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Diode-end-pumped passively mode-locked Nd:GGG laser with a semiconductor saturable mirror

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ABSTRACT

We report on the passive mode-locking of a diode-end-pumped neodymium-doped gadolinium gallium garnet (Nd:GGG) crystal with a semiconductor saturable absorber mirror (SESAM). Continuous wave (CW) mode-locking was obtained. The mode-locked pulse duration was estimated to be ~17.5 ps with a maximum average output power of 0.4 W. The mode-locked pulses have a repetition rate of 121.5 MHz. To our knowledge, this is the first demonstration of passive mode-locking of the diode pumped Nd:GGG lasers.

1. Introduction

In recent years ultra-short pulse lasers have been widely used in the fields of ultrafast spectroscopy, metrology, ultrahigh capacity optical communication, superfine materials processing, microscopy and so on. Passive mode-locking of diode pumped solid-state lasers by semiconductor saturable absorber mirrors (SESAM) have been intensively investigated for generating picosecond and femtosecond optical pulses [1–3]. Keller et al. firstly using antiresonant semiconductor Fabry-Perot saturable absorber, demonstrated continuous wave (CW) mode-locked Nd:YLF laser with 3.3 ps pulse duration [4]. Since then passive mode-locking of the neodymium (Nd)-doped lasers such as Nd:YAG, Nd-doped vanadate crystals and ceramics with SESAM was also investigated and successfully demonstrated [5–9].

Gadolinium gallium garnet (GGG), another crystal suitable for Nd^{3+} doping, was first grown by Gcusic et al. using the Czochralski method in 1964 [10]. Compared with the Nd:YAG crystal, the Nd:GGG crystal has the following advantages. The Nd:GGG crystal with superior optical quality can be grown core-free up to 15 cm in radius [11]. The Nd:GGG crystals also have excellent thermal conductivity, low laser pump threshold, good mechanic properties and large thermal capacity. The GGG crystal has been considered as the best host for the solid-state heat capacity lasers (SSHCL) [12]. The Lawrence Livermore National Laboratory had demonstrated a SSHCL generating 30 kW average power using the Nd:GGG as the active medium in 2004 [13]. Our latest experimental results on the Nd:GGG crystal have also shown that this crystal could have high efficient CW and passive Q-switched operations [14].

The Nd:GGG laser transition at 1064 nm has an upper-state lifetime of 265 μs and a stimulated emission cross section of $2.1 \pm 0.1 \times 10^{-19}$ cm^2 [15]. The mode-locked laser could be easily obtained theoretically. However, to our knowledge so far no mode-locking of the crystal under LD pumping has been demonstrated. In this paper, we report on the CW mode-locking of a diode pumped Nd:GGG with SESAM. Stable mode-locked pulse train with pulse duration of ~17.5 ps and pulse repetition rate of 121.5 MHz has been achieved.

2. Experimental setup

The experimental setup is schematically shown in Fig. 1. A 50 W fiber coupled laser diode bar (Apollo F60-808-6) was used as the pump source. The core size of the fiber is 300 μm in radius, with a numerical aperture of 0.22. The emission wavelength of the laser diode is 806 nm. The pump light was focused into the Nd:GGG crystal by two coupling lenses with a beam compression ratio of 1.8:1. The focal spot in the crystal had a radial size of ~170 μm. The Nd:GGG crystal used has a dimension of $4 \times 4 \times 6$ mm^3. It is ⟨1 1 1⟩-cut and has Nd-doping concentration of 1.0 at.%. Both ends of the crystal were anti-reflection (AR) coated at the fundamental lasing wavelength of 1.06 μm and the pump wavelength of 806 nm. To efficiently remove the generated heat, the crystal was wrapped with indium foil and mounted in a water-cooled copper holder. The temperature of the circulating water was set at 15 °C during the experiment.

