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Diode-Pumped Passively Mode-Locked 1079 nm $Nd:CaGdAlO_4$ Laser *

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We demonstrate a diode-pumped passively cw mode-locked $Nd:CaGdAlO_4$ laser operating at 1079 nm with a semiconductor saturable absorber mirror for the first time to the best of our knowledge. The threshold pump power of the laser is 180 mW. A maximum average output power of 93 mW is obtained under the pump power of 1.94 W. The pulse duration of the mode-locked pulses is 3.1 ps and the repetition rate is 157 MHz.

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$CaGdAlO_4$ is a typical disordered crystal. It belongs to the family of compounds with the general formula $CaLnAlO_4$, where Ln=Y, Gd, La,..., Lu.[1] Such materials normally exhibit a tetragonal perovskite-like K_2NiF_4 type of crystalline structure. $CaGdAlO_4$ crystal has many great features,[2] such as high thermal conductivity and high mechanical strength (mohs hardness 6). In the past two decades, some transition metal ions (Ti^{3+})[3] and rare earth ions (Nd^{3+}, Er^{3+}, Yb^{3+})[2,4,5] have been doped into $CaGdAlO_4$ to obtain emissions with different wavelengths. $Nd:CaGdAlO_4$ crystal possesses inhomogeneous broadened absorption and emission spectra[2] due to the random distribution of the Ca^{2+} and Gd^{3+} ions at the cation sites in the crystal lattice. Its broad absorption spectrum benefits the diode pumping, while broad emission spectrum facilitates ultrashort pulse laser operation. Though $Nd:CaGdAlO_4$ crystal is a promising crystal for diode-pumped solid state laser, there are very few reports relevant to the $Nd:CaGdAlO_4$ laser. In 1997, Lagatskii *et al.*[2] investigated lasing characteristics of a diode-pumped $Nd:CaGdAlO_4$ crystal doped with 2 at.% Nd^{3+} concentration for the first time. The 360 mW output power was obtained at a wavelength of 1078 nm by using a 3 W GaAlAs diode pump source at 806.5 nm. In addition, they also investigated its spectrum characteristics. Its effective stimulated emission cross section for $E//c$ was $1.1\times10^{-19}\,cm^2$ at the wavelength 1078 nm, and its absorption cross section was $2.4\times10^{-20}\,cm^2$ for the $E\perp c$ polarization of light and $1.94\times10^{-20}\,cm^2$ for $E//c$.

In this Letter, a diode-pumped passively ps mode-locked $Nd:CaGdAlO_4$ laser operating at 1079 nm is reported. A maximum average output power of 93 mW with 3.1 ps pulses at a repetition rate of 157 MHz is obtained by using a semiconductor saturable absorber mirror (SESAM). Additionally, the tuning characteristic of the $Nd:CaGdAlO_4$ under the cw operation is also investigated.

The experiment layout is shown in Fig. 1. The pump source was a 2 W fiber-coupled cw laser diode (BWT, Beijing) with a central wavelength of 806 nm. The diameter of the fiber core was 50 µm. A 1:1 coupling system was used to inject the pump laser into a $3\times3\times6\,mm^3$ c-cut $Nd:CaGdAlO_4$ crystal which was doped with 1 at.% Nd^{3+} concentration. Both sides of the $Nd:CaGdAlO_4$ crystal were coated for antireflection (AR) at 806 nm and around 1 µm. To decrease the influence of the thermal lens effect and to make the laser operation stable and efficient, the laser crystal was wrapped with indium foil and mounted in water-cooled copper blocks with the temperature of 11℃. Before the crystal was coated, we measured its fluorescence spectrum from 850 to 1500 nm, as shown in Fig. 2. It can be seen from Fig. 2 that around 1.1 µm there is an emission peak centered at 1079 nm with an FWHM of about 12 nm, which benefits the generation of ultrashort pulses.

A typical X-folded cavity was used in the experiment. The whole length of the cavity was about 955 mm. Folding mirror M1 with curvature radius of 75 mm served as an input coupler, which had high re-

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flection (HR) coating from 1000 nm to 1100 nm and high transmission (HT) coating at 806 nm. The other folding concave mirrors, M2 and M4, were both HR coated around 1 µm. The radii of curvature of the M2 and M4 mirror were 75 mm and 100 mm, respectively. To avoid astigmatism, the fold angle was designed to be as small as possible. M3 was used as the output coupler (OC). In the experiment, two different plane OCs were used. One had a transmission of 0.8% and the other had a transmission of 20% at the wavelength range from 1000 nm to 1100 nm. A commercial reflective SESAM (BATOP, Inc.) was used for self-starting and mode locking, which had a modulation depth of 0.4%, a saturation fluence of 90 µJ/cm^2 and a recovery time of ≤500 fs at the central wavelength of 1064 nm. Analysis of optical resonator with ABCD matrix showed that the spot radii in the Nd:$CaGdAlO_4$ crystal and on the SESAM were about 30 µm and 40 µm, respectively.

