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Diode-pumped passively mode-locked Nd:CLNGG laser

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ABSTRACT

Passive mode-locking of a diode-pumped Nd:CLNGG laser was demonstrated for the first time to our knowledge. The laser operated at a central wavelength of 1061.2 nm with a maximum average output power of 101 mW. The mode-locked pulses have pulse duration of 2.0 ps, a spectral bandwidth of 1.2 nm and a repetition rate of 88.4 MHz. The mode locking of the laser was enabled by a semiconductor saturable absorber mirror (SESAM).

1. Introduction

Garnet crystals are widely used as host materials for solid state lasers. It has properties such as high thermal conductivity, high mechanical strength, and high resistance to radiation damage. Disordered garnet crystals such as calcium niobium gallium garnet with a formula $Ca_3(NbGa)_{2-x}Ga_3O_{12}$ (CNGG) have several advantages compared with the ordered garnet crystals such as YAG. The CNGG crystal lattice has a high isomorphous capacity for Cr^{3+} and rare earth cations (TR^{3+}), therefore, enabling a larger doping level of the ions. Due to enormous variety of different types of ions and cationic vacancies in the regular sites of the host lattice, there is large disordering in the CNGG structure. This causes considerable inhomogeneous broadening and splitting of the spectral lines of the TR^{3+}-impurities doped in the CNGG crystal, thus broad absorption and emission bands [1]. The thermal conductivity of CNGG is 4.7 $Wm^{-1}K^{-1}$. It is about one third of that of YAG, but much larger than that of glasses [2,3]. By introducing Li^+ ions into CNGG, a new crystal calcium lithium niobium gallium garnet with a formula $Ca_3Li_xNb_{1.5+x}Ga_{3.5-2x}O_{12}$ (CLNGG) can be generated. CLNGG crystal overcomes the nonstoichiometric structure property of CNGG. Both CNGG and CLNGG can be grown by Czochralski method.

CNGG and CLNGG crystals doped with Nd^{3+}, Yb^{3+}, Tm^{3+}, Er^{3+}, Cr^{3+} ions have been reported [4–9]. CW emission with output power of 2 W was recently obtained in Yb:CNGG crystal laser under laser diode pumping [8]. Laser output of 20 mW at 2.0 μm in Tm:CNGG crystal was also demonstrated [10]. Both CW and pulsed operation of Nd:CNGG lasers were reported [4,9–12]. For the diode-pumped Nd:CNGG lasers at 1.06 μm, 1.63 W CW and 90 mW mode-locked output have been achieved, respectively [9,10,12]. For diode-pumped Nd:CLNGG laser, cw operation has attained an output power of 170 mW at 1.06 μm [6,10,13]. However, no mode-locked operation has been reported. In this paper, we demonstrate for the first time to our knowledge the passive mode-locking of a diode-pumped Nd:CLNGG laser. Stable mode-locked pulses with pulse width as short as 2.0 ps have been obtained.

2. Experimental setup

Nd:CLNGG has an absorption band from 795 nm to 815 nm, peaked at 807 nm [6]. It has two main lasing wavelengths, one at 1.06 μm corresponding to the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition and the other at 1.33 μm corresponding to the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition [13]. In this laser, mode-locking at 1.06 μm was demonstrated. The Nd:CLNGG crystal used in the experiment was grown by the Czochralski method. It has an Nd-doping concentration of 0.5 at.%, and a dimension of 3 mm × 3 mm in cross section and 4 mm in length. Both sides of the crystal were antireflection-coated at the pump and laser wavelengths. In order to remove the generated heat in the crystal for effective laser operation, the crystal was wrapped in indium foil and mounted tightly in a water-cooled copper holder that is maintained at a temperature of 11 °C. It was observed that the cw mode-locking could lose its long-term stability if the crystal is not sufficiently cooled. The crystal was placed with a small incidence angle to suppress the Fabry–Perot etalon effect.

