Diode-pumped passively mode-locked Nd:YAG laser at 1338 nm with a semiconductor saturable absorber mirror

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We demonstrate a diode-end-pumped passively mode-locked 1338 nm Nd:YAG laser with a semiconductor saturable absorber mirror. At the absorbed pump power of 8.89 W, an average output power of 1.12 W was obtained with a slope efficiency of 14%. The pulse width was 22.4 ps with a repetition rate of 63.9 MHz, corresponding to a peak power of 782 W. In addition, the bandwidth of the mode-locking spectrum is as narrow as 20.44 GHz, which shows the potential application in long-distance ranging and fiber information transmission because of the low dispersion of these ultrashort pulses. © 2011 Optical Society of America

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1. Introduction

Usually, passive mode locking is an efficient and convenient technique to generate ultrafast pulses. Semiconductor saturable absorber mirrors (SESAMs) have been proven as promising saturable absorbers for passively mode-locked all-solid-state lasers for their short pulse duration, inherent simplicity, and reliable operation [1–3]. Depending on the parameters of the saturable absorbers and performance of the laser gain media, laser pulse duration can range from picoseconds to a few femtoseconds. In the past decade, a lot of ultrafast Nd-doped lasers were focused on the 1.06 μm region [4,5]. Recently, because of the wide applications of light sources at 1.3 μm in many fields such as telecommunications, remote sensing, micromachining, data storage, and midinfrared laser pumping, much attention on this wavelength has been attracted. In addition, a 1.3 μm laser source, which coincides with the transmission window of silica optical fiber, is now widely needed. Owing to the development of proper saturable absorbers for continuous-wave (CW) mode locking at 1.3 μm, various Nd-doped crystals have been employed for developing 1.3 μm mode-locked lasers based on the possible $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transitions of Nd^{3+} [6–12]. Attention has been mainly focused on Nd-doped vanadate $Nd{:}YVO_4$ crystal because of its large stimulated cross section (6×10^{-19} cm^2), but the week thermal conductivity (5.14 W/mK) has been the major obstacle for output power by the thermal effects in the laser crystal. As a mature gain medium, Nd-doped yttrium aluminum garnet (Nd:YAG) is also favorable for 1.3 μm mode-locked operation, due to its excellent physical properties, including large thermal conductivity (14 W/mK) and high laser damage threshold (10 GW/cm^2). Continuous-wave mode-locked (CWML) operation at 1.3 μm of the Nd:YAG laser was investigated with a phase modulator, obtaining 162 mW of output power with a pulse duration of 12 ps [13].

In this paper, we demonstrate the diode-pumped passively mode-locked Nd:YAG laser at 1338 nm by use of SESAM. In order to achieve good mode matching between the oscillator mode and pump

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light in the crystal as well as stable mode-locking operation, the laser mode radii in Nd:YAG crystal and on the SESAM were carefully designed. Under the absorbed pump power of 8.89 W, an average output power of 1.12 W has been obtained in a stable mode-locked regime at a repetition rate of 63.9 MHz, and the pulse duration has been measured to be approximately 22.4 ps, which corresponds to a peak power of 782 W.

2. Experiment Setup

The SESAM we used in this mode-locked laser was grown upon a GaAs substrate. The Bragg mirror structure was composed of 27 AlAs/GaAs layers centered at 1338 nm, grown at 600 °C. The saturable absorber part comprised a 10 nm InGaAs quantum well with 48% In concentration separated by 93 nm GaAs half-wavelength layers. The growth temperature of the absorber structure was 330 °C. The SESAM has a saturation fluence of 70 $\mu J/cm^2$ at 1.3 μm and a fast relaxation time of 1 ps. Its modulation depth and nonsaturable loss were 1.2% and 0.8%, respectively.

