Semiconductor quantum-well saturable absorbers for efficient passive Q switching of a diode-pumped 946 nm Nd:YAG laser

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InGaAs quantum wells and a Bragg mirror structure are grown on a GaAs substrate to simultaneously serve as a low-loss saturable absorber and an output coupler for highly efficient Q switching of a diode-pumped Nd:YAG laser operating at 946 nm. With an incident pump power of 9.2 W, the laser produces pulses of 38 ns duration with average pulse energy of as much as 20 μJ at a pulse repetition rate of 55 kHz. © 2007 Optical Society of America

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1. Introduction

Passively Q-switched all-solid-state lasers are of great interest because of their potential applications in remote sensing, ranging, micromachining, and nonlinear wavelength conversion. The Nd:YAG crystal has certainly been one of the preferred gain media for all-solid-state laser systems because of its excellent optical and mechanical properties [1–3]. The majority of the work on the Nd:YAG crystal was focused on the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition in the 1064 nm range. Nevertheless, the lasing wavelength near 946 nm in the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition has attracted much attention during the last decade [4–11], since it is of interest for second-harmonic generation into the blue region. Kellner *et al.* employed a Cr^{4+}:YAG crystal as a saturable absorber in a passively Q-switched 946 nm Nd:YAG laser to achieve as much as 1.6 W average output power with pulse width of 70–100 ns [6]. Recently, Zhang *et al.* demonstrated an average output power of 2.1 W with pulse width of 40.8 ns by using a Nd, Cr:YAG saturable absorber [7]. More recently, Wang *et al.* used a GaAs saturable absorber to obtain an average output power of 1.24 W with pulse width of 70 ns [8]. However, so far the overall Q-switching efficiencies (ratio of the Q-switched average output power to the cw output power at the same pump power) were in the range of 30%–50%. The low Q-switching efficiencies arise from the nonsaturable losses of the saturable absorbers. Since the gain of the Nd:YAG crystal at 946 nm is quite low, a small amount of nonsaturable losses may lead to a considerable reduction in the efficiency. In view of that, it is practical to develop a saturable absorber with low nonsaturable losses for the low gain Nd:YAG laser at 946 nm.

InGaAs/GaAs quantum wells (QWs) have been developed to be semiconductor saturable-absorber mirrors (SESAMs) for Nd-doped lasers in the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition [12]. However, the nonsaturable losses of such QWs were usually rather high in comparison with the gain of the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition in Nd-doped lasers. Nevertheless, the contemporary advancement of the growth methodology has successfully realized the InGaAs QWs with extremely low nonsaturable losses [13–17]. Even so, to the best of our knowledge, InGaAs QWs have not as yet been employed to be a SESAM in a Nd:YAG laser at 946 nm. In this work we report, for what is believed

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to be the first time, on utilizing InGaAs QWs as a saturable absorber in a diode-pumped passively Q-switched 946 nm Nd:YAG laser. With an incident pump power of 9.2 W, the compact laser cavity produces an average output power of 1.1 W at 946 nm with a repetition rate of 55 kHz and pulse width of 38 ns. The corresponding pulse energy and peak power are up to 20 μJ and 0.53 kW, respectively. The extremely low nonsaturable losses of the SESAM bring about the Q-switching efficiency greater than 90%.

2. InGaAs Quantum-Well Saturable Absorber and Experimental Setup

The present saturable absorber was fabricated to combine 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 [18]. The SESAMOC device was monolithically grown on an undoped 350 μm thick GaAs substrate by metal-organic chemical-vapor deposition (MOCVD) to comprise three strained $In_{0.15}Ga_{0.85}As$/GaAs 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 eleven AlAs/GaAs quarter-wavelength layers; designed for a reflectivity in the region of 97%–98% at 946 nm. The back side of the GaAs substrate was coated for antireflection at 946 nm ($R < 1\%$). Figure 1 shows the measured result for the low-intensity transmission spectrum of the SESAMOC. It can be seen that the low-intensity transmission was approximately 1.5% at 946 nm and 56% at 1064 nm. The experimental result for the room-temperature photoluminescence (PL) spectrum of the SESAM device is depicted in Fig. 2. The peak wavelength of the PL spectrum of the absorber is found to be in the vicinity of 946 nm and the full width at half maximum (FWHM) is approximately 20 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 $\mu J/cm^2$.

