# 2277-W continuous-wave diode-pumped heat capacity laser

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A high power continuous-wave (CW) diode-pumped Nd:YAG laser operated in heat capacity mode is demonstrated by use of two identical highly efficient diode-pumped laser heads placed in a plane-plane resonator. The laser heads are uniformly pumped with a five-fold symmetrical side-pumping configuration, and each head is able to output maximum output power of 2200 W at 808 nm. Under a total pump power of 4290 W, the output power of the laser at 1064 nm is up to 2277 W, corresponding to an optical-to-optical efficiency of 53.1%.

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Continuous-wave (CW) all-solid-state laser with several thousand watts output power and high beam quality is of great interest in various industrial, military, and scientific applications[1,2]. However, the combination of volumetric heating of the active material by absorbed pump radiation and surface cooling required for heat extraction results in great thermal effect, which has so far limited the output power of all-solid-state laser to several thousand watts[3−7]. Aiming at supporting operation of the solid-state laser at megawatt levels, the heat capacity laser arouses interest of many scientists, which can be used in the military and the front science study.

In the heat capacity operation mode, the laser operation is broken into two discrete and sequential processes, the lasing phase and the cooling phase. In the lasing phase, the active medium is uniformly pumped, and no cooling takes place. The waster heat generated during lasing is deposited in the active medium. The temperature of the laser medium uniformly rises to a temperature where lasing operation becomes inefficient due to the increase of absorption loss and the decrease of gain in the laser medium[5]. After lasing phase, the pumping stops, and the laser medium is reset to its start temperature by aggressive cooling. Then the heat capacity laser can lase again. Uniform pumping and no cooling at the outside surface of the active medium result in minimized temperature gradients in the cross-section of the laser medium in the lasing phase. This will greatly minimize the thermal effects including thermal focusing, stress birefringence, and nonspherical aberrations in the lasing phase, and enhance the pump power limit, which is associated with the stress fracture of the active medium. Thus very high power operation is possible while maintaining low optical distortions[3−8].

Previous reports on the laser diode (LD) pumped heat capacity laser are all pulse pumped, and the active medium mainly is Nd:GGG disk. In this paper, we demonstrate a CW diode-pumped heat capacity Nd:YAG rod laser. Under a pump power of 4290 W, the heat capacity laser runs one second, and the maximum output power of 2277 W at 1064 nm is achieved. The corresponding optical-to-optical efficiency is 53.1%.

The heat capacity laser approach to laser design is conceptually simple and has the potential to offer revolutionary strides in output power. For diode-pumped heat capacity laser, the total energy that is extracted from the laser medium may be estimated by[5]

$$E=\left[\frac{\rho C_{\mathrm{p}}\Delta T}{\chi}\right]\eta_{\mathrm{ex}}V, \tag{1}$$

where $\rho$ is the density of active medium, $C_{\mathrm{p}}$ the specific heat of the active medium, $\Delta T$ the temperature rise to the condition that produces significant loss in gain, $\chi$ the heating parameter[9], $\eta_{\mathrm{ex}}$ the beam output energy extraction efficiency, and $V$ the volume of the active medium. For the Nd:YAG crystal, $\frac{\rho C_{\mathrm{p}}}{\chi}$ is 8 J/(cm$^3$·K), and $\eta_{\mathrm{ex}}$ might be of the order of 0.6 for a power oscillator of the rod[5]. Different from a laser operated in conventional steady-state mode, the output power of the oscillator operated under heat capacity mode continually decreases for a constant pump power because of the continuous increase of absorption loss and the decrease of gain in active medium caused by the temperature rise of the active medium. For the heat capacity laser, the population of the lower laser level increases continuously due to the temperature rise of the laser medium in the lasing phase, according to Boltzman statistics. This will result in an increase of absorption loss and a decrease of gain continuously. Thus the output power of the oscillator operated in heat capacity mode decreases continually. When the loss increases to a value where the ratio of the total loss to the net small signal gain is approaching unity, the laser operation shuts down. The temperature rise, $\Delta T$, which shuts down lasing, is not a sharply defined value, which increases with the gain-medium pump rate[5]. For our experiment, estimates show that the value of $\Delta T$ is over 100 °C for a room temperature starting condition. However, high temperature of the active medium results in a low efficiency of the oscillator and may damage the silica gel o-rings that serve as a cushion placed between the Nd:YAG rod and metal flange. So the final temperature of Nd:YAG rod of the lasing phase is kept under

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80 °C in our experiment.

Uniform pumping is very important for a diode-pumped heat capacity laser, since nonuniform pumping produces nonuniform temperature distribution in the cross section of rod in lasing phase, which leads to greater thermal effects[10,11]. So we design and fabricate highly efficient and uniform pumped laser heads.