The configuration of the diode-pumped Nd:YAG laser at 1338 nm is illustrated in Fig. 1. The gain medium is doped 1.0 at.% Nd:YAG crystal with dimensions of 3mm × 3mm × 5 mm (5 mm corresponding to the light passing direction), and the two end faces are antireflection (AR) coated at 808 nm and 1.3 μm. In order to reduce the influence of thermal lens effects, the laser crystal was wrapped with indium foil and mounted in a water-cooled copper heat sink at the water temperature of 20 °C. The pump source was a fiber-coupled 808 nm diode laser with a core diameter of 400 μm and a numerical aperture of 0.22. Its radiation was coupled into the laser crystal by a focusing optical system with a 25 mm focal length. The radius of the pump beam within the laser crystal was around 200 μm. The pump absorbance was about 82% during the experiment. The resonator consisted of four mirrors and one SESAM. As the input and folding mirror, M1 was antireflection coated at 808 nm on both surfaces and high reflection (HR, $R > 99.8\%$) coated at 1.3 μm on the concave side with radius of curvature of 1000 mm. The radii of curvature of the folded concave mirrors M2 and M3 were 500 mm and 200 mm, respectively. Both of the two mirrors were HR coated at 1.3 μm. In order to minimize astigmatism, mirrors M1, M2, and M3 were arranged with the smallest possible folded angles. Two plane mirrors with transmission of $T = 3.0\%$ and $T = 8.0\%$ were used as the output coupler M4, respectively. To suppress the oscillation of the 1064 nm laser, all the mirrors were AR coated at 1064 nm. The reflective SESAM was soldered on a small copper block. With the ABCD matrix formalism, the arm lengths of four branches, d1, d2, d3, and d4 were carefully optimized to be 1.55, 0.306, 0.36, and 0.132 m, respectively. The entire length of the laser cavity is about 2.348 m. The laser mode radii were calculated to be about 50 μm on the SESAM and 150 μm in the gain medium, respectively. The CWML pulse train was recorded by a digital oscilloscope (1 GHz bandwidth, 5 Gs/s sampling rate) and a photodetector. Both spectral parameters of CW and CWML operation were monitored by a commercial optical spectrum analyzer with resolution of 0.05 nm.

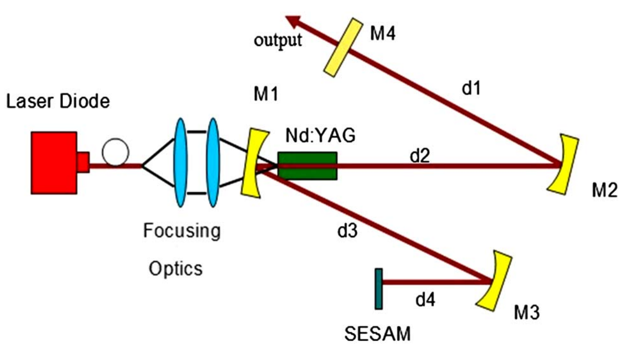

Fig. 1. (Color online) Experimental setup for diode-end-pumped passively mode-locked Nd:YAG laser at 1338 nm.

3. Experiment Results and Discussion

Prior to performing the mode-locked operation of the laser system, the SESAM was replaced by a plane mirror HR coated at 1.3 μm to study the CW performance with different transmission of 3.0% and 8.0% at 1.3 μm, The dependence of the output power on the incident pump power at different transmission in CW operation are illustrated in Fig. 2. The maximum output power of 1.87 W was achieved with the absorbed pump power of 9.82 W, giving a slope efficiency of 21%. The spectrum of the CW laser has multiple peaks, which resulted in unstable oscillation competition, as shown in Fig. 3. When the SESAM and $T = 8\%$ output coupler were used together, the self-started Q-switched mode locking (QML) was achieved at the absorbed pump power ranged from 2.10 W to 2.98 W. According to the analysis in [14], to suppress the QML trend and realize a stable CWML, the intracavity pulse energy E_p should satisfy

