High-power passively Q-switched ultra-thin slab lasers

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Ultra-thin slab with the dimension of $1 \times 10 \times 60$ (mm) is demonstrated to acquire high-power laser output with high beam quality. The output average power of 70 W with diffraction limited beam quality is obtained, and the total optical-optical efficiency is about 32%. It can produce more than 100 W output laser when it operates with multi-mode. Cr^{4+}:YAG is adopted as the saturable absorber, the pulse repetition rate is higher than 10 kHz, and the pulse duration is less than 10 ns. An asymmetrical composite crystal is also studied, the new crystal consists of two layers: one is undoped YAG, the other is Nd-doped YAG layer. It is shown that thermal effects of the new asymmetrical crystal are obviously reduced.

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A diode-pumped solid-state laser (DPSSL) has the characteristics of compact, long life time, and high efficiency. High power slab laser with good beam quality as one kind of DPSSL is widely used. It can be used in cutting, welding, and drilling of metal material. Ultra-thin slab lasers are potential candidates in high average power lasers due to their ultra-thin thickness and large area cooling surfaces. Because the slab thickness is designed to match the size of the fundamental mode, higher order modes can be filtered out, so it is an attractive approach to achieve high-power laser output with good beam quality. Hodgson *et al.* have studied this kind of ultra-thin slab laser and acquired 220-W output laser[1], but it operates under continuous wave state. In real application, pulsed lasers has widely used. The passively Q-switched laser offers advantages of low-cost, reliability, and simplicity in operation and maintaining since it does not need high-voltage and fast electro-optical switch. To our knowledge, passively Q-switching is often used in low power laser, and it is hardly studied in so high power lasers. In our experiment, Cr^{4+}:YAG as saturable absorber is adopted in ultra-thin slab lasers. Passively Q-switching is a simple and practical method to acquire high pulse repetition rate as well as high peak power.

One of the advantages of side-pumped slab laser is that it is convenient to produce high power laser, while the advantage of end-pumped slab lasers is that it makes the pump beam match with the laser beam in the slab, so its optical-optical efficiency is relatively high, and good beam quality can be acquired if pump beam matches with the fundamental laser mode. If these two kinds of advantages are considered simultaneously, we can acquire output laser with high power and good beam quality. So, in our design, side-pumped ultra-thin slab lasers are studied, the pump dimension in the slab is precisely controlled to match with the size of fundamental mode of laser resonator. The beam size in the resonator can be calculated with $ABCD$ matrix. If planar-planar resonator is adopted, the $ABCD$ matrix of a round trip can be written as

$$
\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\dfrac{1}{f} & 1 \end{bmatrix} \begin{bmatrix} 1 & \dfrac{L}{2n} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & \dfrac{1}{n} \end{bmatrix}
$$
$$
\times \begin{bmatrix} 1 & 2d_2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & n \end{bmatrix} \begin{bmatrix} 1 & \dfrac{L}{2n} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\dfrac{1}{f} & 1 \end{bmatrix}
$$

$$
\times \begin{bmatrix} 1 & \dfrac{L}{2n} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & \dfrac{1}{n} \end{bmatrix} \begin{bmatrix} 1 & 2d_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & n \end{bmatrix}
$$
$$
\times \begin{bmatrix} 1 & \dfrac{L}{2n} \\ 0 & 1 \end{bmatrix}, \tag{1}
$$

where n and L are the refractive index and the length of the slab crystal, d_1 and d_2 are distances between the crystal ends and the rear and front mirrors, respectively. In the following calculation, the values of d_1 and d_2 are both 10 mm. The initial reference plane is placed at the middle of the crystal. The relationship of beam waist and the refractive power of the slab is shown in the Fig. 1. From Fig. 1, we can see that the beam radius of the fundamental mode at the middle of the slab is about 0.2 mm. If the pump beam size in the thickness direction is controlled to match with it, the output laser power of the fundamental mode can be maximized, and higher order modes can be inhibited. In order to obtain high power laser output with the fundamental mode in our experiment, the pump beam divergence launched to slab must be controlled at about one degree. A 600-μm fiber lens in diameter is used to collimate the beam. The size of pump beam in the slab can be controlled at about 600 μm, so the good beam quality can be acquired in our experiment.

