≪소논문≫ The Journal of Optical Society of Korea (Korean Edition) Volume 4, Number 3, September 1993

Temperature Limitation for Safe Operation in a Slab Laser Glass Set by Thermal Fracture

Byung-Tai Kim
Department of Physics and Optical Engineering, Chongju University, Chongju 360-764, Korea

(Received: June 21, 1993)

The temperature distribution inside a zigzag slab laser glass was measured using a Mach-Zehnder interferometer. The temperature difference between the center and the surface of the slab caused the fracture of the slab glass. Two laser glasses were fractured at a temperature difference ΔT_o of 110℃, and 62℃, respectively. For the design of high-average power glass laser, it is recommended that the limit of the temperature difference ΔT_o inside the slab glass should be smaller than 50℃ for safe operation.

The design of high-average power solid-state laser is mainly limited by the rate of heat dissipation from an active medium.[1-4] The bulk active medium of a solid-state laser is heated through the absorption of optical pump radiation, but only their surfaces are cooled by a coolant. The temperature distribution in the active material is determined by the balance between the heat generation due to absorption of pump radiation and the heat removal by cooling process.[5,6] The nonuniform temperature distribution at the active medium results in the fracture of the active medium due to thermal stress and the distortion of the laser beam due to a temperature-dependent refractive index.

Advanced Nd:glass laser applications which require increasingly higher average output power necessitate operation near the fracture limit of laser glass.[5] The output power is limited by the possible material fracture arising from thermally induced stress which is basically caused by deposited power in the active medium.

This paper presents the temperature limitation in the slab due to thermal fracture which should be considered in the design of high-average power Nd:glass zigzag slab lasers.

We used two kinds of laser glasses which were a phosphate glass, LHG-5, with 8 wt percent Nd doping with gas cooling and a silicate one, LSG-91H, with 6 wt percent Nd doping with pure water cooling. The slab dimensions on the Brewster angle cut are 228×65×5 mm for LHG-5 and 221×65×5 mm for LSG-91H with a zigzag optical path of 20 internal reflections. The beam at the output face has a rectangular shape of 50×5 mm. The laser glass is supported by Teflon spacers at the both edges of a slab glass in order to eliminate the static wavefront distortions which are often caused by the mechanical O-ring fixtures. This supporting structure acts also as thermal isolation and reduces the beam wavefront distortion caused by the sharp temperature gradient due to the heat conduction in the glass edge. The laser glass is pumped by 32 xenon flashlamps(ILC/5F2C) from both sides of the slab surfaces at a right angle to the optical axis. The pumped cross section is 200×50 mm.

The problems associated with the heat flow in the active medium are well known and should be well understood in order to analyze thermal effects. The temperature distribution[7] in the active medium can be obtained from a two dimensional problem governed by the time dependent equation,

$$\left(\frac{\rho C}{\kappa}\right)\left(\frac{\partial T}{\partial t}\right)=\nabla^2 T+\frac{Q(x,y,t)}{\kappa}, \tag{1}$$

where $T(x, y, t)$ is the temperature, $Q(x, y, t)$ is the thermal power loading per unit volume, κ is the thermal conductivity, C is the specific heat, and ρ is the mass density. At steady state condition Eq. (1) becomes time independent equation

$$\nabla^2 T - \frac{Q(x, y)}{\kappa} \tag{2}$$

The thermal power loading per unit volume at the y-direction, which is the direction of thickness, can be expressed as

$$Q = \chi \alpha P_o \left[\exp\left\{ -\alpha\left(y + \frac{d}{2}\right) \right\} + \exp\left\{ \alpha\left(y - \frac{d}{2}\right) \right\} \right], \tag{3}$$

where d is the slab thickness, α is the absorption coefficient, P_o is the incident power at the slab face, and χ is the ratio of the generated heat to the absorbed pump light by the slab. The thermal boundary conditions at the slab surface in the y-direction are given by

$$\kappa \frac{\partial T}{\partial y} \Big|_{y\ \pm d/2} = h\left[T_c - T\left(y = \pm \frac{d}{2}\right) \right], \tag{4}$$

where the coolant temperature T_c is about 25℃ in the present experiment, and h is the surface heat transfer coefficient.[7] The latter is expressed as

$$h = 0.664 \left(\frac{\kappa_c}{L_c} \right) \left(\frac{U_o L_c}{\nu} \right)^{1/2} P_r^{1/3} \tag{5}$$

under laminar flow condition, where κ_ψ is the thermal conductivity of the coolant, L_c is the effective length of the coolant flow, ν is the kinematic viscosity, U_o is the coolant velocity, and P_r is Prandtl number. The experimental surface heat transfer coefficient[8] can be taken as the relation

$$h = \frac{q}{(T_s - T_c)}, \tag{6}$$

were q is the heat flux, and T_s is the temperature on the slab surface. The coolant velocity can be calculated from

$$U_o = \frac{V_c}{S}, \tag{7}$$

where V_c is the coolant flow, and S is the effective cooled cross section at the slab surface. The Equation (2) has the solution in the y-direction

