mathrm{d}T}$ is the change of the refraction index with temperature, $\sigma_{xx}$, $\sigma_{zz}$ are the stresses of $x$, $y$ directions. Equation (5), along with Figs. 4 and 6, determines the refraction index of the laser material as shown in Fig. 7.

Collimated light beam passes through the material with the index distribution like the laser material we can simulate the thermal lens as Fig. 8. Figure 9 shows the dependence of focus length on the time. From it we can see after 0.2 s the thermal lens focus is shorter than the resonator, the resonator becomes an unstable resonator, this makes the output descend[10]. But when the laser material is cooled by water this decline could be postponed.

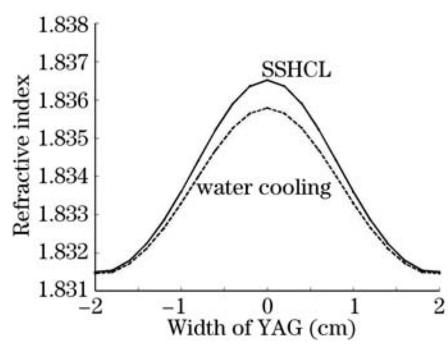


Fig. 7. Refractive index distribution in the laser slab along the $x$ axis after one second.

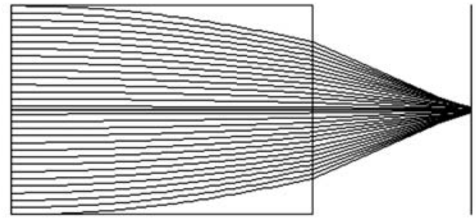

Fig. 8. Calculated light distribution.

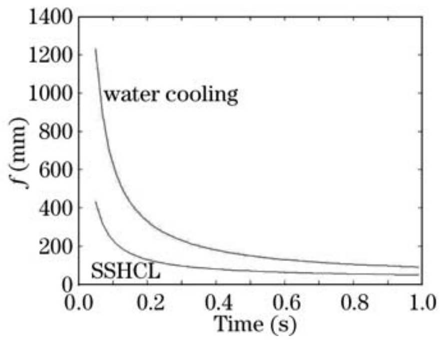


Fig. 9. Dependence of focus length on the time.

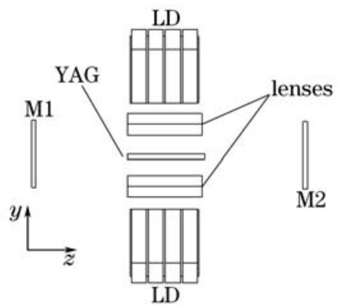


Fig. 10. Configuration of laser system.

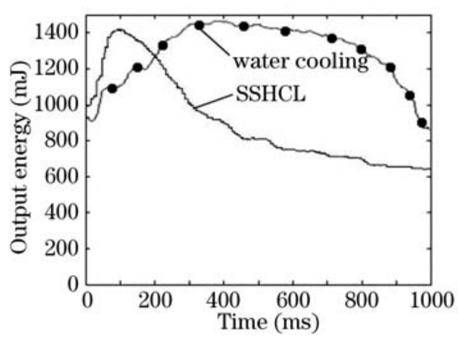


Fig. 11. Dependence of output energy on the time in 1 s.

In the experiment the side-pumped laser material is shown in Fig. 10, where M1 is highly reflecting mirror, M2 is coupling-out mirror. To improve the power density we compress the LD with microlens and cylindrical lens. The maximum output pulse energy of 1 J with the frequency of 1 kHz is achieved from a plano-plano cavity with an output couple of 30%. Figure 11 is the dependence of output energy on the time. From it we know at beginning the output is ascent, but the output becomes descent with the time when the thermal lens focus is shorter than the resonator length. At the end of working time 1 s the output decreases to 60% but the water cooling can postpone and reduce the descent.

In summary, we have successfully designed a laser system with output of 1 J at 1 kHz. The temperature and stress have been thoroughly analyzed in an entirely general way and we got the relationship between thermal lenses with time and pump power. The reason of descent has been found which gives support to design high-power laser system.

J. Li's e-mail address is trampingnow@hotmail.com.

## References

1. G. F. Albrecht, S. B. Sutton, E. V. George, W. R. Sooy, and W. F. Krupke, Laser and Particle Beams **16,** 605 (1998).
2. R. Mark, D. Dane, and D. C. Brent, Photon. Spectra **38,** (8) 44 (2004).
3. G. F. Albrecht, S. B. Sutton, E. V. George, W. R. Sooy, and W. F. Krupke, Proc. SPIE **3343,** 661 (1998).
4. F. Jin and D. Zhou, Laser Technol. (in Chinese) **28,** 534 (2004).
5. W. Xie, J. Yu, and C. Bi, Chin. J. Lasers (in Chinese) **33,** 70 (2006).
6. H. Hu, J. Jiang, B. Tu, L. Cui, T. Zhou, Z. Cai, and C. Tang, Chin. J. Lasers (in Chinese) **32,** 1485 (2005).
7. X. Yuan, X. Jian, and D. Cao, Chin. J. Lasers (in Chinese) **33,** 93 (2006).
8. J. M. Eggleston, T. J. Kane, K. Kuhn, J. Unternahrer, and R. L. Byer, IEEE J. Quantum Electron. **20,** 289 (1984).
9. T. J. Kane, J. M. Eggleston, and R. L. Byer, IEEE J. Quantum Electron. **20,** 289 (1984).
10. J. Liu, J. Lu, and J. Lü, Chin. Phys. Lett. **16,** 181 (1999).