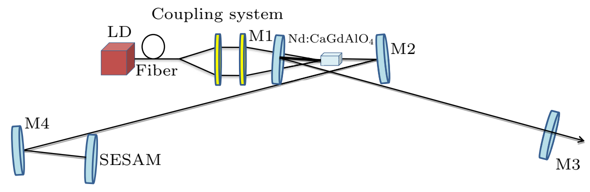

Fig. 1. Experimental setup of the ps mode-locked Nd:$CaGdAlO_4$ laser.

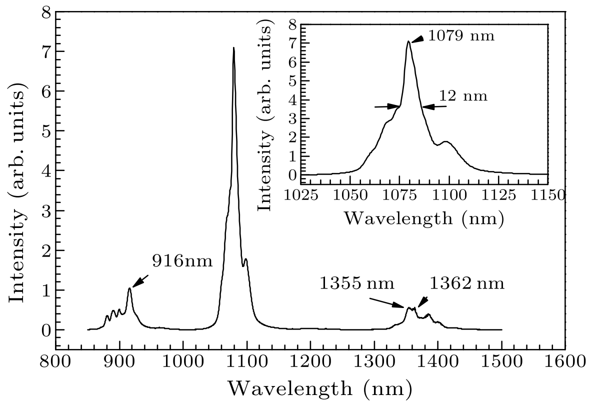

Fig. 2. Fluorescence spectrum of the Nd:$CaGdAlO_4$ crystal.

First, we tested the characteristics of the cw laser operation by replacing the SESAM with a flat mirror which was HR coated around 1 µm. The pump absorption efficiency for the Nd:$CaGdAlO_4$ crystal was about 94%. Figure 3(a) presents the output power versus the incident pump power obtained with different OCs. From Fig. 3(a) we can see that, with an OC transmission of 20%, the threshold pump power was 880 mW and the maximum output power of 400 mW was achieved when the incident pump power was increased to 1.94 W. The optical-to-optical conversion efficiency and slope efficiency were 20.6% and 37.7%, respectively. With an OC transmission of 0.8%, the maximum output power of 115 mW was achieved. The inset of Fig. 3(a) is the spectrum of the output laser with the OC transmission of 0.8% measured by an optical spectrum analyzer (AQ6315A, Ando, Inc.) with a resolution of 0.02 nm, which indicated that the emission was clearly presented at 1078.8 nm. By inserting a prism into the cavity with the 0.8% OC, the tuning range of the laser emission was also investigated. As shown in Fig. 3(b), we obtain a tunability from 1078.2 to 1086.5 nm under the maximum pump power of 1.94 W. Figure 3(b) also indicates that one of the peak wavelengths is located at 1080 nm, which can be used to optically pump metastable helium atoms.[1,6]

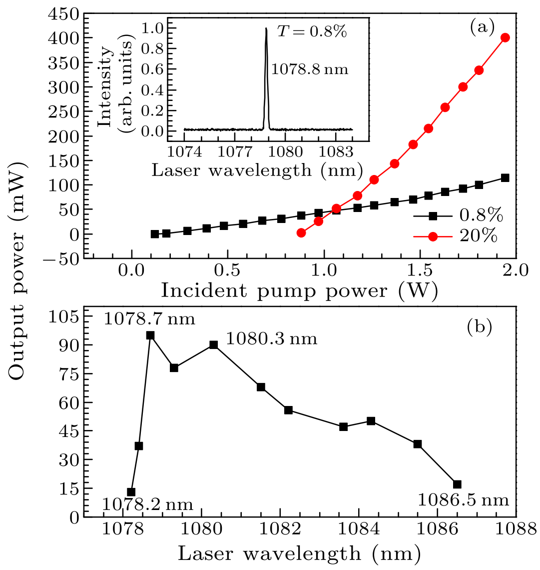

Fig. 3. (a) Output power of the cw Nd:$CaGdAlO_4$ laser. Inset: laser spectrum of the Nd:$CaGdAlO_4$ laser for OC transmission of 0.8% under the cw operation. (b) The cw output power as a function of the laser wavelength at the incident pump power of 1.94 W with OC transmission of 0.8%.

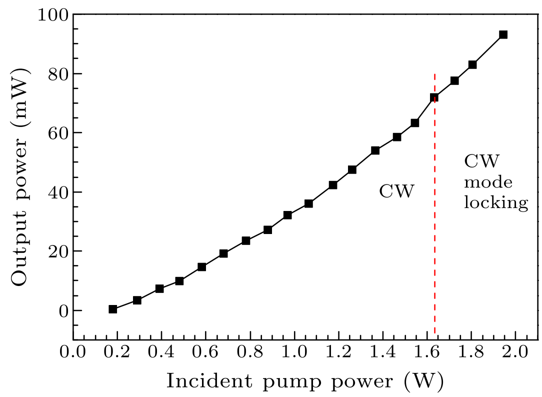

Fig. 4. Output characteristic of the average output power versus the incident pump power.