$$T(y) = T_a + T'(y), \tag{8}$$

where T_a is the average temperature in the slab, and $T'(y)$ is the deviation from the average slab temperature. When χ is assumed to be 1, these are calculated as

$$T_a = T_c + \left(\frac{P_o}{\alpha \kappa} \right) \{1 + \exp(-\alpha d)\} - P_o \left\{ \left(\frac{2}{\alpha^2} \kappa d \right) - \left(\frac{1}{h} \right) \right\} \{1 - \exp(-\alpha d)\}, \tag{9}$$

$$T'(y) = \left(\frac{2P_o}{\alpha^2 \kappa d} \right) \{1 + \exp(-\alpha d)\} - \left(\frac{P_o}{\alpha \kappa} \right) \left[\exp\left\{ -\alpha\left(y + \frac{d}{2}\right) \right\} + \exp\left\{ \alpha\left(y - \frac{d}{2}\right) \right\} \right]. \tag{10}$$

The temperature distribution depends on the product of the absorption coefficient, α, and the thickness, d, of the active material. Using Equations (8), (9), and (10), the temperature variation in the slab of LHG-5 phosphate glass with a thickness of 5 mm was calculated under the condition of an input pumping power of 2 kW and a N_2 gas flow of 360 l/min. Fig. 1 shows the temperature variation in the slab of LHG-5 phosphate glass cooled by N_2 gas. Following these calculation data the active medium has to be carefully selected in the development of high-average power laser because the large product αd results in large temperature elevation of the active medium and the coolant, which have a crucial effect on the fracture of the active medium.

The fracture of the slab glass depends on the tem-

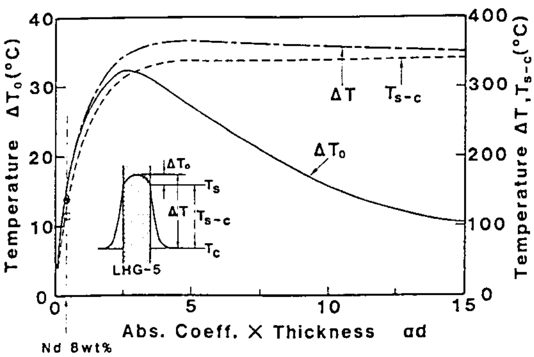

Fig. 1. Temperature variation in the slab and the coolant with 2 kW input power and 360 l/min N_2 gas flow.

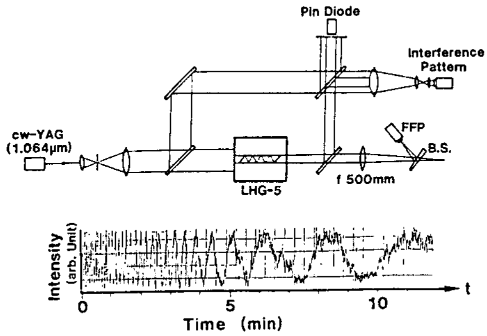

Fig. 2. Optical arrangement using Mach-Zehnder interfermeter to measure the fringe shift due to the temperature change.

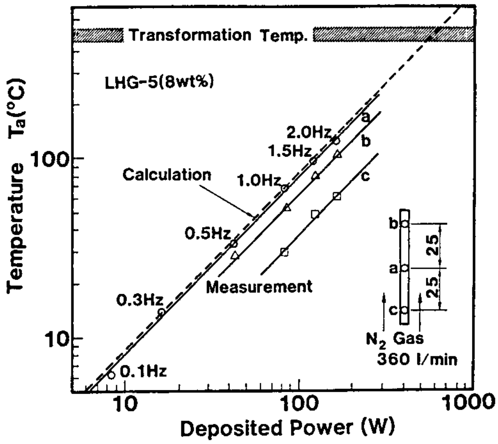

Fig. 3. Temperature distribution in the slab and the coolant under steady state operation of 0.1 Hz to 2 Hz repetition rate with a pumping energy of 1 kJ and a N_2 gas flow of 360 l/min.

perature difference inside the active medium under repetitive pulsed operation. The temperature in the slab laser glasses was measured using a Mach-Zehnder interferometer as shown in Fig. 2. A cw-YAG laser with a wavelength of 1.064 μm was used as a probe beam. The lower part of Fig. 2 was the fringe shift of the probe beam, which was recorded by a pen recorder with a pin diode. It was recorded while interference patterns and far field patterns(FFP) of the probe beam were checking up using CCD camera. The fringe shift of the probe beam was counted at the center of the slab and at ±2.5 cm away from the center through a pinhole with 400 μm diameter. The temperature rise can be calculated by the following relation[9]

$$T_a=\left(\frac{N_f\lambda}{l}\right)\left\{(n-1)\beta+\left(\frac{dn}{dT}\right)\right\}^{-1}$$

