Diode-pumped passively mode-locked Nd:GSAG laser at 942 nm

Changwen Xu,[1] Zhiyi Wei,[1,*] Yongdong Zhang,[1] Dehua Li,[1] Zhiguo Zhang,[1] X. Wang,[2] S. Wang,[2] H. J. Eichler,[2] Chunyu Zhang,[3] and Chunqing Gao[3]

[1]*Laboratory of Optical Physics, Institute of Physics, Beijing National Laboratory for Condensed Matter Physics, Chinese Academy of Sciences, Beijing 100190, China*

[2]*TU Berlin, Institut für Optik und Atomare Physik, Straße des 17. Juni 135, 10623 Berlin, Germany*

[3]*Department of Opto-Electronics, Beijing Institute of Technology, Beijing 10080, China*

**Corresponding author: zywei@aphy.iphy.ac.cn*

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Stable mode-locking of a diode-pumped Nd:GSAG laser emitting at 942 nm between the $^4F_{2/3}-^4I_{9/2}$ transition has been demonstrated. With a *z* cavity and a semiconductor saturable absorber mirror passive mode locker, we obtained 8.7 ps pulses at repetition rate of 95.6 MHz and average output power of 510 mW. The total optical efficiency is about 3.1%. © 2009 Optical Society of America

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During the past few years, the Nd^{3+} laser on the $^4F_{2/3}-^4I_{9/2}$ transition has attracted wide interest because of emission wavelengths of around 900–950 nm. One important application for this quasi-three-level pulsed laser is that it could be used for lidar detection of water vapor in atmosphere [1] because of characteristic absorption in the 935 nm, 942 nm, and 944 nm wavelength regions. Continuous-wave characteristics of several Nd-doped laser crystals that can emit radiation at these wavelengths have been investigated, such as Nd:GSAG at 942 nm [2], Nd:YGG at 935 nm [2], and Nd:CNGG at 935 nm [3] *et al.* Compared with optical parametric oscillators, generation of above wavelengths by Nd-doped crystal laser is much easier. Among those lasers, a Nd:GSAG laser at 942 nm has been further developed to operate in the pulsed mode (non-mode locking) [4–6]. As is well known, passively mode locking of Nd^{3+} lasers around 1 μm have been realized by a lot of groups in many laser media; however, the passively mode-locked quasi-three-level Nd^{3+} lasers were reported with only a few crystals: 1.9 ps pulses at 930 nm with $Nd:YAlO_3$ pumped by Ti:sapphire [7], 3 ps and 8.8 ps pulses at 914 nm with $Nd:YVO_4$ pumped by Ti:sapphire and laser diode (LD) [8,9], 6.5 ps pulses at 912 nm with $Nd:GdVO_4$ [10] pumped by an LD, and 6.7 ps pulses at 916 nm with $Nd:LuVO_4$ pumped by an LD [11]. The quasi-three-level laser is more difficult to operate than the four-level laser for Nd^{3+} lasing, because there are two disadvantages for the former: one is that the lower-laser level is at the top of the ground-state stark sublevels, so there is some population on the lower-laser level at room temperature, and the other is that emission cross section of the quasi-three-level laser is much smaller than that of the four-level laser. For Nd:GSAG, about 0.7% ions occupy the terminal laser level at room temperature, which give rises to the reabsorption loss. A peak emission cross section of $\sigma_e = 2.7\times10^{-20}$ cm^2 at 942.7 nm [4] and a peak emission cross section of $\sigma_e = 3.2\times10^{-19}$ cm^2 around 1.06 μm [12] were determined by Kallmeyer *et al.* and Brandle *et al.*, respectively. One can see the emission cross section at 942 nm is less than one-tenth the emission cross section at 1.06 μm. This leads to an increased threshold pump power and decreased optical conversion efficiency. Frequency doubling of mode-locked quasi-three-level Nd^{3+} lasers generates picosecond blue pulses, which have potential application in many fields, such as life science, holography, and semiconductor inspection [13]. It is desirable to obtain as high fundamental power as possible for high conversion efficiency.

In this Letter, we report on what is believed to be the first the diode-pumped passively mode-locked Nd:GSAG quasi-three-level laser. The laser central wavelength is at 942.6 nm. Pulses as short as 8.7 ps at a repetition rate of 95.6 MHz have been obtained. The maximum output power is 510 mW at incident pump power of 16.7 W.