A Z-fold cavity was used to achieve an intensely focused spot on the SESAM and simultaneously an optimized mode matching with the pump beam in the Nd:GGG crystal. A flat mirror (M_1) was used as the input coupler. It was AR coated at the pump wavelength of 808 nm on the side faced to the laser diode, whereas

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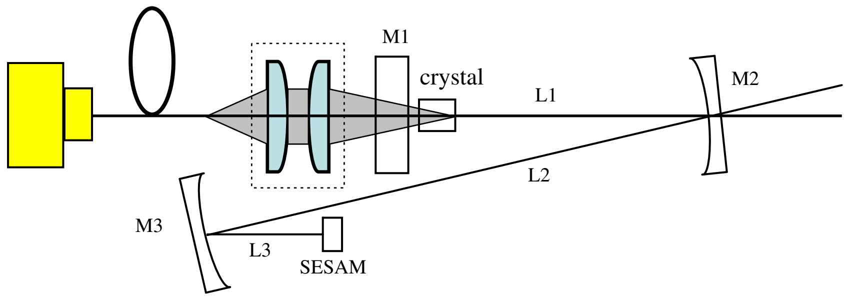

Fig. 1. Experimental scheme of Nd:GGG mode-locked laser setup, $L1 = 280$ mm, $L2 = 890$ mm, $L3 = 48$ mm.

the other surface was AR coated at 808 nm and high-reflectance (HR) coated at 1.06 μm. The resonator also consisted of a highly reflective (at 1064 nm) mirror M_3 and an output coupling (M_2) with a reflectivity of 98% at 1064 nm. The laser mode radii in the crystal and on the SESAM were calculated to be ~120 μm and ~25 μm, respectively. The SESAM used is a commercial product of BATOP. It has central absorption at 1040 nm with saturable absorption strength of 1%.

3. Results and discussion

Fig. 2 shows the measured room-temperature absorption and fluorescence spectra of the Nd:GGG crystal. This crystal has broad absorption from 770 nm to 830 nm, with a full-width-at-half-maximum (FWHM) of 23 nm. The absorption peak of 806 nm is the characteristic absorption of Nd^{3+} ion assigned to $^4I_{9/2}$ and $^4F_{5/2}$ transition. The fluorescence spectrum was measured by a TRIAX550 spectrophotometer. The strongest emission peak is located at 1061.2 nm with a FWHM of about 5 nm. There is no reabsorption near 1062 nm.

Like other diode pumped solid-state lasers mode-locked with the semiconductor saturable absorber, the laser clearly showed two regimes of mode-locked operation [2,16,17]. At low pump power level, the Q-switched mode-locking was generated. Fig. 3 shows a typical Q-switched pulse profile recorded with a 1-GHz bandwidth digital oscilloscope. Under Q-switched mode-locking the mode-locked pulse modulation could reach almost 100%. When the pump power increased slightly higher than 6 W, stable CW mode-locked pulses were then obtained. A typical CW mode-

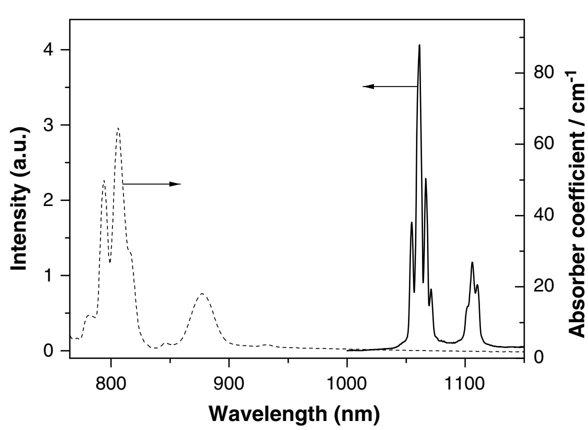

Fig. 2. Room-temperature absorption and fluorescence spectra of the Nd:GGG crystal.

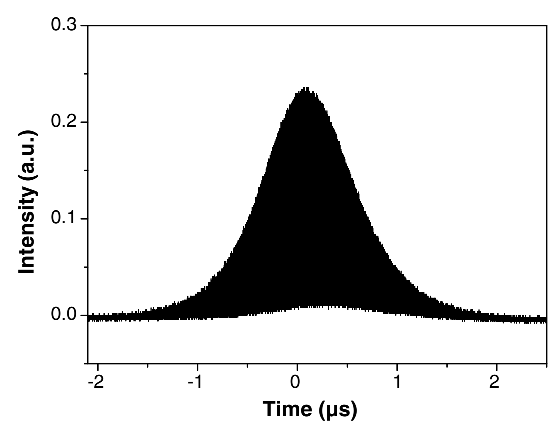

Fig. 3. Oscilloscope trace of a Q-switching mode-locked pulse train.

