InAs/GaAs quantum-dot saturable absorbers for diode-pumped passively *Q*-switched Nd-doped 1.3-μm lasers

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A low-loss semiconductor saturable absorber based on InAs/GaAs quantum dots was developed for Q switching of a diode-pumped Nd-doped laser operating at 1.3 μm. With an InAs/GaAs quantum-dot saturable absorber, a diode-pumped Nd:YVO_4 laser at 1342 nm was achieved. With an incident pump power of 2.2 W, an average output power of 360 mW with a Q-switched pulse width of 90 ns at a pulse repetition rate of 770 kHz was obtained. © 2005 Optical Society of America

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Saturable absorbers for short-pulse generation in diode-pumped lasers at 1.3 μm have attracted considerable interest because of their important practical applications such as fiber sensing and intracavity Raman conversion to the 1.5-μm eye-safe spectral region. The most commonly known saturable absorbers for 1.3-μm Nd-doped lasers include V^{3+}:YAG,[1] Co^{2+}:$MgAl_2O_4$,[2] PbS-doped phosphate glasses,[3] and semiconductor saturable-absorber mirrors (SESAMs).[4] Previously the two main types of material for SESAMs at the 1.3-μm wavelength were InGaAs/GaAs and InGaAsP/InP quantum wells.[4,5] An InGaAs-based SESAM for a 1.3-μm laser usually leads to significant residual nonsaturable losses because the required indium concentration is beyond the critical strain-thickness limit. Although an InGaAsP-based SESAM could offer an absorber layer with a smaller lattice mismatch, it has inherent disadvantages such as poor thermal properties and scarcity of appropriate mirror materials.

To reach a wavelength near 1.3 μm for applications of short-distance fiber-optic communication, two main approaches based on the GaAs material system were recently proposed. One technique is the use of GaInNAs quantum wells with a low nitrogen concentration in an active region[6] and the other is the use of InAs/GaAs quantum-dot multilayer structures.[7] Recently GaInNAs-based SESAMs were used successfully to mode lock Nd-doped lasers at 1.3 μm.[8,9] However, to our knowledge, there has been no study of using InAs/GaAs quantum dots as saturable absorbers in Nd-doped lasers at 1.3 μm. Here, for what is believed to be the first time, a diode-pumped passively Q-switched 1.34-mm Nd:YVO_4 laser with InAs/GaAs quantum dots as a saturable absorber is reported. With an incident pump power of 2.2 W, the compact laser cavity produces an average output power of 360 mW at 1342 nm with a repetition rate of 770 kHz and a pulse width of 90 ns.

This InAs/GaAs quantum-dot structure was monolithically grown upon an undoped GaAs substrate by metalorganic chemical-vapor deposition to serve simultaneously as a SESAM and an output coupler in the passively Q-switched 1.34-μm laser. The Bragg mirror structure consists of 15 AlAs/GaAs quarter-wavelength layers, designed for a reflectivity of 96%. The saturable-absorber region was grown at 500 °C to comprise three very thin (3–5-nm) InAs quantum-dot layers separated by GaAs half-wavelength layers.

Figure 1 shows the measured results for the low-intensity reflectivity and room-temperature photoluminescence (PL) spectrum of the InAs SESAM. The PL peak wavelength was found to be in the vicinity of 1340 nm with a FWHM of 45 nm. It can be seen that the dip in reflectivity is correlated to the maximum in the PL spectrum. One of the advantages of this SESAM compared with the earlier one based on GaInNAs quantum wells is that here no annealing is required. It is well known that postgrowth annealing in the GaInNAs SESAM is essential to reduce nonradiative defects and to tune the PL wavelength close to the lasing wavelength.[10,11] Experimental results revealed that the present SESAM device has a modulation depth of 6.7%, nonsaturable losses of 1.8%, and a saturation fluence of 25 $\mu J\,cm^{-2}$.

