InGaAs quantum-well saturable absorbers for a diode-pumped passively Q-switched Nd:YAG laser at 1123 nm

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A low-loss semiconductor saturable absorber based on InGaAs quantum wells was developed for highly efficient Q switching of a diode-pumped Nd:YAG laser operating at 1123 nm. With an incident pump power of 16 W, an average output power of 3.1 W with a Q-switched pulse width of 77 ns at a pulse repetition rate of 100 kHz was obtained. © 2007 Optical Society of America

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1. Introduction

Nd:YAG crystals that have excellent optical and mechanical properties have been identified to be one of the promising gain media in diode-pumped solid-state lasers.[1–3] Most of the research involving the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition of Nd:YAG crystals were focused on the wavelength of 1064 nm. However, there are many Stark components in the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition of the Nd:YAG crystal, such as 1112, 1117, and 1123 nm.[1] Even though the fluorescent intensity at 1123 nm is in excess of ten times smaller than that at 1064 nm, the diode-end-pumped configuration has been successfully used to achieve highly efficient Nd:YAG 1123 nm lasers.[4–8] The 1123 nm laser has been demonstrated to be a useful pump source for a thulium upconversion fiber laser with blue light emission.[4,9] Recently, a diode-pumped passively Q-switched Nd:YAG 1123 nm laser has been achieved by the use of a Cr^{4+}:YAG crystal with a low modulation depth as a saturable absorber.[7] Note that the modulation depth is defined as the maximum change of absorption (or reflectivity), which can be induced by incident light with a given wavelength. Nevertheless, the nonsaturable losses of the Cr^{4+}:YAG crystal are relatively high in comparison with the gain of the Nd:YAG crystal at 1123 nm. As a consequence, the Cr^{4+}:YAG crystal brings about a considerably low Q-switching efficiency (ratio of the Q-switched average output power to the cw output power at the same pump power) in the Nd:YAG 1123 nm laser. Therefore it is of practical value to develop the saturable absorbers with low modulation depths ($<5\%$) as well as low nonsaturable losses for the low-gain Nd:YAG 1123 nm laser.

InGaAs/GaAs quantum wells (QWs) have often been used as semiconductor saturable-absorber mirrors (SESAMs) in Nd-doped lasers at 1.06 μm.[10] Even so, such highly strained QWs were previously difficult to use as saturable absorbers for the wavelengths beyond 1.1 μm because of their high nonsaturable losses.[11] Recent progress in the growth methodology has made it possible to realize InGaAs QWs with emission wavelengths up to and somewhat beyond 1.2 μm.[12–14] However, to our knowledge, there has been no work using InGaAs QWs to be SESAMs in Nd:YAG lasers at 1123 nm. Here, for what is believed to be the first time, a diode-pumped passively Q-switched 1123 nm Nd:YAG laser with InGaAs QWs as a saturable absorber is reported. With an incident pump power of 16 W, the compact laser cavity produces an average output power of 3.1 W at 1123 nm with a repetition rate of 100 kHz and a pulse width of 77 ns. The extremely low nonsaturable losses of the SESAM lead to the Q-switching efficiency to be up to 94%.

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2. Device Fabrication and Experimental Setup

The SESAM structure was monolithically grown on an undoped GaAs substrate by metal-organic chemical-vapor deposition (MOCVD) to simultaneously serve as a saturable absorber and an output coupler in the passively Q-switched laser at 1123 nm. Note that the concept of combining the SESAM with an output coupler has been realized in passively Q-switched lasers.[15] The Bragg mirror structure consists of 12 AlAs/GaAs quarter-wavelength layers, designed for a reflectivity of 96% at 1123 nm. The saturable absorber region was grown to comprise two 8 nm thick $ln_{0.34}Ga_{0.66}As$ QWs separated by a 10 nm thick GaAs layer. Figure 1 shows the measured results for the low-intensity reflectivity and room-temperature photoluminescence (PL) spectrum of the InGaAs SESAM. It can be seen that the peak wavelength of the PL spectrum is in the vicinity of 1123 nm and the FWHM is approximately 40 nm. Furthermore, the dip in the reflectivity correlates with the maximum in the PL spectrum. The z-scan technique was used to find that the present SESAM device has a modulation depth of

