Diode-end-pumped passively mode-locked high-power $Nd:YVO_4$ laser with a relaxed saturable Bragg reflector

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We demonstrate a high-power passively mode-locked $Nd:YVO_4$ laser that uses a saturable Bragg reflector (SBR) with strain relaxation. 23.5 W of average power with ~21.5-ps cw mode-locked pulse trains was generated at a 50-W pump power. Experimental results show that appropriate strain relaxation in the SBR makes the mode-locking operation less sensitive to temperature variation.

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Substantial developments have been made in passively mode-locked solid-state lasers through the application of semiconductor-based saturable absorbers. Demonstrated semiconductor structures include antiresonant Fabry–Perot saturable absorbers[1] and semiconductor saturable absorber mirrors.[2] Recently, two groups adopted side-pumping schemes to obtain more than 20 W of average power with an ~20-ps pulse duration.[3,4] One group used multiple Nd:YAG laser heads with antiresonant Fabry–Perot saturable absorbers to avoid thermally induced fracture of the laser crystal. The other group employed a strain-compensated saturable Bragg reflector (SBR) to increase the damage threshold of an InGaAs quantum well (QW). The optical–optical conversion efficiencies in both results were less than 25% because of poor overlap efficiency in the side-pumping scheme. In this Letter we present an efficient diode-end-pumped passively mode-locked laser with average power of more than 23 W, with a relaxed single-quantum-well (SQW) SBR.

Like the semiconductor saturable absorber mirror, the SQW SBR is fabricated by single-stage growth and requires no postpocessing. For the SBR device the ratio of nonsaturable and saturable losses is typically less than 0.2. Achieving saturable absorption at 1.06-μm usually requires that the indium-atom fractions in the $In_xGa_{1-x}As$ SQW be near $x \approx 0.30$. The critical thickness of the $In_{0.3}Ga_{0.7}As$ SQW without significant strain relaxation is ~8 nm.[5] In this work we used molecular beam epitaxy to grow a 7-nm $In_xGa_{1-x}As$ SQW at 520 °C, with the intended nominal indium-atom fractions of 0.30 embedded within the topmost layer of a 35-pair GaAs/AlAs Bragg stack. The reflectivity of the Bragg mirror was measured without a QW. The value was found to be higher than 99.5%. The surface of the finished SBR did not reveal any visible defects or dislocations. Photoluminescence (PL) was obtained at room temperature, allowing us to study the optical property of the finished device. As shown in Fig. 1, the spectrum is very broad and the peak position is roughly centered on 1.1 μm. The indium-atom fractions that fit the experimental PL peak turn out to be 0.35. The discrepancy in the indium concentrations could have arisen from the molecular beam epitaxy system calibration, which is accurate only for low concentrations. The FWHM of the PL peak was found to be ~60 meV, which is considerably larger than that obtained in an InGaAs/GaAs SQW without strain relaxation (4–9 meV).[6] The broadening of the PL spectrum indicates that the present SBR is in a relaxed state and not in a highly strained state. X-ray diffraction was also employed to investigate the degree of strain relaxation. However, the result did not reveal any misfitted dislocations. Therefore we

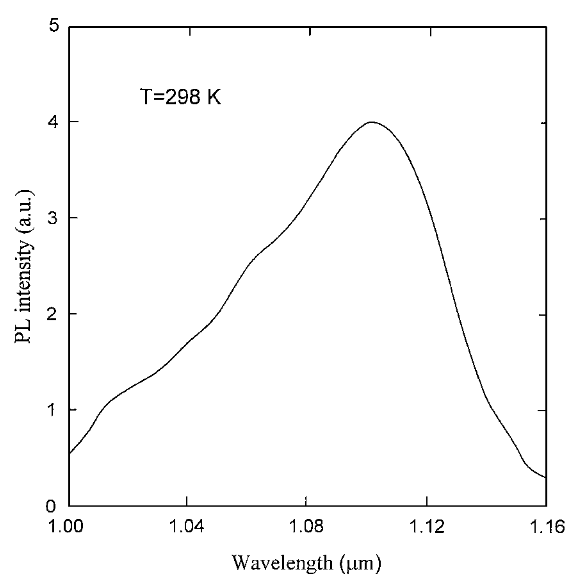

Fig. 1. PL at 25 °C for the finished SBR.

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conclude that the present SBR is partially relaxed. It is a well-known fact that strain relaxation can happen during low-temperature molecular beam epitaxy growth. In addition, the thickness of the present QW exceeded the critical thickness because the actual indium-atom fractions are somewhat greater than the intended nominal concentrations. Even so, strain relaxation was observed in an earlier device[3] in which a 25-nm-thick absorber was used, although with a lower indium concentration. Furthermore, recent studies of ultrafast pulse generation at the 1.5-μm wavelength[7] showed that a SBR with high strain relaxation still had excellent nonlinear optical absorption, with a response time of the order of a few picoseconds. The present SBR device has a modulation depth of 1.0%, nonsaturable losses of 0.2%, a saturation fluence of 40 μJ cm^{-2}, and a recovery time of ~20 ps. In the experiments described here, we found that the broad absorption spectrum of the relaxed SBR results in a mode-locking operation that is less sensitive to temperature variation.