Figure 2 shows the experimental configuration for the passively Q-switched 1.34-μm Nd:YVO_4 laser with InAs/GaAs quantum dots used as a saturable

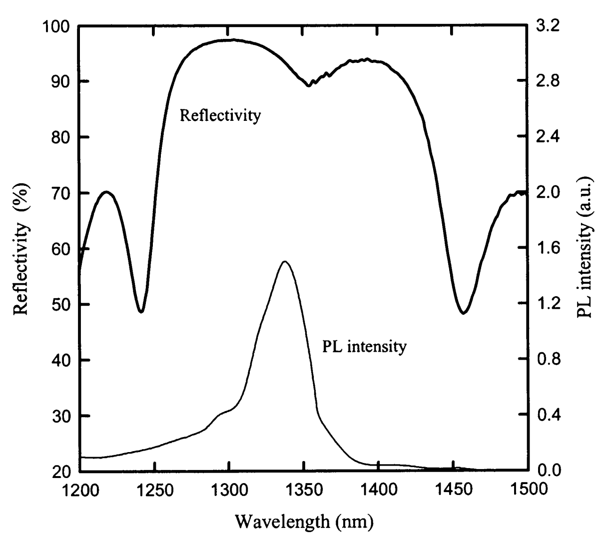

Fig. 1. Measured results for the low-intensity reflectivity and room-temperature PL spectrum of the InAs/GaAs quantum-dot SESAM.

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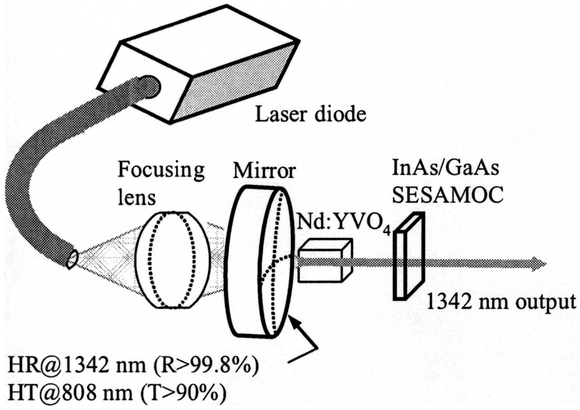

Fig. 2. Schematic of a diode-pumped passively Q-switched $Nd:YVO_4$ laser at 1342 nm: HR, high reflection; HT, high transmission.

absorber and an output coupler (SESAMOC). The active medium was a 2.0-at.% Nd^{3+}, 1-mm-long $Nd:YVO_4$ crystal. Both sides of the laser crystal were coated for antireflection at 1.34 μm ($R < 0.2\%$). The pump source was a 2.5-W 808-nm fiber-coupled laser diode with a core diameter of 200 μm and a numerical aperture of 0.16. A focusing lens with 16.5-mm focal length and 90% coupling efficiency was used to reimage the pump beam into the laser crystal. The pump spot radius was ~100 μm. The input mirror, M1, was a 500-mm radius-of-curvature concave mirror with antireflection coating at the diode wavelength on the entrance face ($R < 0.2\%$), high-reflection coating at the lasing wavelength ($R > 99.8\%$), and high-transmission coating at the diode wavelength on the other surface ($T > 90\%$). Note that the laser crystal was placed near the input mirror for spatial overlap of the transverse mode structure and the radial pump power distribution. The overall $Nd:YVO_4$ laser cavity length was approximately 20 mm. The spectral information of the laser was monitored by an optical spectrum analyzer (Advantest Q8381A). A spectrum analyzer that employs a diffraction lattice monochromator can be used for high-speed measurement of pulsed light with a resolution of 0.1 nm. The pulse's temporal behavior was recorded by a LeCroy digital oscilloscope (Wavepro 7100; 10 Gsamples/s, 1-GHz bandwidth) with a fast p–i–n photodiode.