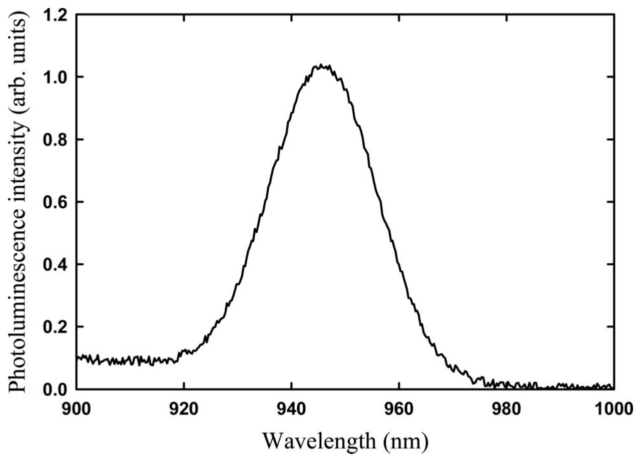

Fig. 2. Room-temperature PL spectrum of the InGaAs QW saturable absorber.

Figure 3 shows the experimental configuration of the passively Q-switched 946 nm Nd:YAG laser with InGaAs QWs as a SESAMOC. The active medium was 1.1 at. % Nd:YAG crystal with a length of 2.0 mm. Since a short crystal length was used to reduce the reabsorption losses, only approximately 52% of the pump light was absorbed in the gain medium. The entrance surface of the laser crystal was coated to be high reflection at 946 nm ($R > 99.8\%$) and high transmission 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 water-cooled copper block. The pump source was a 10 W 808 nm fiber-coupled laser diode with a core diameter of 600 μm and a numerical aperture of 0.16. A focusing lens with 5 mm focal length and 92% coupling efficiency was used to reimage the pump beam into the laser crystal. The pump spot radius was approximately 160 μm. The cavity length was approximately 15 mm. The spectral infor-

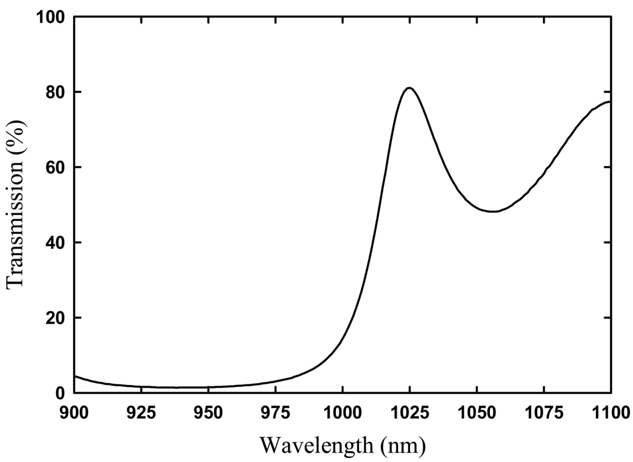

Fig. 1. Measured results for the low-intensity transmission spectrum.

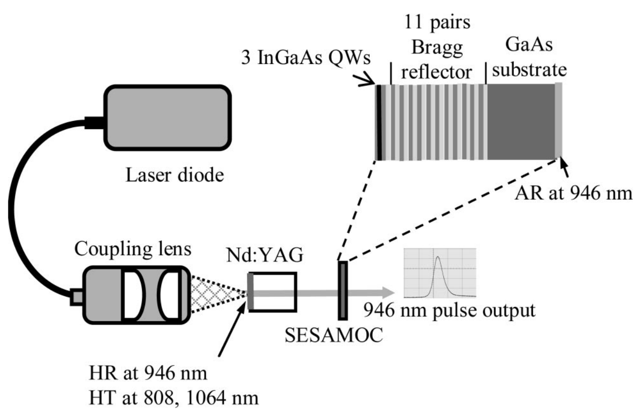

Fig. 3. Schematic of a diode-pumped passively Q-switched Nd:YAG laser at 946 nm HR, high reflection; HT, high transmission; and AR, antireflection.

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

3. Experimental Results

The optimum cw operation at 946 nm was first investigated to obtain the baseline for evaluating the passively Q-switched efficiency. For this investigation an output coupler with partial reflection at 946 nm was used instead of the above-mentioned SESAMOC. Based on thorough experiments the optimum reflectivity of the output coupler was found to be approximately 97%. The average output powers at 946 nm with respect to the incident pump power in cw and passively Q-switching operations are depicted in Fig. 4. The output power in the cw operation reached 1.21 W at an incident pump power of 9.2 W. In the passively Q-switching regime an average output power of 1.1 W was obtained at an incident pump power of 9.2 W. Experimental results indicate that the Q-switching efficiency (ratio of the Q-switched output power to the cw one at the maximum pump power) exceed 90%. The extremely high Q-switching efficiency signifies the nonsaturable losses of the present SESAMOC to be considerably low.

Figure 5 shows the pulse repetition rate and the pulse energy versus the incident pump power. It was found that the pulse repetition rate was linearly proportional to the pump power and reached approximately 55 kHz at an incident pump power of 9.2 W. Like typically passively Q-switched lasers, the pulse energy is almost unrelated to the pump power and its value is 20 μJ on average. On the whole, the pulse duration was approximately 38 ns. With the measured pulse energy and pulse width, the peak power can be found to be up to 0.53 kW. A typical oscilloscope trace of a train of output pulses and an expanded shape of a single pulse are shown in Fig. 6. Under the optimum alignment condition, the pulse-to-pulse amplitude fluctuation was less than ±5% for the pump power lower than 6 W and within ±15% at the maximum pump power of 9.2 W. The peak-to-peak instability was experimentally found to come from the switching of the polarization state. Although controlling the polarization state can improve the output stability, the lasing efficiency will be considerably reduced. In other words, the trade-off between the output stability and the lasing efficiency is a design issue.