The experimental setup is shown in Fig. 1. A *z* cavity, which is usual in the end-pumped configuration, was employed with a focal length of about 2.5 cm of the coupling system. The two beams behind the output coupler M3 have nearly the same power (the difference between them is less than 4% of single-beam output power), and the average power mentioned be-

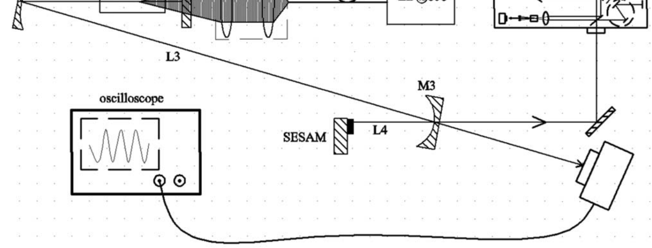

Fig. 1. Schematic diagram of the experimental setup. Mirrors: M1: HT@808 nm and 106 nm, HR@942 nm; M2: HR@942 nm, HT@1064 nm, radius of curvature (RoC)=500 nm; M3: T=3%@942 nm, HT@1064 nm, RoC=100 nm. Distances: L1=8 mm, L2=250 mm, L3=1250 mm, L4=47 mm.

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low is the sum of the two beams. The pump source is a commercial fiber-coupled LD (LIMO GmbH, Germany), with rated maximum power of 25 W at 808 nm, a core diameter of 200 μm, and an NA of 0.22. The circular spot was imaged into the crystal with a coupling system with a magnification of 1:1. The crystal used in the experiment has dimensions of $\varnothing$4 mm$\times$4 mm and Nd^{3+} concentration of 1 at. %. The both facets of the crystal have been antireflection (AR) coated at 942 nm ($R\approx 0.15\%$), 808 nm ($R \approx 1\%$) and at 1061 nm ($R\approx 2\%$). The crystal was wrapped with indium foil and mounted on a water-cooled copper heat sink and the water temperature was maintained at 10°C.

The semiconductor saturable absorber mirror (SESAM) for mode locking was purchased from BATOP GmbH, Germany, with a saturable absorptance of 4% at 940 nm, a saturation fluence of 70 μJ/cm^2, and relaxation time of less than 10 ps. It is soldered on a small copper heat sink so that the loaded heat can be easily removed. The laser spot size on the SESAM is estimated to be 27 μm $\times$20 μm (tangential direction$\times$sagittal direction) using the ABCD matrix theory. A power meter and a fast detector connected to an oscilloscope were put into the two output beams for measurement and signal monitoring. The dependence of the total output power on the incident pump power is shown in Fig. 2. The threshold incident pump power is about 9 W. When the total output power was exceeding 103 mW at the pump power of about 11.4 W, the laser changed from the Q-switched mode-locking regime (QML) to the cw mode-locking regime. Increasing the incident pump power, the output power increased, while the laser kept the stable cw mode-locking regime. When the incident pump power reached 16.7 W, the output power rose to 510 mW, corresponding to a global optical efficiency of 3.1%, and the pulse energy inside the cavity and outside the cavity are about 88.3 nJ and 2.65 nJ, respectively. The high threshold pump power and the low efficiency are mainly due to the relatively high total transmission of 6% brought by the folded output coupler. If suitable output couplers are available and an SESAM with lower saturable absorptance than that one used in the experiment is used, we believe the output power at watt level should be possible. The beam quality of the laser is very important for the stability of passively mode locking. Under incident pump power of 16.7 W, the laser pattern performed a Gaussian transversal mode and the M^2 parameters were measured with a CCD that could translate along a straight and slick track. After fitting the measured data, as shown in Fig. 3, we found that M^2 parameters are 1.83 and 1.55 for tangential direction (Rx) and sagittal direction (Ry), respectively. The stable cw mode-locking regime held well for several hours.

Figure 4 shows the pulse train recorded with an oscilloscope. The repetition rate of the pulses is 95.6 MHz. The pulse duration was measured with an intensity autocorrelator (FR-103MN, Femtochrome Research, Inc.) at the maximum output power, as shown in Fig. 5. The measurement at the maximum pump power revealed that the pulse duration is about 8.7 ps assuming a Gaussian shape. The corre-

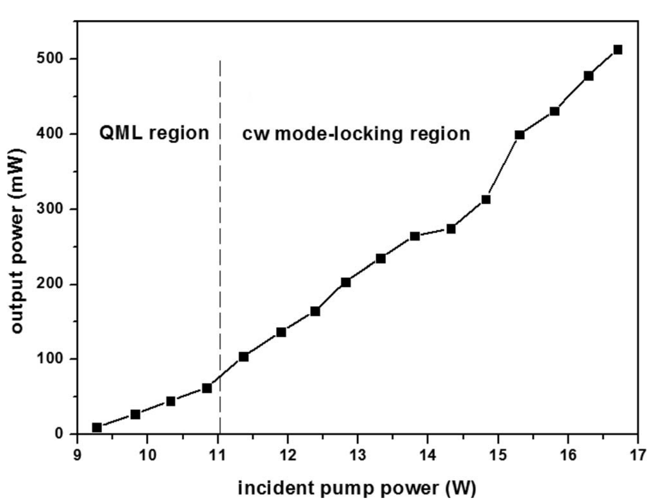

Fig. 2. Dependence of the mode-locked laser output power on incident pump power.