In order to investigate the effects of key parameters on output pulse, the rate equations of the passively Q-switched laser are solved numerically. The rate equation of the passively Q-switched laser can be described as[2−6]

$$
\begin{cases}
\dfrac{\mathrm{d}\varphi}{\mathrm{d}t} = \dfrac{\varphi}{t_{\mathrm{r}}}\Big[2\sigma N l - 2g\sigma_{\mathrm{g}}N_{\mathrm{g}}l_{\mathrm{s}} - 2\sigma_{\mathrm{e}}(N_{\mathrm{s0}} - N_{\mathrm{g}})l_{\mathrm{s}} \\
\qquad - \ln\left(\dfrac{1}{R}\right) - L\Big] \\
\dfrac{\mathrm{d}N}{\mathrm{d}t} = W_{\mathrm{p}} - \sigma c N\varphi - \dfrac{N}{\tau} \\
\dfrac{\mathrm{d}N_{\mathrm{g}}}{\mathrm{d}t} = -\sigma_{\mathrm{g}}cN_{\mathrm{g}}\varphi + \dfrac{(N_{\mathrm{s0}} - N_{\mathrm{g}})}{\tau_{\mathrm{s}}}
\end{cases}, \tag{2}
$$

where φ is the photon density in the resonators, N the instantaneous population inversion density of laser crystal, N_{g}, and N_{s0} the ground-state and total population densities of the saturable absorber, respectively; σ is
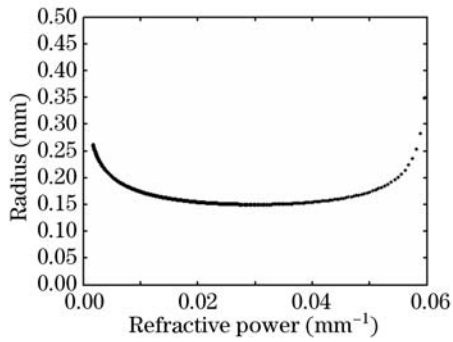

Fig. 1. Beam radius of fundamental mode at the middle of the slab versus refractive power of the slab.

the stimulated emission cross section of laser crystal, σ_g and σ_s are the ground-state and excited-state absorption cross sections of saturable absorber, l and l_s the length of laser crystal and saturable absorber, τ and τ_s the life-times of the upper state of laser crystal and the excited state of saturable absorber, t_r the cavity round-trip time, R is the reflectivity of the output coupler, L the nonsaturable intracavity round-trip dissipative optical loss, W_p the pump rate. Data used in calculation are: $l = 60$ mm, $l_s = 0.1$ cm, $L = 0.04$, $W_p = 4.4 \times 10^{21}$ cm^{-3}, N_g, $N_{s0} = 7 \times 10^{17}$ cm^{-3}, $\tau_s = 3.4$ μs, $\tau = 230$ μs, $\sigma_g = 4.3 \times 10^{-18}$ cm^{-3}, $\sigma_e = 8.2 \times 10^{-19}$ cm^{-3}, $\sigma = 2.8 \times 10^{-19}$ cm^{-3}. The calculated results are shown in Fig. 2, from which we can get that the pulse width is less than 10 ns, the repetition rate is 15 kHz.

In our first experiment, a Nd-doped YAG slab with the dimension of $1 \times 10 \times 60$ (mm) is adopted. As is demonstrated in Fig. 3, the pump light from LD stacks is collimated by the micro-cylindrical lenses, and the divergence angle of collimated light can be controlled at less than 1.0 degree. More than 95% coupling efficiency is obtained. Collimated light are delivered from the two
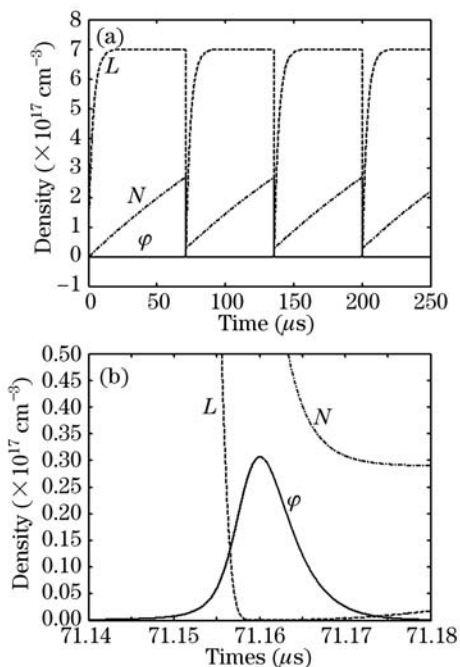
edges of Nd:YAG slab. The pump light is precisely controlled to 600 μm in thickness inside the Nd:YAG slab to match with the fundamental laser mode. When the pump power is 300 W, the thermal focal length is measured to be about 80 mm. The laser works in the stable zone I, and the beam size of the fundamental mode inside the slab is about 300 μm.

