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High-average-power and high-conversion-efficiency continuous wave mode-locked $Nd:YVO_4$ laser with a semiconductor absorber mirror

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Abstract

A high-power continuous wave (cw) mode-locked $Nd:YVO_4$ solid-state laser was demonstrated by use of a semiconductor absorber mirror (SAM). The maximum average output power was 8.1 W and the optic-to-optic conversion efficiency was about 41%. At the maximum incident pump power, the pulse width was about 8.6 ps and the repetition rate was 130 MHz. Experimental results indicated that this absorber was suitable for high power mode-locked solid-state lasers.

Keywords: High-average-power; High-efficiency; CW mode-locked

1. Introduction

Since the first cw mode-locked (CML) solid-state laser with SESAM was demonstrated the mode-locked solid-state lasers were well developed in recent years [1–5]. One of the important frontiers is high average power [6]. Picosecond high-power diode-pumped solid-state lasers with good beam quality are attracting growing interest because of numerous applications in medicine, material processing and nonlinear frequency conversion. The main challenges for high-power lasers were Q-switching instabilities and the SESAM damage. With single LD pumping, one group has achieved 6.2 W average output power with a slope efficiency of 35% and the other group has achieved 5.3 W average output power with a conversion efficiency of 30% [7,8]. The thermal lens of the laser crystal and the SESAM damage were the main reason for the limiting average output power. In this experiment, we used a super SAM as the saturable absorber which had a high damage threshold and we designed the laser cavity elaborately for mitigating the effect of the thermal lens. Finally, we achieved a high average output power of 8.1 W at the maximum incident pump power in CML operation; the optic-to-optic conversion efficiency was about 41%. The nonsaturable losses of the SAM was small and the SAM was not damaged in the experiment.

2. Theoretical discussion about the thermal lens

It is worthwhile to analyze the thermal lens in the $Nd:YVO_4$ crystal, which affects the output power of the laser and the stability of the resonator. For a laser pumped by a fiber-coupled diode the focal length of the thermal lens f_{th} can be approximately given by [9–11]

$$f_{th} = \frac{\pi K_c \omega_p^2}{P_{ph}(dn/dT)} \frac{1}{1-\exp(-\alpha l)}.$$

Where K_c is the thermal conductivity, ω_p is the average pump size in the laser crystal, P_{ph} is the fraction of pump power that results in heating, dn/dT is the thermo-optic coefficient, α is the absorption coefficient, l is the length of the laser crystal. Usually about 24% of the pump power is

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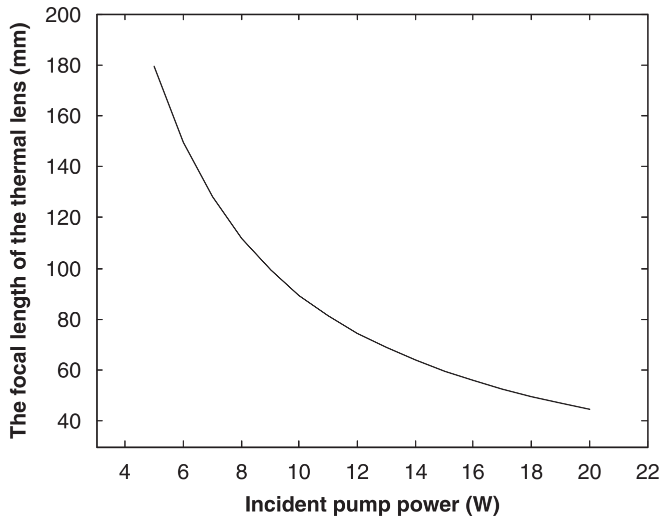

Fig. 1. The calculated focal length of the thermal lens as a function of the incident pump power.

