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High-peak-power passively Q-switched Nd:YAG laser at 946 nm

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ABSTRACT We demonstrate a high-peak-power quasi-continuous-wave diode-pumped passive Q-switched Nd:YAG laser at 946 nm. We make a thorough comparison of the output performance between the saturable absorbers of InGaAs quantum wells (QWs) and a Cr^{4+}:YAG crystal. Experimental results reveal that the saturable absorber of InGaAs QWs is superior to the Cr^{4+}:YAG crystal because of the low nonsaturable losses and leads to a pulse energy of 330 μJ with a peak power greater than 11 kW.

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1 Introduction

Nd:YAG crystals have been widely used as gain media in all-solid-state lasers as a consequence of their excellent optical and mechanical properties [1–3]. Most lasers on Nd:YAG crystals were focused on the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition in the 1064-nm range. In recent years, the quasi-three-level $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition near 946 nm has attracted much attention because of a large number of applications [4–12]. Although the second-harmonic generation of continuous-wave (cw) 946-nm laser beams is useful for applications such as holography, optical data storage, and color displays, high-peak-power pulsed lasers are highly desirable for other applications such as remote sensing, ranging, and micromachining. Kellner et al. obtained a pulse energy of 80 μJ with a peak power of approximately 1 kW in a passively Q-switched Nd:YAG 946-nm laser with a Cr^{4+}:YAG crystal as a saturable absorber [5]. Recently, Kimmelma et al. utilized a compact Cr^{4+}:YAG/Nd:YAG cavity to achieve a pulse energy of 23 μJ with a peak power as much as 3.7 kW [7]. In addition to Cr^{4+}:YAG crystals, semiconductor materials based on the GaAs substrate have been developed to be saturable absorbers in Nd:YAG lasers at 946 nm [8, 9]. Up to now, the maximum pulse energy and highest peak power of passively Q-switched Nd:YAG 946-nm lasers with semiconductor saturable absorbers are 20 μJ and 0.53 kW, respectively [9].

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In this work we report a high-power quasi-continuous-wave (QCW) diode-pumped Nd:YAG laser at 946 nm. Approximately 4.5 mJ of output pulse energy at 946 nm was obtained with a pump energy of 83 mJ at a repetition rate of 35 Hz. The QCW laser is passively Q-switched by use of different saturable absorbers including InGaAs QWs and a Cr^{4+}:YAG crystal. Using InGaAs QWs as a saturable absorber, the compact passively Q-switched laser yields a pulse energy of 330 μJ with a peak power greater than 11 kW. To our best knowledge, these are the largest pulse energy and the highest peak power ever achieved in diode-end-pumped Nd:YAG lasers at 946 nm.

2 Experimental setup

Figure 1a and b show the experimental setups for high-power QCW diode-pumped passively Q-switched Nd:YAG lasers at 946 nm with a Cr^{4+}:YAG crystal and an InGaAs QW structure as a saturable absorber, respectively. The pump source is a high-power QCW diode stack (Quantel laser diodes) that consists of three 10-mm-long diode bars generating 130 W per bar, for a total of 390 W at the central wavelength of 808 nm. The diode stack is designed with 0.4-mm spacing between the diode bars so that the overall area of emission is approximately 10 mm (slow axis) × 0.8 mm (fast axis). The full divergence angles in the fast and slow axes are approximately 35° and 10°, respectively.

A lens duct was utilized to efficiently couple the pump radiation from the diode stack into the laser crystal. In comparison with other coupling methods such as optical fibers, gradient-index lenses, or aspheric lenses, the lens duct has the benefits of simple structure and high coupling efficiency and is impervious to slight misalignment. These benefits are practically important for the end-pumped solid-state lasers with laser-diode stacks in which there is a significant geometric mismatch between the effective diode emitter area and the available input aperture of the gain medium. As shown in Fig. 2, there are five geometric parameters, r, L, H_1, H_2, and H_3, for a lens duct, where r is the radius of the input surface, L is the length of the duct, H_1 is the width of the input surface, H_2 is the width of the output surface, and H_3 is the thickness of the duct [13, 14]. Here, a lens duct with the parameters $r = 10$ mm, $L = 32$ mm, $H_1 = 12$ mm, $H_2 = 1.6$ mm, and $H_3 = 1.6$ mm was manufactured and used in the experi-