A Cr^{4+}:YAG crystal chip with the initial transmission of 90% is used as the saturable absorber. Its dimensions are 0.5 mm in thickness, 5 mm in height, and 15 mm in width. The back surface of the Cr^{4+}:YAG chip coated with the high-reflective coating at 1.06 μm is used also as the rear mirror, and the front surface is coated with anti-reflective coating at 1.06 μm to reduce the loss in the resonators. The output coupler is a planar mirror with 90% reflectivity at 1.06 μm. The relationship of output laser power and input LD power is illustrated in Fig. 4, 70 W output laser power with diffraction limited beam quality can be obtained when 220-W pump light from LD stacks is launched to the slab. The total optical-optical efficiency is 32%. In addition, the maximum average output power of multi-mode is more than 100 W. From Fig. 4, we can see that output laser power increases linearly with input pump power, this kind of ultra-thin slab can be scalable to higher power. If unstable resonators[7−9] are used or graded reflectivity mirror is adopted as the output coupler, the output laser beam quality in wide direction can be improved further.

The measured pulse sequences are shown in Fig. 5. The pulse repetition rate is higher than 10 kHz, and the pulse duration is less than 10 ns. The peak power fluctuation from pulse to pulse is about 5%. The experiment results agree with the theory well. The laser head is very compact with the size of only $60 \times 74 \times 150$ (mm), which
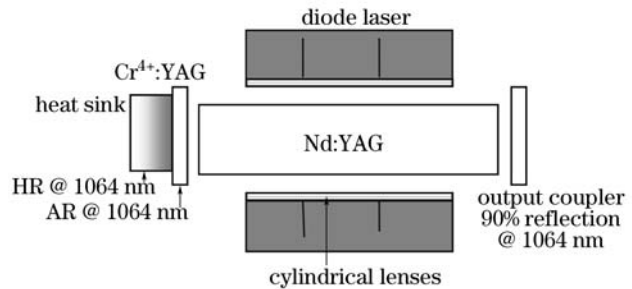

Fig. 2. (a) Evolution of photon density φ, population inversion N, and loss L. (b) The temporary profile of the Q-switched laser pulse.

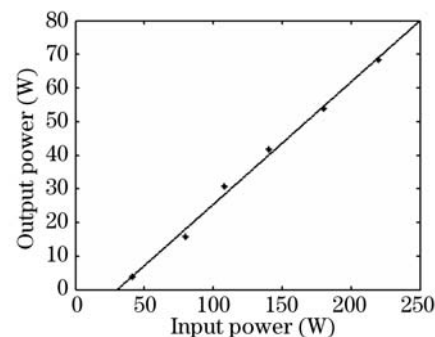Fig. 3. Experimental setup of the ultra-thin slab laser.

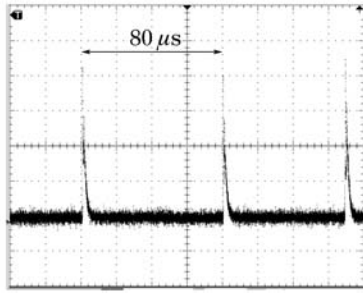Fig. 4. Output laser power versus input LD power.

Fig. 5. Measured passively Q-switched laser pulses.

can be easily to be implemented in the auto-machines.

In the second experiment, a new kind of composite slab is applied. The composite crystal slab used in the experiment is different from the conventional composite slabs with symmetric structures. It consists of two layers: one is 800-μm-thick undoped YAG layer, the other is 200-μm-thick Nd-doped YAG layer. The total thickness of the composite slab is 1 mm. Because the Nd-doped YAG layer can be conducted directly to the heat sink, it can dissipate the heat more efficient than the sandwiched structure slab. Even with non-optimized cooling, the thermal effects are largely reduced compared with sandwiched structure slab under 360-W pump power. More than 20-W continuous wave power has been obtained.

In conclusion, ultra-thin slab laser as one potential method to acquire high output laser power with good beam quality is studied in this paper. Diffraction limited laser beam with average output power of 70 W is obtained, and it can be scalable to higher power. One new kind of composite crystal structure is proposed, it is proved that its thermal effects are greatly reduced and can work with higher pump density.

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