The cw performance of the $Nd:YVO_4$ laser at 1342 nm was studied first. For this investigation an output coupler with partial reflection at 1342 nm was used instead of the InAs quantum-dots SESAM mentioned above. The optimum reflectivity of the output coupler was approximately 94%. The optimum cw performance at 1342 nm provides the baseline for evaluating the passively Q-switched efficiency. Figure 3 shows the average output powers at 1342 nm with respect to the incident pump power in cw and passive Q-switching operation. In the cw regime the laser had a slope efficiency of 40%; the output power reached 640 mW at an incident pump power of 2.2 W. In the passive Q-switching regime an average output power of 360 mW was obtained at an incident pump power of 2.2 W. The Q-switching efficiency (ratio of the Q-switched output power to the cw power at the maximum pump power) was estimated to be 56%. This Q-switching efficiency is considerably higher than those of 1.3-μm lasers with other known absorbers.[1–4,12] This superior performance indicates that the nonsaturable losses of the present InAs quantum-dot SESAM are relatively 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 almost saturated at approximately 770 kHz beyond 1.6 W of incident pump power. The pulse width decreases from 360 ns at threshold to 90 ns at 2.2 W of incident pump power, however. As a consequence, the peak power was found to be higher than 5 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 less than ±10%.

InAs/GaAs quantum dots were used as a low-loss semiconductor saturable-absorber output coupler for

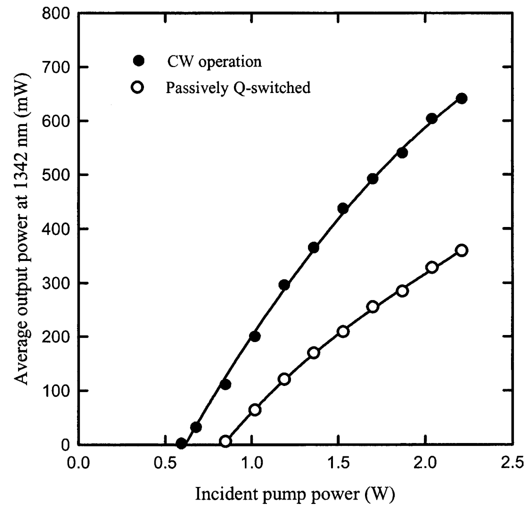

Fig. 3. Average output powers at 1342 nm with respect to the incident pump power in cw and passive Q-switching operation.

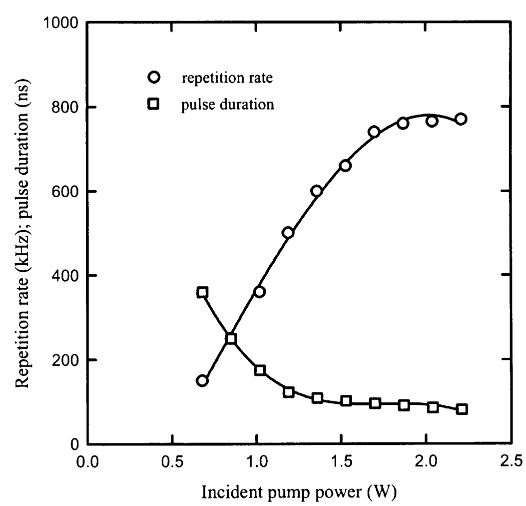

Fig. 4. Experimental results for pulse repetition rate and pulse width versus incident pump power.

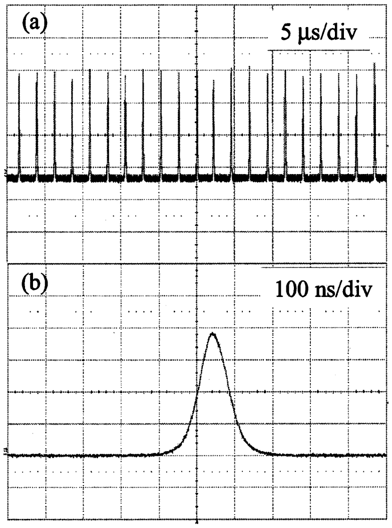

Fig. 5. (a) Typical oscilloscope trace of a train of output pulses and (b) expanded shape of a single pulse.

Q switching of a diode-pumped Nd:YVO_4 laser operating at 1342 nm. An average output power of 360 mW with a Q-switching efficiency of 56% was obtained at an incident pump power of 2.2 W. Stable Q-switched pulses of 90-ns duration with a repetition rate of 770 kHz were generated. The present result indicates the possibility of using an InAs/GaAs quantum-dot structure to mode lock a Nd-doped laser at 1.3 μm. Attempts to use InAs-based SESAM to mode lock a 1.3-μm Nd-doped laser are under way.

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