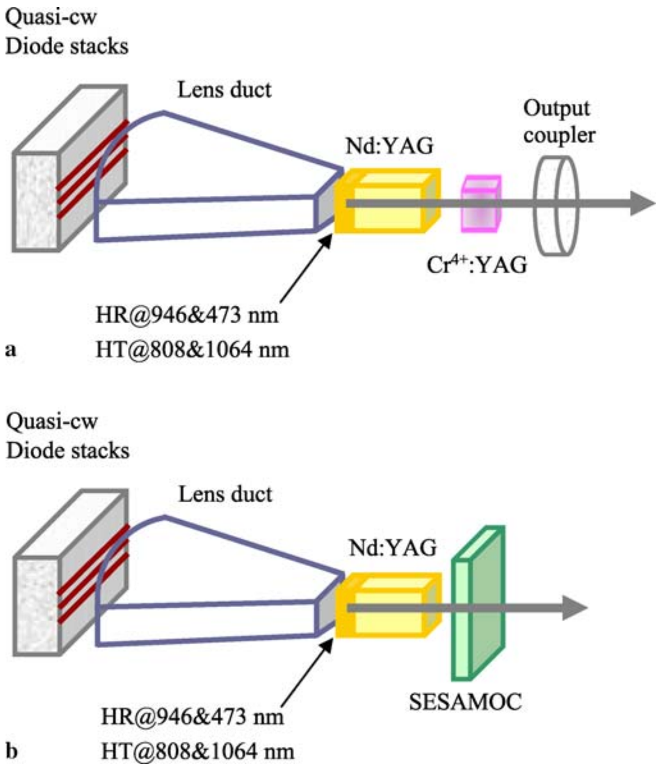

FIGURE 1 Schematic of a diode-pumped passively Q-switched Nd:YAG laser at 946 nm: HR, high reflection; HT, high transmission. (**a**) with the Cr^{4+}:YAG crystal as a saturable absorber; (**b**) with the InGaAs QWs as a saturable absorber and output coupler

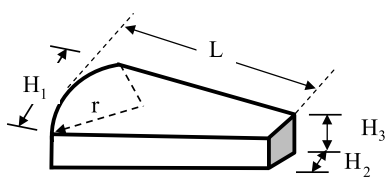

FIGURE 2 Schematic of a lens duct, in which r is the radius of the input surface, L is the length of the duct, H_1 is the width of the input surface, H_2 is the width of the output surface, and H_3 is the thickness of the duct

ment. The coupling efficiency of this lens duct is experimentally found to be approximately 78%. The active medium was a 1.1 at. % Nd:YAG crystal with a length of 5.0 mm and a transverse aperture of $3 \times 3\,mm^2$. Approximately 75% of the pump light was absorbed in the gain medium. The entrance surface of the laser crystal was coated to be highly reflective at 946 nm ($R > 99.8\%$) and highly transmissive at 808 nm ($T > 90\%$) and 1064 nm ($T > 85\%$). The other surface of the laser crystal was coated for antireflection at 946 nm ($R < 0.2\%$). The laser crystal was wrapped with indium foil and mounted in a copper block.

A Cr^{4+}:YAG crystal is used as a saturable absorber for the passive Q-switching operation. The Cr^{4+}:YAG crystal had a thickness of 1 mm with 95% initial transmission at 946 nm. Both sides of the Cr^{4+}:YAG crystal were coated for antireflection at 946 nm. A plane mirror is chosen to be the output coupler, whose reflection at 946 and 1064 nm was 95% and $< 20\%$, respectively.

The other passive Q-switching operation is to employ a semiconductor saturable absorber mirror (SESAM) [15–17]. The present saturable absorber was fabricated to combine

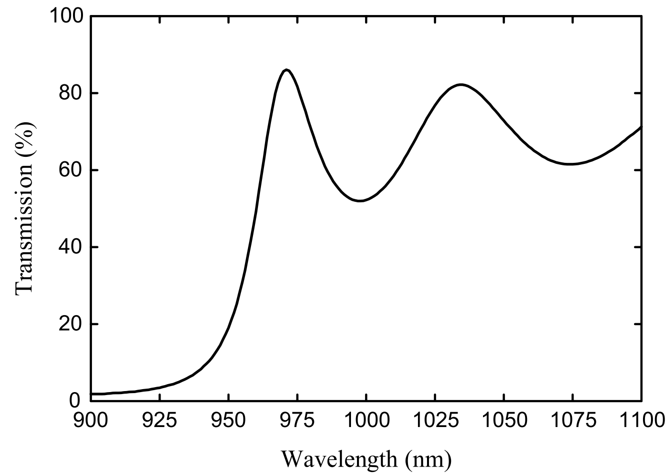

FIGURE 3 Measured results of the low-intensity transmission spectrum for the InGaAs SESAMOC