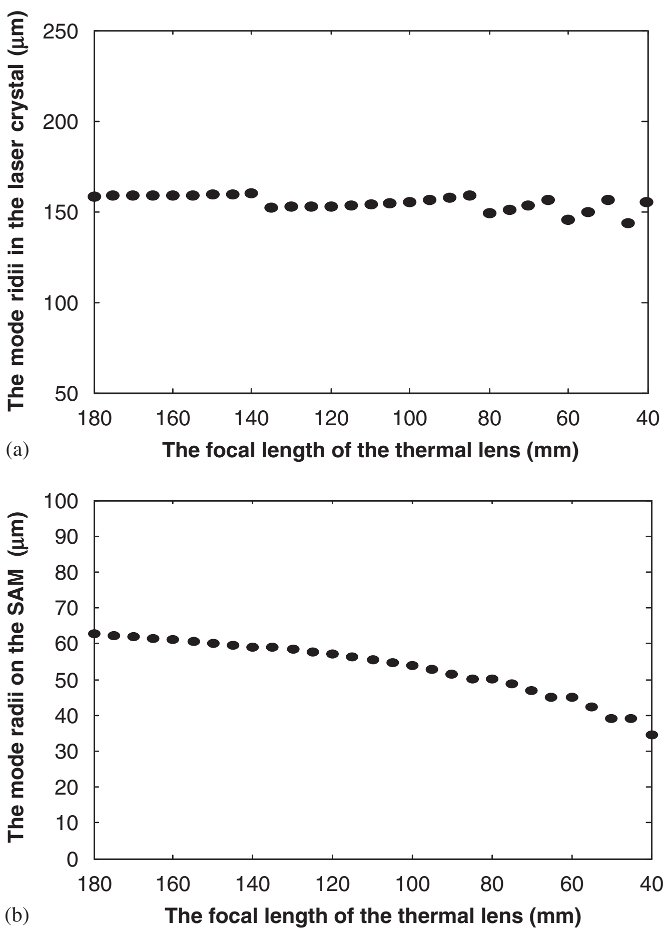

Fig. 2. (a) The calculated mode radii in the laser crystal at different focal length of the thermal lens; (b) the calculated mode radii on the SAM at different focal length of the thermal lens.

changed to heat. The focal length of the thermal lens is estimated by using the following parameters: $K_c = 0.051\,\mathrm{W/K\,cm}$, $\mathrm{d}n/\mathrm{d}T = 3.0\times10^{-6}/\mathrm{K}$, $\omega_p = 0.2\,\mathrm{mm}$, $\alpha = 10\,\mathrm{cm}^{-1}$, and $l = 5\,\mathrm{mm}$. The calculated focal length of the thermal lens as a function of the absorbed pump power was shown in Fig. 1. The focal length of the thermal lens was found to be about 45 mm at 20 W pump power. Considering the thermal lens effect, we designed a thermal-stable cavity. The cavity was designed to easily allow mode matching with the pump beam and to provide the proper spot size on the SAM. The mode radii in the laser crystal was about 140–160 µm (0.7–0.8 times of the pump size); the mode radii on the SAM was approximately 30–60 µm. The mode radii were calculated by the laser transfers matrix. Fig. 2 showed the mode radii at different focal length. From Fig. 1 we knew that when the incident pump power was increased, the thermal lens effect became more serious. In this case, to keep precise mode-matching and achieve high conversion efficiency, the distance between the mirror M2 and the SAM should be changed slightly. The distance was controlled to be 102–98 mm. For obviously revealing the mode radii variation with the distance, the 1 mm changing pace was taken. One step occurred in the curves of Fig. 2 when the distance changed 1 mm.

3. Experimental setup and results

The SAM was grown on GaAs substrate by metal-organic chemical-vapor deposition. The SAM consisted of 22 pairs of GaAs/AlAs quarter-wave Bragg layers with high reflectivity of 99.5% at lasing wavelength of 1064 nm and a 15-nm relaxed $In_{0.3}Ga_{0.7}As$ single quantum well (embedded in the topmost layer of the Bragg stack) for achieving saturable absorption at 1064 nm. The Bragg layers and the $In_{0.3}Ga_{0.7}As$ absorber were grown at temperatures of 720 and 500 °C, respectively. For getting a high damage threshold, the SAM was coated with three pairs of SiO_2/Al_2O_3 as the protective film and the reflectivity was about 50%. The $In_{0.3}Ga_{0.7}As$ absorber was grown at 500 °C low temperature for a fast recovery time. The structure is shown in detail in Fig. 3.

The cavity configuration was shown in Fig. 4. The Nd^{3+} concentration of the laser crystal was 0.5 at%, and its length was 5 mm. The laser crystal was wrapped with indium foil and mounted in a copper block cooled by a thermo-electric cooler. One side of the laser crystal was coated antireflection for 808 nm ($T>98\%$) pump wavelength and high reflection ($R>99.8\%$) for the 1064 nm lasing radiation, the other side was coated antireflection for 1064 nm. The pump source was 20 W fiber-coupled laser diode with a core diameter of 0.4 mm and a numerical aperture of 0.22. The central wavelength of the LD was 810.2 nm at 25 °C and can be tuned by changing the working temperature of the LD to match the best absorption of the laser crystal. The fiber output was focused into the laser crystal and the pump spot radii were about 200 µm. The resonator consisted of two highly reflective (at 1064 nm) mirrors, M1 and M2; one partially reflective (PR) mirror, output coupler (OC); a laser crystal; and a SAM. OC is a flat mirror; the radii of curvature for