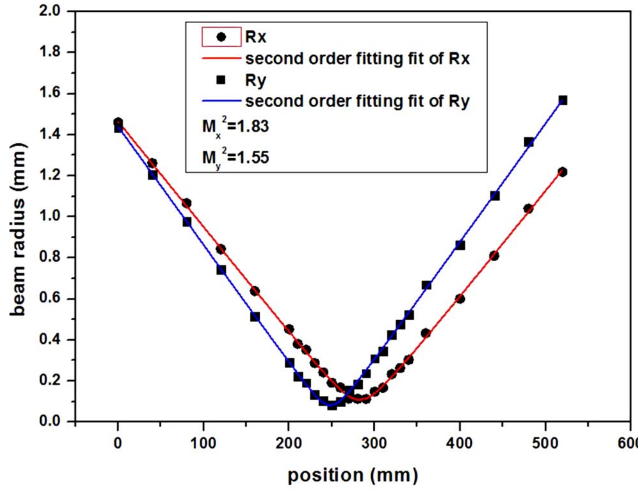

Fig. 3. (Color online) Measured M^2 for tangential direction (Rx) and sagittal direction (Ry).

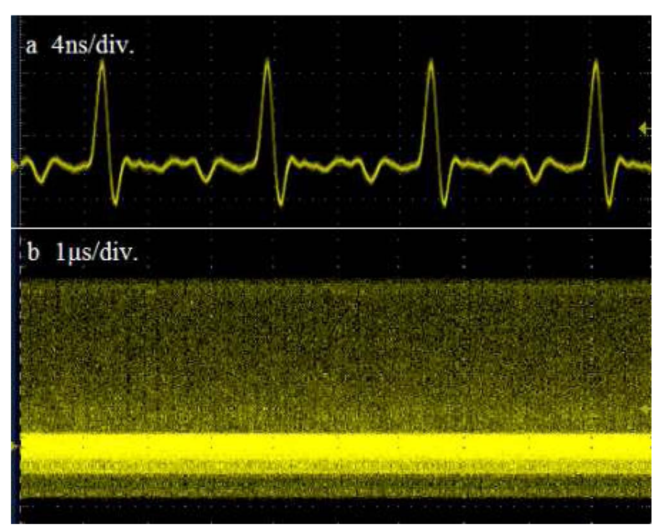

Fig. 4. (Color online) Pulse trains observed with two different time scales: a, 4 ns/div; b, 1 μs/div.

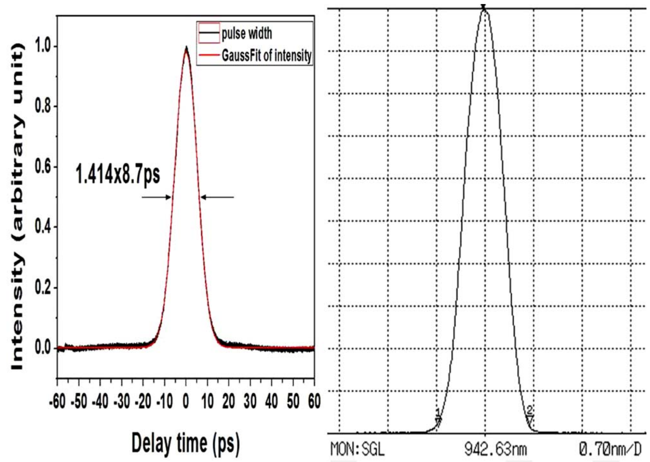

Fig. 5. (Color online) The autocorrelation signal indicates 8.7 ps pulse duration if a Gaussian shape (left) is assumed. The corresponding mode-locked pulse spectrum (right) has a width of 0.65 nm.

sponding spectrum was centered at 942.6 nm [measured with an optical spectrum analyzer (AQ6315A, YOKOGAWA)] and has an FWHM of about 0.65 nm, also shown in Fig. 5. The time–bandwidth product of the pulses is 1.91, which is 4.3 times the transform limit for Gaussian pulses. The primary reason for this is that positive group-velocity dispersion introduced by crystal itself stretched the pulses.

In conclusion, we demonstrated a stable LD-pumped mode-locked Nd:GSAG laser at 942.6 nm. The mode-locked pulses are emitted at a repetition rate of 95.6 MHz with a pulse duration of 8.7 ps. The maximum average output power of 510 mW is obtained at the incident pump power of 16.7 W. We believe a more robust and higher efficient mode-locked Nd:GSAG laser at 942 nm and pulses as short as 2 ps could be obtained if some improvements would be made, such as a suitable output coupler and intracavity dispersion compensation. Using a delta cavity [8] to make the laser output in one single beam and enhancing the output is beneficial to obtain high-energy picosecond blue pluses by the means of extra-cavity frequency doubling, and will be our future work.

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