a SESAM with an output coupler (SESAMOC) that was originally proposed by Spühler et al. to simplify the cavity configuration in passively Q-switched lasers [17]. The SESAMOC device was monolithically grown on an undoped 350-μm-thick GaAs substrate by metalorganic chemical vapor deposition (MOCVD) to comprise three strained $In_{0.15}Ga_{0.85}As$/GaAs quantum wells (QWs) grown on the Bragg mirror. The QWs have a thickness of 8 nm and are separated by 10-nm-thick GaAs layers. The Bragg mirror consists of eight AlAs/GaAs quarter-wavelength layers, designed for a reflectivity in the region of 90–91% at 946 nm. The back side of the GaAs substrate was coated for antireflection at 946 nm ($R < 1\%$).

Figure 3 shows the measured result for the low-intensity transmission spectrum of the SESAMOC. The low-intensity transmission at 946 nm and 1064 nm can be found to be approximately 10% and 64%, respectively. The SESAMOC with high transmission at 1064 nm is particularly critical to suppress the ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition and to lead to the lasing at 946 nm. The saturation measurements were performed using nanosecond Q-switched laser pulses to coincide with the present Q-switched experiment. Experimental results revealed that the present SESAM device had a modulation depth of 1.5% and a saturation fluence of $20\,\mu J/cm^2$.

The pulse temporal behavior was recorded by a LeCroy digital oscilloscope (Wavepro 7100; 10 G samples/s; 1-GHz bandwidth) with a fast InGaAs photodiode. The spectral information of the laser was monitored by an optical spectrum analyzer (Advantest Q8381A). The spectrum analyzer employing a diffraction grating monochromator can be used for high-speed measurement of pulse light with the resolution of 0.1 nm.

3 Experimental results and discussion

First of all, the quasi-cw free-running operation without saturable absorber was performed to confirm the pumping efficiency of the lens duct and the quality of the laser crystal. For this investigation the diode stack was driven to emit optical pulses 270-μs long, at a repetition rate of 35 Hz, with a duty cycle of approximately

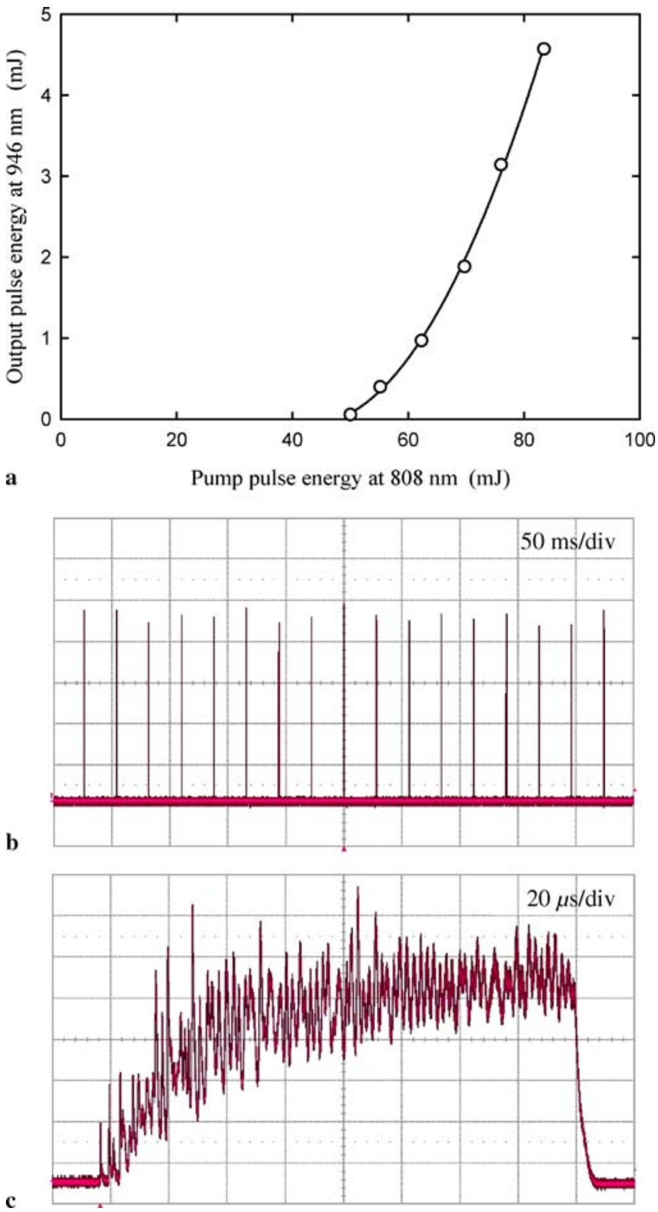

FIGURE 4 (**a**) Experimental results of the free-running operation for the output pulse energy as a function of the pump energy; (**b**) experimental pulse train at 83 mJ of pump energy; (**c**) temporal shape of a single pulse