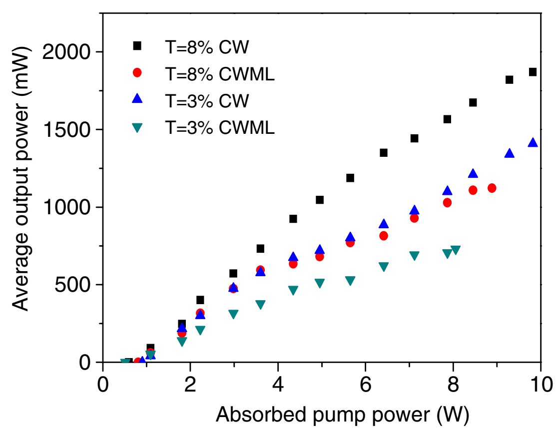

Fig. 2. (Color online) Average output power versus absorbed pump power for CW operation and CWML operation with $T = 3\%$ and 8% output couplers.

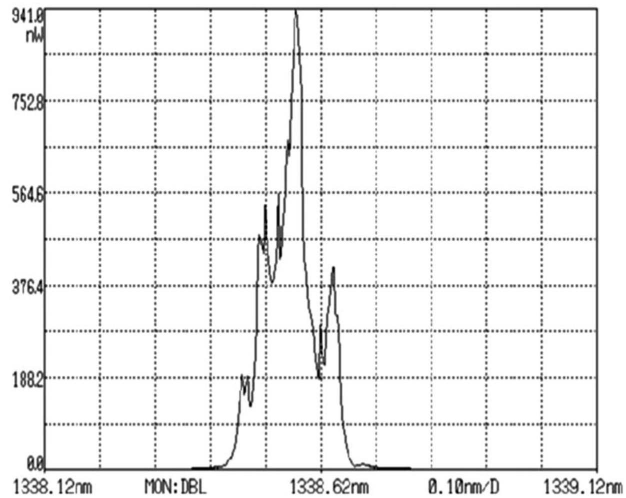

Fig. 3. The spectrum of CW lasing operation around 1338 nm.

$$E_p > (F_{\mathrm{sat},L} A_{\mathrm{eff},L} F_{\mathrm{sat},A} A_{\mathrm{eff},A} \Delta R)^{1/2}, \qquad (1)$$

where $F_{\mathrm{sat},L}$ and $F_{\mathrm{sat},A}$ are the saturation fluence of the gain medium and of the SESAM, respectively; $A_{\mathrm{eff},L}$ and $A_{\mathrm{eff},A}$ are the effective laser mode in the gain and on the SESAM, respectively; and ΔR is the modulation depth of the SESAM. From Eq. (1), for our Nd:YAG laser, the calculated minimum intracavity pulse energy for CWML operation is 152 nJ. In the experiment, typical stable CW mode-locking operation free of QML instabilities can be obtained when the absorbed pump power exceeded 2.98 W, corresponding to an intracavity pulse energy of 178 nJ, which agreed with the calculated result. Output power of 1.12 W was realized under the absorbed pump power of 8.89 W, corresponding to a slope efficiency of 14%. When an output coupler of 3% transmission at 1.3 μm was used, the maximum output power was found to be 0.73 W under the absorbed pump power of 8.06 W due to a strong gain saturation effect.

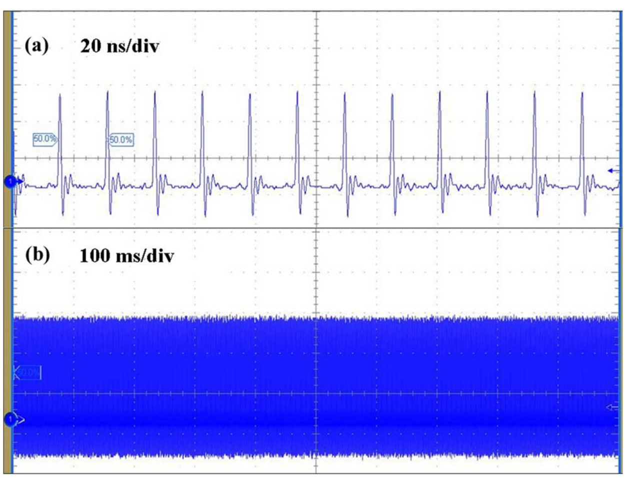

Fig. 4. (Color online) Pulse trains on two different time scales: (a) time span of 20 ns, demonstrating mode-locked pulse and (b) time span of 100 ms, demonstrating amplitude stability.