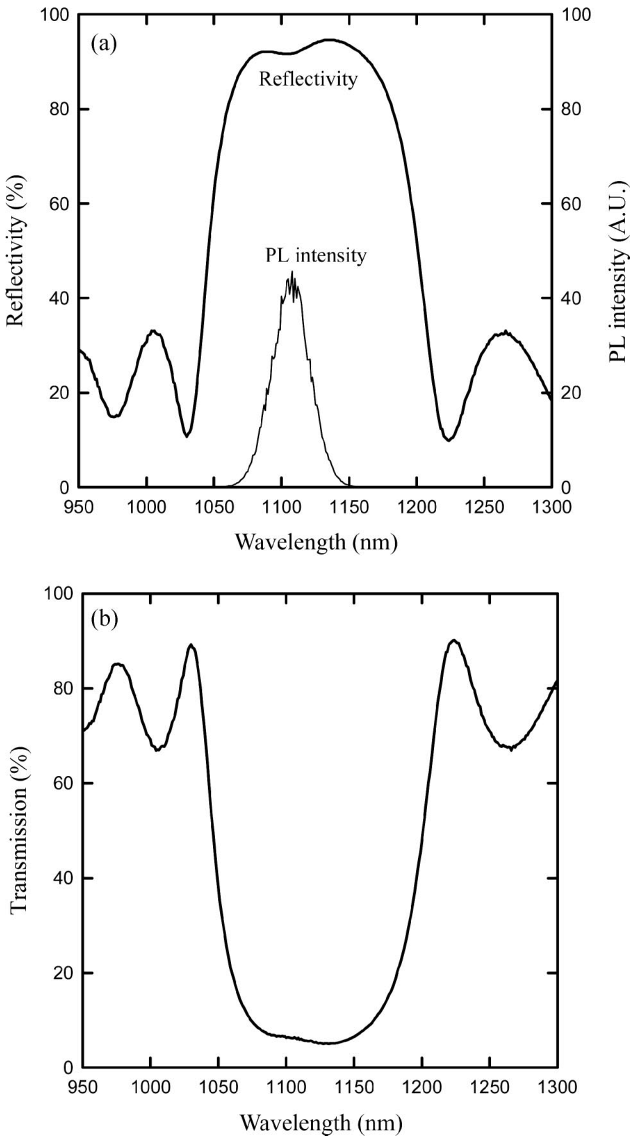

Fig. 1. (a) Measured results for the low-intensity reflectivity and room-temperature PL spectrum of the InGaAs QWS SESAM. (b) Measured results for the low-intensity transmission spectrum.

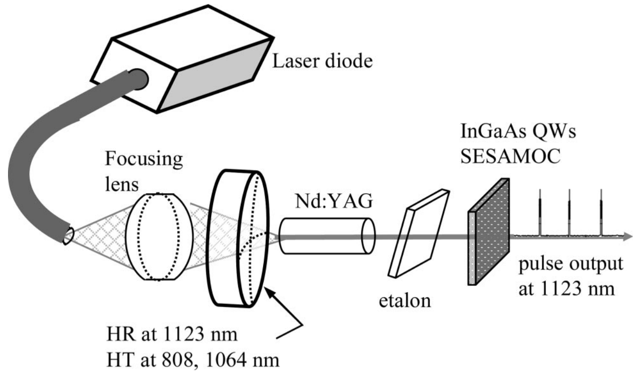

Fig. 2. Schematic of a diode-pumped passively Q-switched Nd:YAG laser at 1123 nm. HR, high reflection; HT, high transmission.

2.8%, nonsaturable losses of 0.4%, and a saturation fluence of 30 $\mu J\ cm^{-2}$.