1%. Figure 4a plots the experimental results of the free-running operation for the output pulse energy as a function of the pump energy. At 83 mJ of pump energy, the output energy at 946 nm is found to be approximately 4.5 mJ. The overall slope efficiency can be found to be nearly 15%. The moderate slope efficiency ensures the practicability of the pump scheme. Figure 4b depicts the experimental pulse train at 83 mJ of pump energy. The temporal shape of a single pulse, as shown in Fig. 4c, exhibits relaxation-oscillation-driven spikings. Although the pump pulse width is 270 μs, the lasing threshold leads to the output pulse width to be approximately 155 μs. With the experimental pulse width and the pulse energy, the 'on-time' average output power can be estimated to be 29 W at 83 mJ of pump energy, corresponding to 307 W of the on-time average pump power.

Operation of the first passively Q-switched Nd:YAG laser at 946 nm was performed by inserting a Cr^{4+}:YAG crystal into the same plano–plano cavity. The threshold of the Q-switched laser operation was found to be approximately 75 mJ and the output pulse energy at 946 nm was measured to be 95 μJ. The effective pulse width was found to be 28 ns; consequently, the peak power was approximately 3.4 kW. As shown in Fig. 4a, the output pulse energy in the free-running regime is 2.1 mJ at 75 mJ of pump energy. Consequently, the extraction efficiency with respect to the output pulse energy from the free-running operation is approximately 4.5%. When the pump energy is higher than 80 mJ, the laser cavity generates double pulses with the pulse characteristics nearly the same as the single-pulse output, as shown in Fig. 5.

The second passive Q-switching operation was performed by employing the above-mentioned SESAMOC to replace the Cr^{4+}:YAG saturable absorber and the output coupler. The threshold of the Q-switched laser operation was found to be approximately 73 mJ and the output pulse energy at 946 nm was measured to be 330 μJ. As shown in Fig. 6a, the effective pulse width was found to be approximately 30 ns; consequently, the peak power was greater than 11 kW. As shown in Fig. 4a, the output pulse energy in the free-running regime is 2.1 mJ at 75 mJ of pump energy. Therefore, the extraction efficiency with respect to the output pulse energy from the free-running operation can be found to be approximately 15.8%. Compared to the results obtained with the Cr^{4+}:YAG saturable absorber, both lasing thresholds are almost equal; however, the output pulse energy and efficiency with the present SESAMOC are three times higher. The superior performance of the present SESAMOC comes from the considerably low nonsaturable losses [9]. When the pump energy is higher than 80 mJ, the laser cavity can generate triple pulses with the pulse characteristics nearly as good as the single-pulse output, as

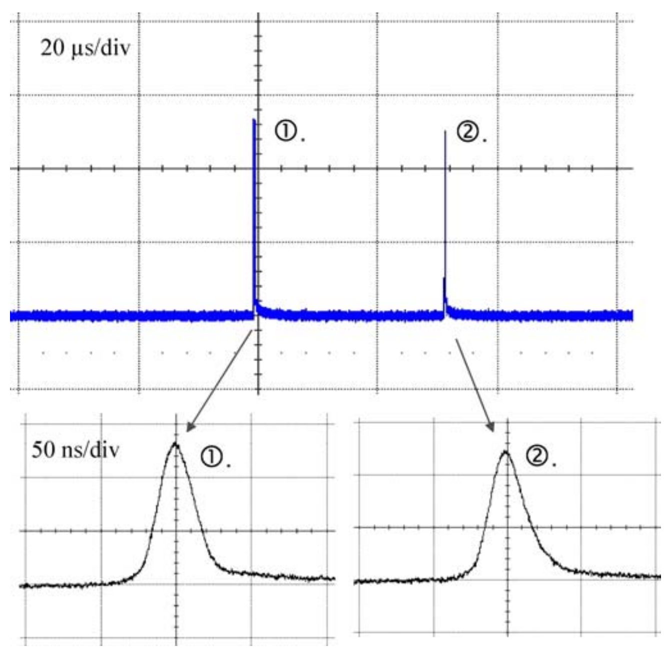

FIGURE 5 *Upper trace*: typical result of double pulses in the passively Q-switched Nd:YAG/Cr^{4+}:YAG laser at 946 nm; *lower traces*: expanded shape of each pulse