A standard X-folded laser cavity was adopted for the mode-locked laser as schematically shown in Fig. 1. A single-emitter laser diode was used as the pump source. The emission wavelength of the laser diode changes in the range of 802–807 nm as the output power varies. The pump beam from the diode was focused by two 1:1 reimaging lenses of 8-cm focal length. The focused pump spot size in the crystal was ∼100 μm × 250 μm. The cavity consisted of a SESAM, an output coupler (OC) and three mirrors M1, M2 and M3. The ROCs (radii of curvature) of M1, M2 and M3 were 100, 300 and 100 mm, respectively. The concave mirror M1 was the

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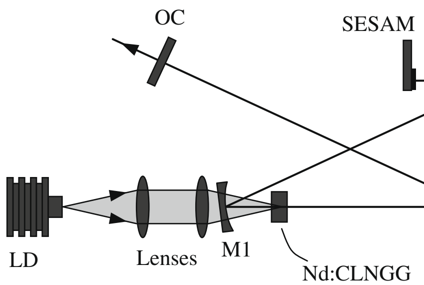

Fig. 1. Experimental setup for the mode-locked Nd:CLNGG laser. M1, M2, M3 – concave mirrors. OC – output coupler.

pump input mirror, coated for high transmission in pump wavelength and high reflection in a broad bandwidth around 1.06 μm. The concave mirrors M2 and M3 have high reflection in a broadband around 1.06 μm. A plano–plano OC mirror with transmission $T = 2\%$ at 1.06 μm was used. The separation length between M1 and M2 was 230 mm, between M1 and M3 was 500 mm, between M2 and the OC was 915 mm, and that between M2 and SESAM was ~52 mm. The total cavity length added up to 1697 mm.

The SESAM (BATOP GmbH, SAM-1064-2) used in our experiment has a central absorption wavelength of 1064 nm and 2% initial absorption strength. The modulation depth of the SESAM was 1.2%. The relaxation time was ~500 fs and the saturation fluence was 70 μJ/cm^2. The SESAM was mounted on a copper holder. The laser mode sizes in the crystal and on the SESAM were calculated to be ~90 μm and ~70 μm in diameter, respectively. No dispersion compensation element, e.g., intracavity prisms, was applied. The mode-locked pulse train was detected with a fast photoreceiver. Spectra and autocorrelation traces of the mode-locked pulses were measured with an optical spectrum analyzer (ANDO AQ-6315) and a commercial autocorrelator (Femtochrome Research, Inc. FR-103XL).

3. Results and discussion

Stable cw mode-locking was established above an absorbed pump power of 1.65 W. Fig. 2 shows the mode-locked pulse trains captured by an oscilloscope. Fig. 2a and b shows the pulse trains of the stable cw mode-locking in 100 μs and 200 ns time scales, respectively. As the absorbed pump power fell below 1.65 W, the laser pulses switched to a Q-switched mode-locking regime as shown in Fig. 2c. Experimentally it was observed that by merely increasing the pump power beyond a certain higher level, the stable cw mode-locking could lose its stability and even disappear. We believe it could be caused by the strong thermal lensing in the crystal. The thermal lensing effect changed the intracavity mode size, which then caused the unstable mode-locking. For the "x" folding cavity lasers mode locking usually operates at the edge of the cavity stability region. In this case thermal lensing effect could greatly change the cavity stability region. We believe this could be why the mode locking of our laser is much sensitive to the pump power change. Since the heat accumulation in the laser was mostly due to the pump absorption in the crystal, we tried to overcome the problem by gradually adjusting the crystal to a position away from the pump focus while increasing the pump power. In this way the thermal lensing became less influential and stable cw mode-locking was sustained even at relatively higher pump power.

The laser output power attained a maximum value of 101 mW at an absorbed pump power of 2.84 W, which gives the maximum optical–optical conversion efficiency of 3.6%. The slope efficiency of the laser was about 8.9% as shown in Fig. 3. The maximum output power is higher than that obtained on a diode-pumped and mode-locked Nd:CNGG crystal laser, whose maximum output power was about 90 mW [12]. The efficiency of the laser is very low. Therefore, a large amount of the pump power was converted to heat in the crystal, which can well explain the strong thermal lensing effect encountered. The cw mode-locked pulses have a repetition rate of 88.4 MHz, and the pulse-to-pulse intensity fluctuation was estimated 2.1%. Under stable mode locking the laser emitted in good TEM_{00} transverse mode.