Secondly, we carried out the mode-locking experiment with a 0.8% OC. Figure 4 shows the output characteristic of the passively mode-locked Nd:$CaGdAlO_4$

laser. From Fig. 4, we can see that the threshold pump power of the laser was about 180 mW. The average output power basically increased linearly with the incident pump power. With the increase of the pump power up to 1.63 W, stable mode-locking operation was self-starting. The maximum average output power of 93 mW was obtained under the incident pump power of 1.94 W. The efficiency is rather low, which could be partially explained by the relatively high additional losses induced by the SESAM.

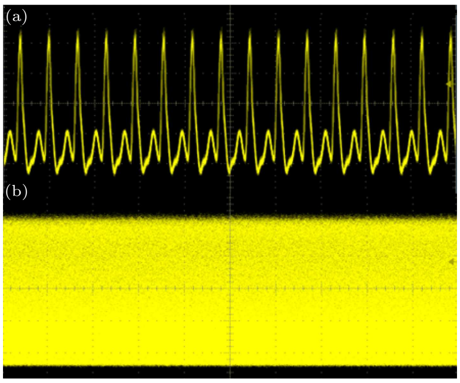

Fig. 5. Measured mode-locked pulse trains in ns and µs time scales (a) 10 ns/div and (b) 40 µs/div.

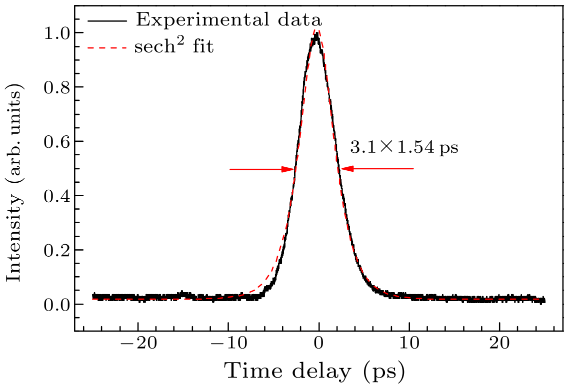

Fig. 6. Intensity autocorrelation trace of the mode-locked pulses.

Figure 5 shows a typical mode-locked pulse train measured with a timescale of 10 ns/div (Fig. 5(a)) and 40 µs/div (Fig. 5(b)). The mode-locked pulses have a repetition rate of 157 MHz, which correspond to the whole length of the cavity. In the experiment, the pulse-to-pulse intensity fluctuation was less than 3% and the stable cw mode locking could be sustained for several hours without any cavity adjustment.

We measured the intensity autocorrelation trace using a commercial autocorrelator (Femtochrome, FR-103MN). After fitting the autocorrelation signal with a Sech^2 pulse profile, we obtained an FWHM pulse duration of 3.1×1.54 ps, which can be seen in Fig. 6. Figure 7 is the corresponding laser spectrum centered at 1079 nm with an FWHM width of 1.8 nm. These values correspond to a time-bandwidth product of 1.44, which is 4.57 times the transform limit for the Sech^2 pulse. We attribute the high time–bandwidth product to the high group-delay dispersion in the laser cavity. The 1.8 nm spectral bandwidth we obtained, according to the theory calculation, supports 679 fs pulses. The existing outcomes have confidently indicated that narrower pulse duration can be achieved by applying proper dispersion compensation, which will be studied in the future work.

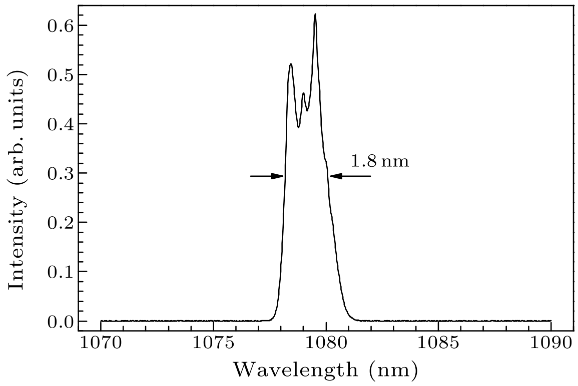

Fig. 7. Spectrum of the mode-locked laser pulses.

In conclusion, the passive mode-locking performance of a diode pumped c-cut Nd:$CaGdAlO_4$ crystal has been experimentally investigated for the first time. The threshold pump power of the laser is 180 mW. We obtain a maximum average output power of 93 mW with 3.1 ps pulses at a repetition rate of 157 MHz. The FWHM width of the laser spectrum is 1.8 nm, corresponding to 4.57 times the width of a time-bandwidth limited for sech^2 pulse. We will use a more powerful pump source and appropriate dispersion compensation in further experiments to obtain a narrower pulse duration.

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