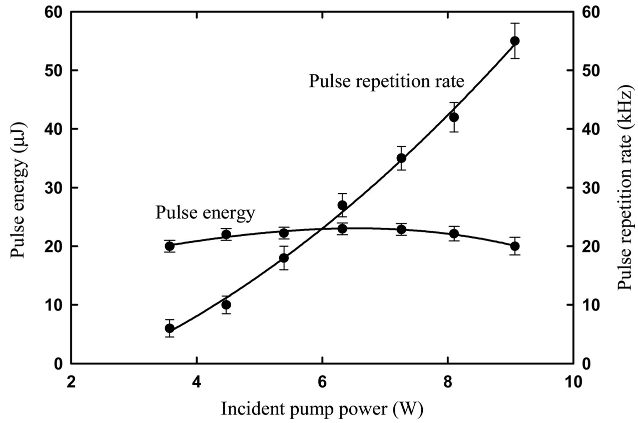

Fig. 5. Experimental results for pulse repetition rate and pulse energy versus incident pump power.

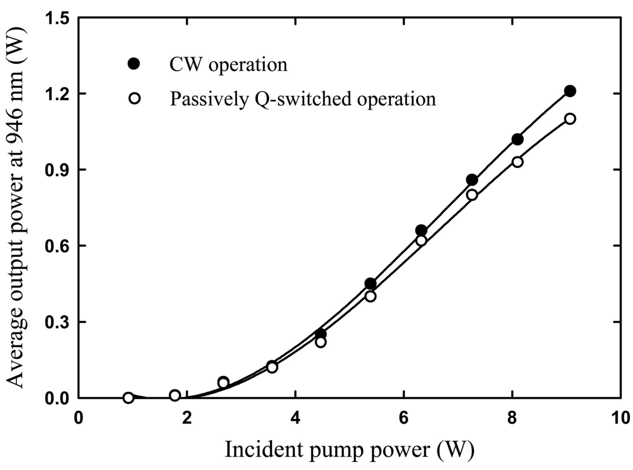

Fig. 4. Average output powers at 946 nm with respect to the incident pump power in CW and passively Q-switching operations.

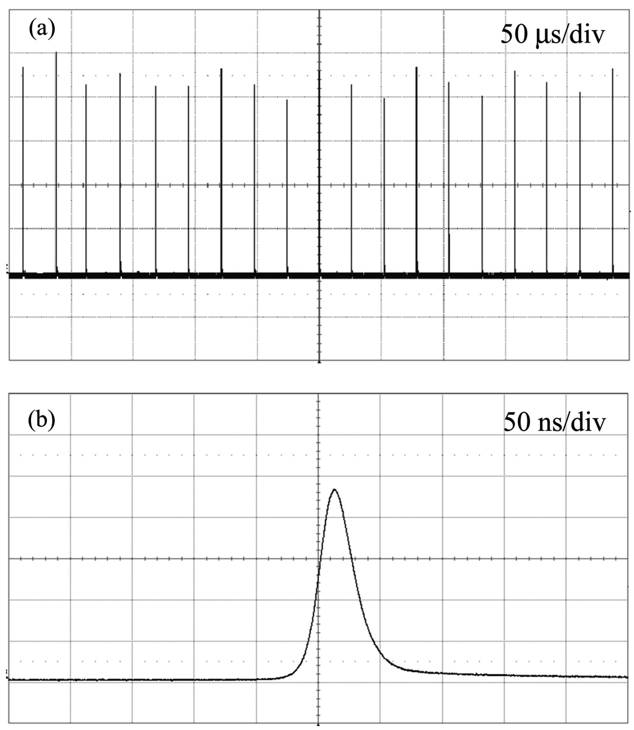

Fig. 6. (a) Typical oscilloscope trace of a train of output pulses and (b) expanded shape of a single pulse.

4. Conclusion

We have, for the first time to the best of our knowledge, demonstrated the use of InGaAs QWs to be low-loss semiconductor saturable-absorber output couplers for passive Q switching of a diode-pumped Nd:YAG laser operating at 946 nm. An average output power of 1.1 W was obtained at an incident pump power of 9.2 W. The maximum peak power was found to be up to 0.53 kW and the overall Q-switching efficiency was generally greater than 90%. The present result indicates the possibility of using InGaAs QW structures to generate the high-peak-power blue laser at 473 nm with intracavity second-harmonic generation.

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