Figure 2 shows the experimental configuration for the passively Q-switched 1123 nm Nd:YAG laser with InGaAs QWs used as a saturable absorber and a semiconductor saturable-absorber mirror output coupler (SESAMOC). The active medium was a 1.0 at. % Nd:YAG crystal with a length of 10 mm. Both sides of the laser crystal were coated for antireflection at 1123 nm ($R < 0.2\%$). The laser crystal was wrapped with indium foil and mounted on a water-cooled copper block. The pump source was a 20 W 808 nm fiber-coupled laser diode with a core diameter of 800 μm and a numerical aperture of 0.16. A focusing lens with a 12.5 mm focal length and a 90% coupling efficiency was used to reimage the pump beam into the laser crystal. The pump spot radius was approximately 250 μm. The input mirror was a 200 mm radius-of-curvature concave mirror with an antireflection coating at the pump wavelength of 808 nm on the entrance face ($R < 0.2\%$), a high-reflection coating at 1123 nm ($R > 99.8\%$), a high-transmission coating at 808 nm ($T > 90\%$), and 1064 nm ($T > 70\%$) on the other surface. The cavity length was approximately 35 mm. A 0.2 mm thick glass without a coating was used as an etalon to suppress the lasing channels at 1112 and 1116 nm. Without the etalon, simultaneous emission among three wavelengths of 1112, 1116, and 1123 nm was intermittently found at the pump power higher than 12 W. The spectral information of the laser was monitored by an optical spectrum analyzer (Advantest Q8381A). The spectrum analyzer employing a diffraction lattice monochromator can be used for the 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 Gs/s, 1 GHz bandwidth) with a fast p-i-n photodiode.

3. Experimental Results

The cw performance of the Nd:YAG laser at 1123 nm was studied first. For this investigation, an output coupler with partial reflection at 1123 nm was used

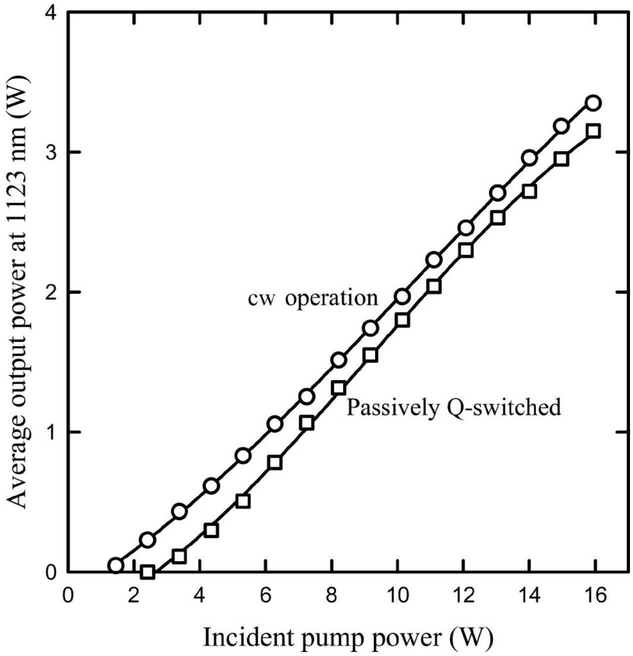

Fig. 3. Average output powers at 1123 nm with respect to the incident pump power in cw and passively Q-switching operations.

instead of the above-mentioned InGaAs SESAM. The optimum reflectivity of the output coupler was found to be approximately 96%. The optimum cw performance at 1123 nm provides the baseline for evaluating the passively Q-switched efficiency. Figure 3 shows the average output powers at 1123 nm with respect to the incident pump power in cw and passively Q-switching operations. In the cw regime, the laser had a slope efficiency of 22.8%; the output power reached 3.3 W at an incident pump power of 16 W. In