$$=\left(\frac{N_f\lambda}{l}\right)\left(\frac{dl}{dT}\right)^{-1}, \tag{11}$$

where N_f is the number of fringe shift at steady state, λ is the appropriate Nd:YAG wavelength, n is the refractive index, β is the thermal expansion coefficient, and l is the optical path length. In the case of the LHG-5 phosphate glass with $dl/dT=4.6\times10^{-6}$/℃ and $l=249$ mm, the average temperature can be written as

$$T_a=\frac{N_f\lambda}{1.1454} \tag{12}$$

Fig. 3 shows the temperature distribution in the slab and the coolant as a function of deposited thermal power. The temperature was measured at the center, top, and bottom of the slab at steady state of 0.1 Hz to 2 Hz repetition rate under an input energy of 1 kJ and a N_2 gas flow of 360 l/min. With 2 kW pumping power the average temperature T_a of the slab at the position **a** was 119℃, and the temperature difference ΔT_o between the center and the surface of the slab at the position **a** was calculated to be 13.6℃ using Eq. (12). The temperature difference between the position **a** and the position **c** was about 63℃, which was affected by the coolant flow direction.

The fracture of slab glasses was tested for two silicate glasses, LSG-91H. The LSG-91H silicate glass was operated under an input power of 20 kW(4 kJ/5 Hz) which was a deposited power density of 36.4 W/cm^3 in the laser glass, and a pure water flow of 25 l/min, and it was fractured after 70 second operation. The average temperature T_a and the temperature difference ΔT_o inside the slab were about 195℃ and 110℃, respectively. Another laser glass was fractured at a deposited power density of 20.6 W/cm^3 in another experiment, too. In this case, the temperature difference ΔT_o in the slab was 62℃. Fig. 4 shows the temperature differences, ΔT and ΔT_o, in the slab and the coolant, respectively, which are calculated by the Eq. (8) below 4kJ pumping energy. From this result the temperature

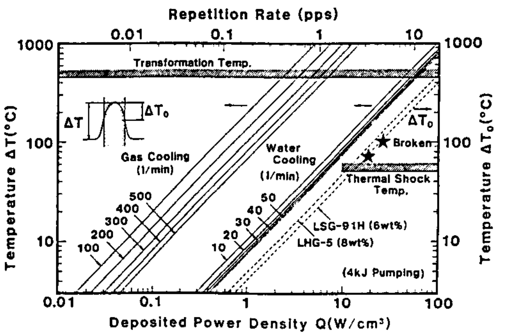

Fig. 4. Temperature difference in the slab, LHG-5 phosphate glass and LSG-91H silicate glass, and coolant for safe operation with respect to deposited power density and repetition rate.

difference ΔT_o causes the slab fracture, which is over 50℃. The maximum deposited power per unit volume is about 16 W/cm^3 under pure water cooling. In the case of N_2 gas cooling, the temperature difference ΔT limits the laser operation. It seems to be below half of the transformation temperature of the laser glass, which is about 200℃. The maximum deposited power per unit volume is about 3 W/cm^3. It is because of the capacity difference of heat removal between N_2 gas and pure water, which is due to the thermal conductivity of the coolant. The laser operation limitation can be estimated by using these data in the present apparatus. And this temperature limitation will be a crucial point in the design of a high-average power Nd:glass slab laser.

In conclusion, the temperature distribution was calculated and measured in the slab laser glasses. In order to design high-average power glass laser, the product of the absorption coefficient and the slab thickness is a very important parameter because the large one results in large temperature elevation of the slab and the coolant. The large temperature difference between the center and the surface of the slab caused the fracture of the slab glass during the repetitive operation. In the design of high-average power glass laser, it is recommended that temperature difference inside the slab laser glass should be smaller than 50℃ for safe operation.

The author would like to thank Mr. Y. Oishibashi of the Sanyo Electrical LTD. for his experimental helps, and Prof. M. Nakatsuka and Prof. S. Nakai for the valuable and patient guidence of this research at ILE, Osaka University.

참 고 문 헌

[1] J. E: Marion, J. Appl. Phys. **60**(1), 69(1986).
[2] D. Eimerl, J. Marion, E. K. Graham, SPIE **736**, 54(1987).
[3] K. Mann and H. Weber, J. Appl. Phys. **64**(3), 1015 (1988).
[4] W. Koechner, *Solid-State Laser Engineering* (Springer-Verlag, Berlin, 1988).
[5] M. S. Mangir and D. A. Rockwell, IEEE J. Quantum Electron. **QE-22**, 574(1986).
[6] I. A. Shcherbakov, IEEE J. Quantum Electron. **QE-24**, 979(1988).
[7] J. A. Adams, D. F. Rogers, *Computer Aided Heat Transfer Analysis* (McGraw-Hill Kogakusha, Toyko, 1973).
[8] F. P. Incropera and D. P. DeWitt, *Introduction to Heat Transfer* (John Wiley & Sons, Inc. 1985).
[9] D. S. Sumida, D. A. Rockwell, and M. S. Mangir, IEEE J. Quantum Electron. **QE-24**, 985(1988).