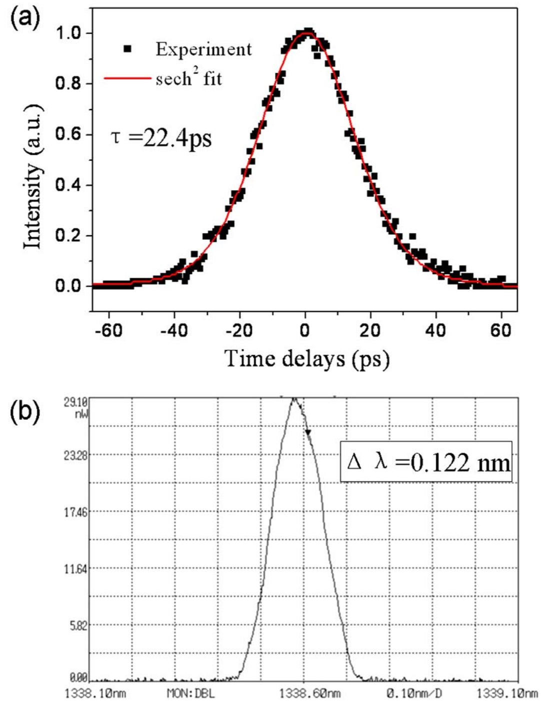

Fig. 5. (Color online) (a) Autocorrelation trace. The pulse width was 22.4 ps assuming a sech^2 pulse shape. (b) Spectrum of CWML laser at 1338 nm.

Damage in the SESAM or the crystal was not observed for long-term operation.

Once the CWML lasing threshold was reached, we could observe the nearly perfect mode-locked pulse train, as shown in Fig. 4(a). The repetition rate was measured to be 63.9 MHz, which was consistent with the round-trip time of the cavity length. Figure 4(b) shows the pulse train with time span of 100 ms, demonstrating the amplitude stability. As an extremely important parameter for a CW mode-locking laser, the pulse width was measured with a commercial Pulse Check noncollinear autocorrelator. As shown in Fig. 5(a), the pulse duration was 22.4 ps, assuming a sech^2 pulse shape. The output pulse energy was calculated to be 17.5 nJ, resulting in a pulse peak power of 782 W. As shown in Fig. 5(b), the spectral FWHM was found to be 0.122 nm, corresponding to 20.44 GHz at the central wavelength of 1338 nm. The time-bandwidth product of the mode-locked pulse was approximately 0.458, indicating the pulse to be frequency chirped. Compared with CW operation, the mode-locked operation has a smoother and neater spectrum because of the fixed amplitude and phase relationships of each mode. The narrow bandwidth of the laser might be due to the spatial hole burning effect related to the long separation (about 15 mm) between the laser crystal and the input mirror [15,16]. The watt-level output power and narrow bandwidth laser can be used as a seed source of the amplifier and can be used for long-distance ranging and fiber information transmission without signal loss and variation, for its low dispersion and excellent coherence.

4. Conclusion

In summary, we have demonstrated a diode-end-pumped CW mode-locked 1338 nm Nd:YAG laser with a SESAM. At the absorbed pump power of 8.89 W, average output power of 1.12 W was obtained with pulse repetition rate of 63.9 MHz and pulse width of 22.4 ps. The results indicate that our mode-locked Nd:YAG laser with watt-level output power and narrow bandwidth of 20.44 GHz has potential for the seeding of amplifiers and use for long-distance ranging and fiber information transmission.

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