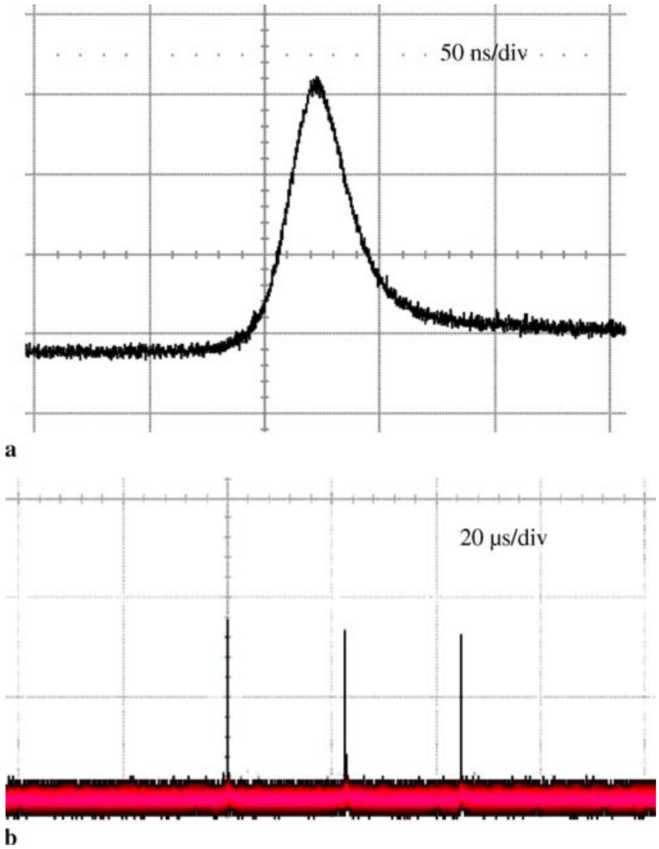

FIGURE 6 (**a**) Typical oscilloscope trace of a single pulse; (**b**) typical oscilloscope trace of triple pulses with the InGaAs QWs as a saturable absorber

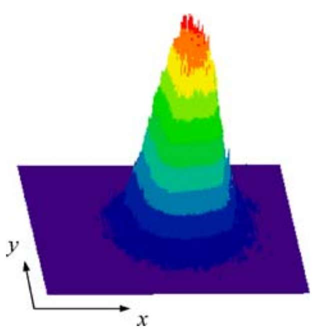

FIGURE 7 Spatial distribution of the output beam recorded with an infrared CCD

depicted in Fig. 6b. Under the optimal alignment condition, the pulse-to-pulse amplitude fluctuation was found to be approximately ±10%. The residual pump light irradiating the SESAMOC was not clearly revealed to cause any influence on the output performance. Finally, the spatial distribution of the output beam was recorded with an infrared CCD and displayed in Fig. 7. The beam quality factor $M_x^2 \times M_y^2$ was measured and found to be 3.5×1.3, where the x and y directions are parallel to the slow and fast axes of the diode stack. Although the present beam quality is about four times worse than the diffraction-limited result reported in the previous Q-switched 946-nm laser generating about 80 μJ [5], the peak power enhancement leads to the present brightness to be approximately increased by 2.7 times.

4 Conclusion

We have demonstrated a high-power quasi-continuous-wave (QCW) diode-pumped Nd:YAG laser at 946 nm and its passive Q-switching operation with two kinds of saturable absorbers including InGaAs QWs and a Cr^{4+}:YAG crystal. Approximately 4.5 mJ of output energy at 946 nm is generated with a pump energy of 83 mJ at a repetition rate of 35 Hz. With the experimental pulse width and the pulse energy, the on-time average output power is estimated to be 29 W. For the passive Q-switching operation, the InGaAs SESAMOC leads to a pulse energy of 330 μJ with a peak power greater than 11 kW and this pulse energy is nearly three times greater than that obtained with the Cr^{4+}:YAG crystal under almost the same threshold. Experimental results reveal that the InGaAs SESAM is superior to the Cr^{4+}:YAG crystal for passively Q-switched Nd:YAG lasers at 946 nm because of the low nonsaturable losses.

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