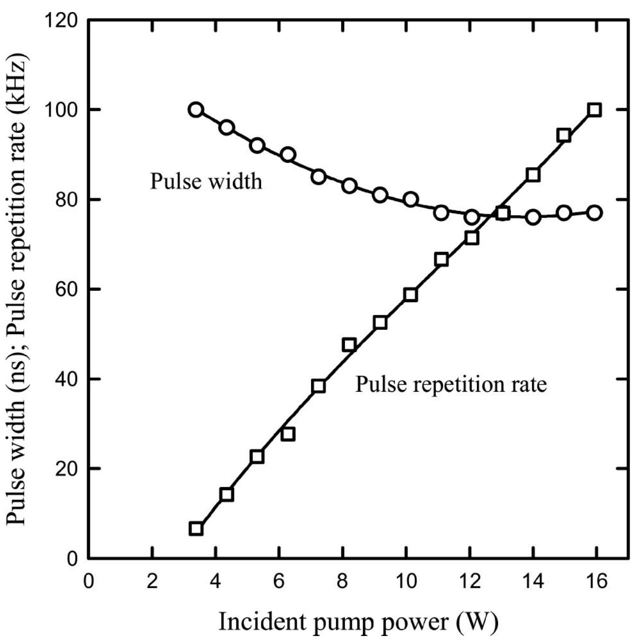

Fig. 4. Experimental results for the pulse repetition rate and the pulse width versus the incident pump power.

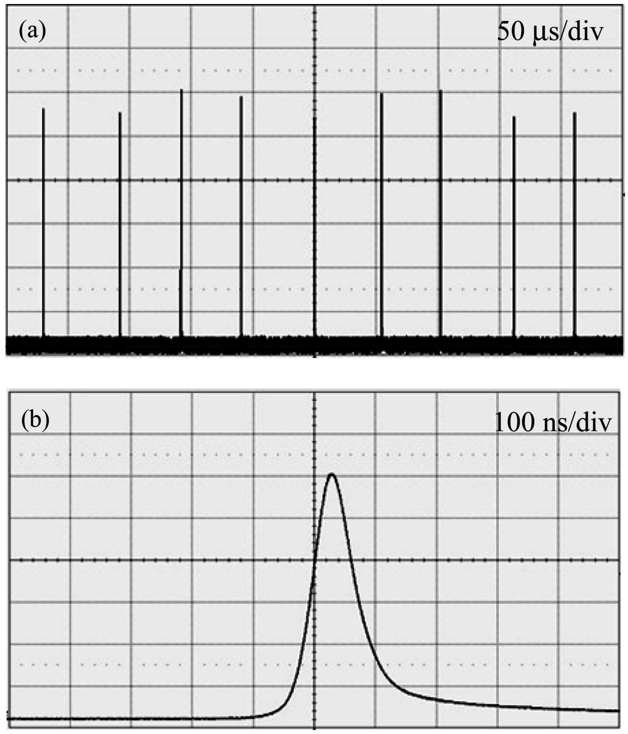

Fig. 5. (a) Typical oscilloscope trace of a train of output pulses and (b) expanded shape of a single pulse.

the passively Q-switching regime, an average output power of 3.1 W was obtained at an incident pump power of 16 W. The Q-switching efficiency (ratio of the Q-switched output power to the cw output power at the maximum pump power) was found to be up to 94%. The nearly perfect Q-switching efficiency indicates that the nonsaturable losses of the present InGaAs QWs' SESAM is significantly low.

Figure 4 shows the pulse repetition rate and the pulse width versus the incident pump power. The pulse repetition rate initially increases with pump power and is up to approximately 100 kHz at an incident pump power of 16 W. On the other hand, the pulse width decreases from 100 ns at the threshold to 77 ns at the maximum pump power. As a consequence, the peak power was found to be higher than 400 W. A typical oscilloscope trace of a train of output pulses and an expanded shape of a single pulse are shown in Fig. 5. Under the optimum alignment condition, the pulse-to-pulse amplitude fluctuation was found to be within $\pm 10\%$.

4. Conclusion

InGaAs QWs have been used to be a low-loss semiconductor saturable-absorber output coupler for passive Q switching of a diode-pumped Nd:YAG laser operating at 1123 nm. An average output power of 3.1 W with a Q-switching efficiency of 94% was obtained at an incident pump power of 16 W. Stable Q-switched pulses of 77 ns duration with a repetition rate of 100 kHz were generated. The present result indicates the possibility of using an InGaAs QW structure to mode lock a Nd:YAG laser at 1123 nm. Furthermore, the low-loss SESAM may be employed to generate the high-peak-power yellow laser at 561 nm with intracavity second-harmonic generation.

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