The measured autocorrelation trace of the cw mode-locked pulses is shown in Fig. 4. From the autocorrelation trace, the FWHM pulse duration was estimated to be 2.0 ps if a Gaussian pulse profile is assumed. The spectral bandwidth of the mode-

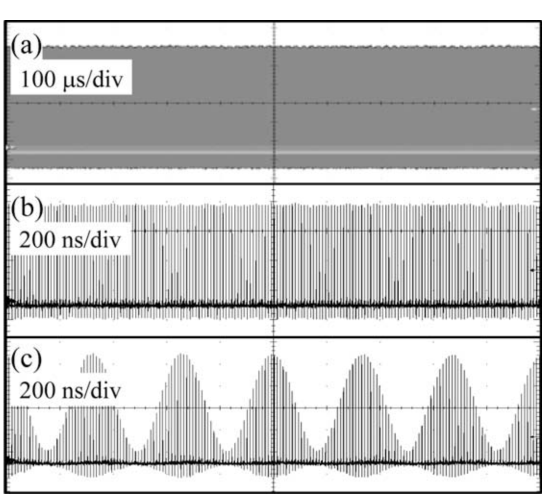

Fig. 2. Pulse trains of (a, b) cw mode-locking and (c) Q-switched mode-locking.

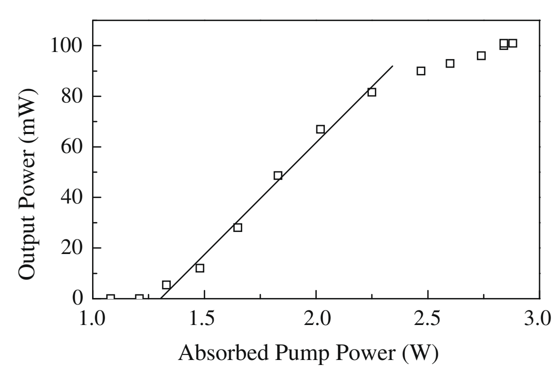

Fig. 3. Output power versus absorbed pump power of the mode-locked laser.

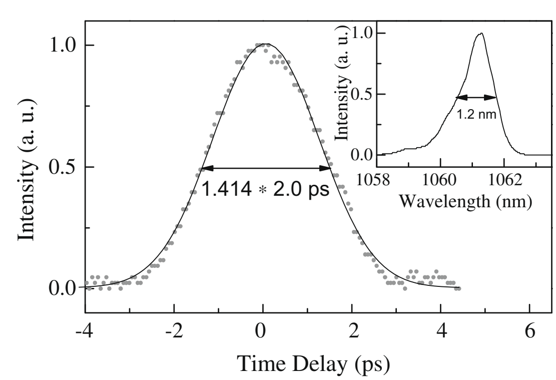

Fig. 4. Autocorrelation trace of the mode-locked pulses. Inset: corresponding spectrum.

locked pulses was 1.2 nm at FWHM, centered at wavelength of 1061.2 nm (Fig. 4, inset). The spectrum was measured at a resolution of 0.1 nm. According to the pulse duration and bandwidth, the pulse width was 1.5 times transform-limited. The mode-locked pulse duration is much shorter than that obtained previously on a Xe-lamp-pumped actively mode-locked Nd:CLNGG laser, whose pulse duration was about 10 ps [10].

4. Conclusions

In conclusion, we have experimentally achieved stable cw mode-locking of a diode-pumped Nd:CLNGG crystal laser with the SESAM mode-locking technique. At an absorbed pump power of 2.84 W the output power of the laser attained to 101 mW. The mode-locked pulses had duration of 2.0 ps at 1061.2 nm. To our knowledge, this is the first demonstration of passive mode-locking of Nd:CLNGG crystal pumped by laser diode. We believe that the mode-locking performance of the laser can be further improved if the crystal doping concentration is optimized. Our results suggest that Nd:CLNGG could be a promising gain medium for the ultrashort pulse generation at 1 μm.

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