Figure 2 shows the basic outline of the passively mode-locked laser setup with the finished SBR. The pump power comes from two 30-W fiber-coupled diode-laser arrays (Coherent FAP-81-30C-800-B), with the output wavelengths of the lasers at 25 °C ranging from 807 to 810 nm. The fibers were drawn into round bundles of 0.8-mm diameter and with a numerical aperture of 0.2. A focusing lens with a 35-mm focal length and 85% coupling efficiency was used to reimage the pump beam into the laser crystal. The waist diameter of the pump beam was ~600 μm. The a-cut 0.3-at.% 9-mm-length Nd:YVO$_4$ crystal was 0.5° wedged and coated for antireflection at 1064 nm ($R < 0.2\%$) on both end surfaces. We used a Nd:YVO$_4$ crystal with a low doping concentration to avoid thermally induced fracture.[8,9] The laser crystal was wrapped with indium foil and mounted in a water-cooled copper block. The water temperature was maintained at 20 °C. The cavity was designed to easily allow mode matching with the pump beam and to provide the proper spot size in the saturable absorber. The mode diameter in the absorber was approximately 80–100 μm. The resonator consisted of three highly reflective (at 1064 nm) mirrors, M1, M2, and M4; one partially reflective (PR) mirror, M3 ($R = 80\%$ at 1064 nm); and a SBR device. Mirrors M1 and M2 are flat mirrors; the radii of curvature for M3 and M4 are 50 and 10 cm, respectively. M3 and M4 were separated by 60 cm. M3 had a reflectivity of 80% at 1064 nm, giving a total output coupling of ~36%. The total cavity length was ~1 m. The SBR was simply mounted on a copper heat sink, but no active cooling was applied. Note that we could readily achieve a single-output beam by replacing M1 with an appropriate partially transmitting mirror and using a focusing lens with sufficient working distance to add a mirror between M1 and the focusing lens for reflection of the output beam. However, a dual-output beam cavity was used because of limited mirror availability.

With the cavity shown in Fig. 2, the laser outputs follow a general behavior that is a function of the pump power. Near oscillation threshold the output is effectively cw; slightly increasing the pump power initiates a Q-switched mode-locked (QML) state. As shown in Fig. 3(a), there are many sidebands along with the order of the relaxation oscillation frequency to the carrier frequency. When the pump power is increased further, the QML state is transformed into a cw mode-locked (CML) state. Figure 3(b) shows the power spectrum for the CML state at 20-W output power. It can be seen that the relaxation oscillations are suppressed to less than −50 dBc in a resolution bandwidth of 1 kHz. Figure 4 illustrates the average output power as a function of the incident pump power. The repetition rate is ~147 MHz (see the inset of Fig. 4). The pump threshold for lasing is less than 3 W. The low pump threshold indicates that the present SBR did not induce significant nonsaturable losses, even though it is in the relaxed state. The transition point from the QML to the CML state is at ~4-W output power,

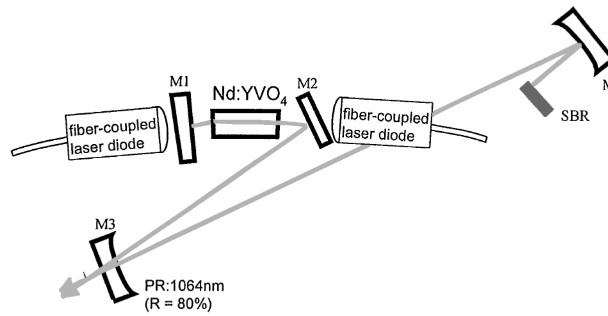

Fig. 2. Configuration of a passively mode-locked Nd:YVO$_4$ laser with a SBR.