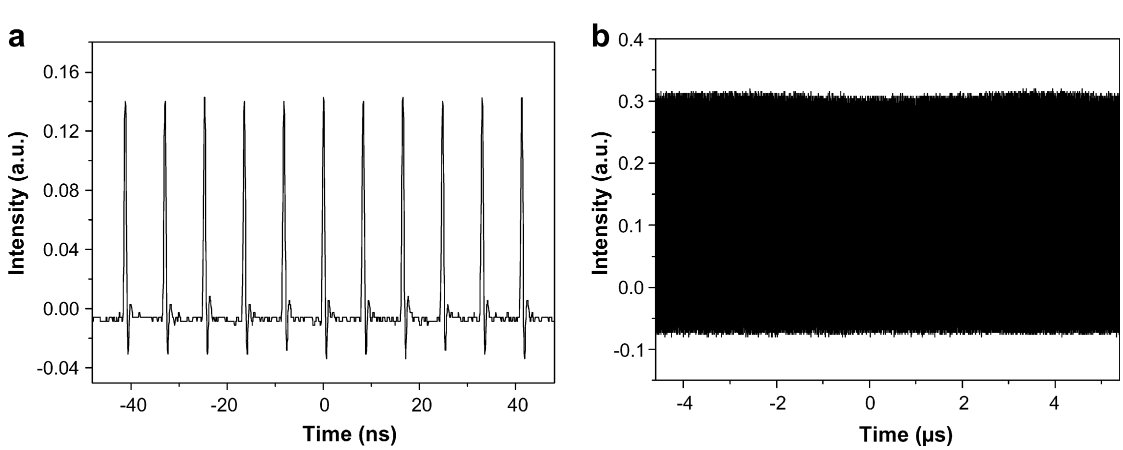

Fig. 4. Oscilloscope traces of the CW mode-locked pulse trains. (a) Under nanosecond scale and (b) under microsecond scale.

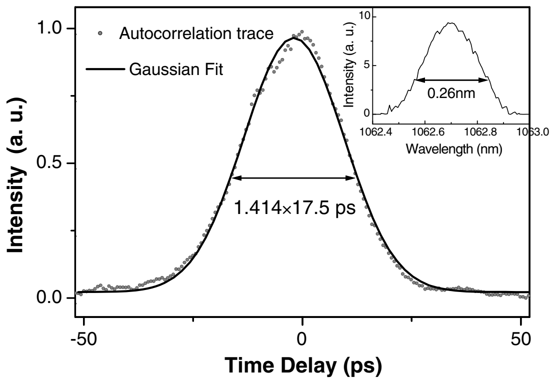

Fig. 5. Measured autocorrelation trace of the mode-locked pulses. Assuming a Gaussian pulse shape, the pulse duration is about 17.5 ps. Inset: spectrum of the mode-locked pulses.

locked pulse train is shown in Fig. 4. In either nanosecond time scale (Fig. 4a) or microsecond time scale (Fig. 4b) the mode-locked pulses exhibited good stability. Fig. 4a clearly shows that the pulse period is 8.23 ns, which corresponds to a repetition rate of 121.5 MHz as determined by the cavity length. The pulse-to-pulse intensity fluctuation is estimated to be less than 2%. The result shown in Fig. 4 was recorded under a pump power of 8.5 W. The corresponding average output power of the laser was 0.4 W. The average output power tended to saturate beyond the pump power of 8.5 W, then the mode-locked pulse train became unstable, and the SESAM could be easily damaged. When this occurred, the mode-locking then stopped. We believe it could be due to that the intensity on the SESAM exceeded its damage threshold ($\sim$1 mJ/cm^2).

A typical autocorrelation trace of the mode-locked pulses is shown in Fig. 5. The FWHM of the autocorrelation trace is about 25 ps. If a Gaussian pulse shape is assumed, the pulse duration of the mode-locked pulses is about 17.5 ps. A slight CW pedestal existed in the autocorrelation signal, which could be suppressed by employing a SESAM with larger modulation depth. The spectrum of the mode-locked pulses is shown in the inset of Fig. 5. It has a FWHM of about 0.26 nm. Therefore, the time-bandwidth product of the pulses is 1.209, which is 2.7 times of the value of a transform-limited Gaussian pulse. The result suggests that the mode-locked pulses are strongly chirped and the pulse duration can be further suppressed.

4. Conclusions

In conclusion, we have demonstrated passive mode-locking of a diode pumped Nd:GGG laser by a SESAM. Despite of the fact that Nd:GGG crystal has small stimulated emission cross section, using a SESAM with small saturable absorption strength, stable CW mode-locking of the laser could still be obtained. The mode-locked pulses have a duration of about 17.5 ps with a repetition rate of 121.5 MHz.

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