The schematic edge view of the side-pumped laser head used in the experiments is shown in Fig. 1. It satisfies the requirements of uniform pumping and high efficiency. A Nd:YAG rod (7 mm in diameter and 180 mm in length with 0.6% $\mathrm{Nd}^{3+}$ doping concentration) placed in the center of a quartz tube is thermally isolated by a stagnant air gap formed by the rod outside surface and the quartz tube. Five CW two-dimensional (2D) LD arrays symmetrically surround the Nd:YAG rod to produce uniform pump light distribution in the Nd:YAG rod cross section. One 2D LD array comprises two rows, and each row contains eleven bars. The slow axis of every bar is parallel to the axis of Nd:YAG rod, and the pump light at the Nd:YAG rod mainly distributes at a region of 12 cm along the axis of the Nd:YAG rod. The pump light from the bars is directly coupled into rod without the aid of intervening lens, which can avoid the Fresnel reflection loss on the surface of intervening lens. For a maximum drive current of 25 A, one laser head is able to output 2200 W at 808 nm. The distance between the bars and the side surface of the Nd:YAG rod is optimized by use of our calculating program to obtain uniform pump light distribution in the Nd:YAG rod cross section and higher pump efficiency at the same time. As shown in Fig. 1(b), the fluorescence distribution of the laser head measured at the rod end by a CCD is uniform.

The schematic of the oscillator is shown in Fig. 2. The symmetrical resonator consists of a flat total reflector, a flat 30%-reflectivity output coupler (OC) mirror separated by 500 cm and two identical laser heads placed in the middle of the resonator. A quartz 90° rotator is placed between two side-pumped laser heads to compensate the birefringence in the Nd:YAG rod.

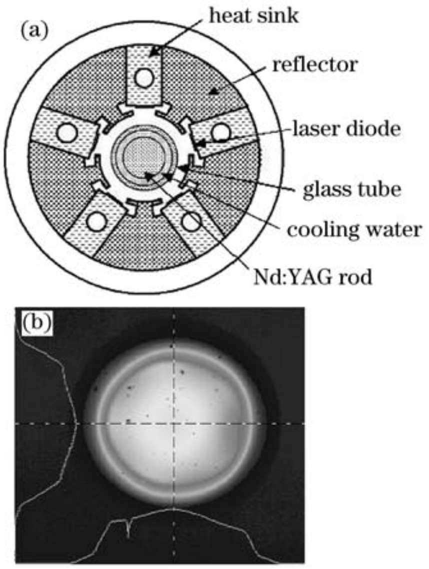

Fig. 1. (a) Schematic edge view and (b) fluorescence distribution of the diode-side-pumped laser head.

Setting the running time of the heat capacity laser to one second, the output power of the heat capacity laser at 1064 nm as a function of pump power was measured, as shown in Fig. 3. An output power of 2277 W is achieved for a pump power of 4290 W, corresponding to an optical-to-optical efficiency of 53.1%. According to Eq. (1), the temperature of the active medium at the end of lasing phase is about 76 °C under this pump power (the room temperature is about 20 °C). Figure 4 shows the output power of the heat capacity laser as a function of time during one second under the pump powers of 4180, 3740, 3300, and 2970 W, respectively. As mentioned above, the output power of the heat capacity laser drops under a constant pump power because of the increase of absorption loss and the decrease of gain. In Fig. 4, it can also be seen that the dropping rate of output power under a high pump power is higher than that under a lower pump power. This is mainly because that a high pump power leads to a high temperature rise rate of the laser medium, which will cause a fast increase of absorption loss and a fast decrease of gain in the active medium. Thus the dropping rate of output power for a

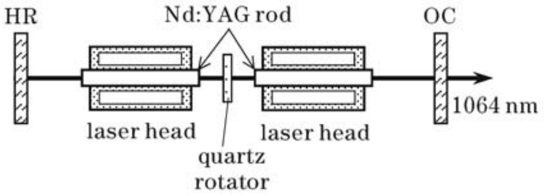

Fig. 2. Schematic of CW heat capacity laser. HR: high reflector.

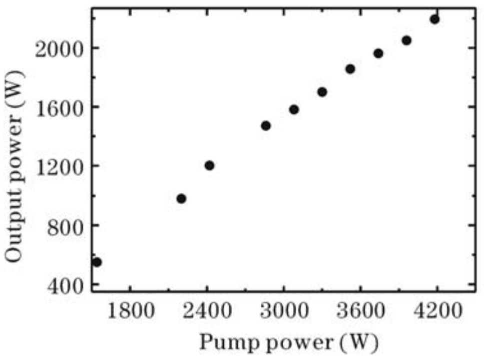

Fig. 3. Output power as a function of the pump power.

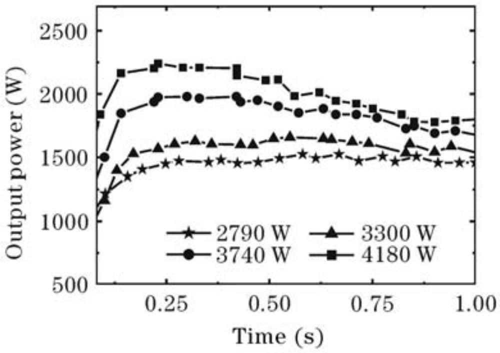

Fig. 4. Output power of the heat capacity laser versus time in one second under pump powers of 4180, 3740, 3300, and 2970 W, respectively.

higher pump power is higher than that for a lower pump power.

In conclusion, a high-power CW side-pumped all-solid-state Nd:YAG heat capacity laser operation is presented. The laser contains two highly efficient diode-pumped laser heads with a five-fold symmetrical side-pumping configuration. Each head is able to output 2200 W at 808 nm. Under a total pump power of 4290 W, a maximum output power of 2277 W at 1064 nm is obtained, corresponding to an optical-to-optical efficiency of 53.1%.

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