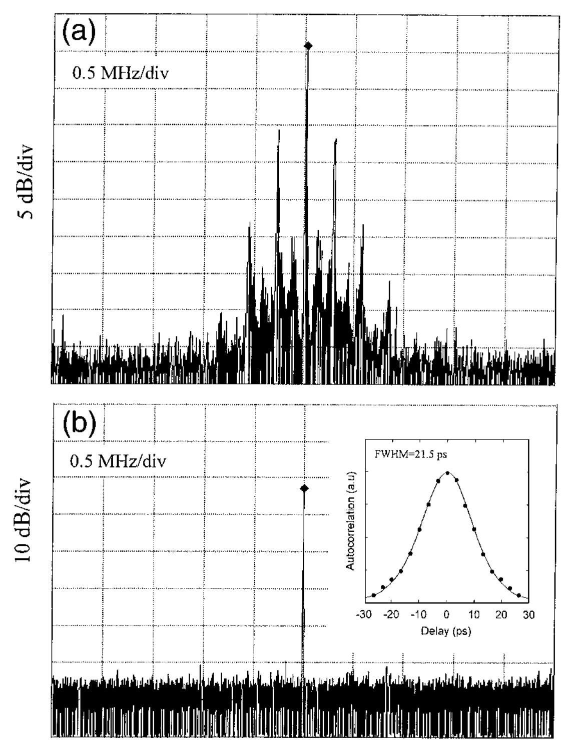

Fig. 3. Power spectrum analyzer signal for the (a) QML and (b) CML states. Autocorrelation of 21.5-ps pulses at 20-W output power is shown in the inset of (b).

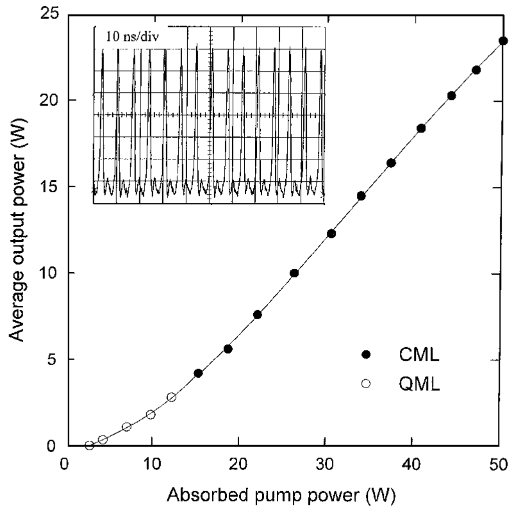

Fig. 4. Dependence of the average output power on the absorbed pump power. Self-starting cw mode locking is obtained for more than 4-W output power.

corresponding to 14-W pump power. For a maximum power of 50 W, 23.5-W average output power is obtained. The overall optical–optical efficiency reaches 47%. To our knowledge, this is the highest conversion efficiency ever reported for passively mode-locked lasers with output power greater than 20 W. The pulse duration was found to be a function of pump power from 27 ps at 10-W output, to 24 ps at 15 W, to 21.5 ps at the output power of 20 W. The autocorrelation of the 21.5-ps pulses is shown in the inset of Fig. 3(b). The pulse duration obtained here was nearly the same as the performance obtained by use of an antiresonant Fabry–Perot saturable absorber[3] or a strained SBR.[4] This result means that the present SBR showed an excellent nonlinear optical absorption on ultrafast pulse generation. So far, the fast recovery of the relaxed SBR nonlinear response was explained by the dislocations, which act as nonradiative recombination centers.[7]

No damage to the relaxed SBR was observed over several hours of operation, and the laser performance was reproducible on a day-to-day basis. Burns *et al.*[4] reported that the strained SBR could be sustained only for ~10 s at a peak intensity of 0.53 GW/cm^2. The maximum peak intensity in the present SBR was ~0.25 GW/cm^2. To investigate the homogeneity of the present absorber we swept the beam spot on a different region of the SBR. It was also found that the mode-locking operation is insensitive to the position of the SBR. The defect and dislocation induced by the strain relaxation in the present SBR do not seem to cause the so-called sweep spot problem.

To study the sensitivity of the SBR to temperature variation, it was mounted on a thermoelectric device capable of varying the temperature of the device within the range 20–60 °C. The output power corresponding to the transition from the QML state to the stable CML state decreased from 4.0 to 3.3 W as the SBR temperature was increased from 20 to 60 °C. However, the output power corresponding to the transition between cw operation to the QML state increased from 0.8 to 1.5 W as the SBR temperature was increased from 20 to 60 °C. The temperature-tuning characteristics indicate that the modulation depth of the SBR decreases as the temperature increases. This result is consisent with the PL measurement shown in Fig. 1. As the temperature of the SBR increases, the PL spectrum shifts to longer wavelengths (at ~0.3 nm/°C); thus the laser experiences smaller saturable absorption. Owing to the broadened PL spectrum, the transition power is rather insensitive to temperature. The advantage of a relaxed SBR in passively mode-locked high-power lasers has been demonstrated, but it remains to study further the amount of appropriate relaxation for applications.

We have demonstrated the use of relaxed SBR to obtain a high-power diode-end-pumped mode-locked Nd:YVO_4 laser. 23.5 W of average power with 147-MHz cw mode-locked pulse trains with pulse duration of ~21.5 ps was generated at a 50-W pump power. Experimental results show that the insertion loss of the relaxed SBR is fairly small, and its uniformity is also sufficient for mode-locking operation. We believe that the high reliability and stability of this laser make it of considerable interest for laser applications.

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