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

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ABSTRACT

We present an efficient diode-end-pumped passively mode-locked $Nd:YVO_4$ laser with a relaxed single-quantum-well saturable Bragg reflector (SBR), which average output power is more than 23 W and pulse duration 21.5 ps cw mode-locking is generated corresponding to 50 W pumping power. The overall optical-optical efficiency reaches 47% and to our knowledge, this is the highest conversion efficiency ever reported for passively mode-locked laser with average output power over 20 W. In this experiment, the broad absorption spectrum of the relaxed SBR leads a mode-locking operation to less sensitive to temperature variation. The output power corresponding to the transition from cw operation to QML and QML to CWML were also investigated. We believe the high reliability and stability of this mode-locked laser with a relaxed SBR will be interesting in laser application.
Keywords: diode-pumped solid state laser, mode-locked laser, saturable Bragg reflector, $Nd:YVO_4$,

1. INTRODUCTION

Many researches have been made in passively mode-locked solid-state lasers through the application of semiconductor-base saturable absorbers. The demonstrated saturable absorber structures include anti-resonant Fabry-Perot saturable absorber [1] and semiconductor saturable absorber mirrors [2]. Recently, the average output power over 20-W was reported within pulse duration 20-ps by side-pumping schemes [3]. One group used a strain compensated saturable Bragg reflector (SBR) to increase the damage threshold of InGaAs quantum well. The optical to optical conversion efficiency was less than 25 % owing to the poor overlap efficiency in this side-pumping scheme. Therefore we present an efficient diode-end-pumped passively mode-locked $Nd:YVO_4$ laser with an average output power 23W using a relaxed single quantum well saturable absorber.

2. EXPERIMENTAL SCHEME AND RESULTS

For the SBR device, the ratio of nonsaturable loss to saturable loss is typically less than 0.2. In order to achieve the absorption of 1.064-μm for SBR, the indium atom fraction of $In_xGa_{1-x}As$ for SBR was near 0.3 and the critical thickness of $In_{0.3}Ga_{0.7}As$ (SQW) without significant relation was about 8 nm [4]. In our work, we use the molecular beam epitaxy to grow a 7-nm $In_xGa_{1-x}As$ SQW at 520 °C within the intended indium atom fraction to 0.3 embedded at the topmost layer of a 35 pairs of GaAs/AlAs Bragg stack. The Bragg mirror reflectivity value was measured higher than 99.5% without QW. The surface of the SBR device did not reveal any visible defects or dislocations. The photoluminescence (PL) at room temperature was also applied to measure the property of the SBR. From the PL spectrum indicates that the spectrum was very broad and the peak was roughly centered on 1.1μm as shown in Fig 1. The indium fraction fitting the experimental PL spectrum turns out to be 0.35. The discrepancy of indium fractions could be owing to the molecular beam epitaxy system calibration, which is accurate only for low contents. The full width at half maximum (FHWM) of the PL peak was found about 60 meV, which is considerably larger than that obtained in an InGaAs/GaAs SQW without strain relaxation (4-9 meV) [5]. The broadening PL spectrum shows that the 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 and the results didn't reveal any misfit dislocation. Therefore we conclude the present SBR is partially relaxed. Recently studies of ultrafast pulse generation at the 1.5 μm showed that a SBR with high strain relaxation still had excellent nonlinear optical absorption [6]. 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 the recovery time of 20 ps. In this experiment described here, we found the broad absorption spectrum of the relaxed SBR results in a mode-locked operation that is less sensitive to temperature variation.

Fig 2 shows the scheme of the passively mode-locked with SBR laser. The YVO_4 crystal was pumped by the 30 W fiber-coupled diode-laser array with the output wavelength ranges from 807-810nm at 25 °C. The fibers were draw into round bundles of 0.8 mm with NA of 0.2. 35 mm focusing lens and 85 % coupling efficiency were used to re-image the pumping spot approximately 0.6 mm onto the laser crystal. The 0.3 % doped, 9 mm long, 0.5° wedged one side and coated antireflection at 1064 nm both sides of Nd:YVO_4 was used for laser crystal. The lower doping concentration was to avoid the thermal fracture [7,8]. The cavity was designed to mode matching with pumping beam and the proper spot size about 80 μm on SBR. The resonator consisted of three highly reflective mirrors for 1064 nm (M1, M2 and M4), partially reflective mirror (M3, R=80% at 1064 nm) and SBR device. The radius of M3 and M4 are 500 and 100 mm respectively. The distance between M3 and M4 is 600mm and the total cavity length is approximately 1m. The SBR device was mounted on a copper sink without any actively cooling. We could achieve a single-output beam by replacing M1 with an appropriate partially transmitting mirror, using a coupling lens with sufficient working distance and adding a mirror reflection for the output beam between M1 and the coupling lens. However a dual-output beam cavity was used due to the limitation of mirrors availability.

With the present cavity, the laser outputs follow a general behavior that is a function of the pumping power. Near oscillation threshold the output is effectively cw; slightly increasing the pumping power initiates a Q-switched mode-locked (QML) state. There are many sidebands along with the order of the relaxation oscillation frequency to the carrier frequency in the Fig 3a. While the pumping power is increased further, the QML state is transformed into a cw mode-locked (CML) state shown in Fig 3b. The fig 3c shows the oscilloscope signal of CML states. Fig 4 illustrates the average output power as a function of the incident pumping power. The repetition rate is 148 MHz. The pumping threshold less than 3 W 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 corresponding to 14 W pumping power. For the maximum pumping power 50 W, 23.5 W average output power is obtained. The overall optical-to-optical efficiency reaches 47%. The pulse duration was found to be a function of pumping power from 27 ps at 10 W output, 24 ps at 15W and 21.5 ps at the output power of 20 W as shown in Fig. 5. The pulse duration obtained here in this experiment is nearly the same to the results of an antiresonant Fabry-Perot saturable absorber [3] or a strained SBR [9]. The experimental results mean 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. No damage to the relaxed SBR was observed over several hours of operation and the laser performance was reproduced on a day-to-day basis. In order to investigate the homogeneity of the absorber, we swept the beam spot on different regions of the SBR. The mode-locked operation was also found to be 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 sweep spot problem.

In order to study the sensitivity of the SBR device to temperature variation, the SBR device was mounted on a thermoelectric cooler of varying the temperature range from 20 °C to 90 °C. The pumping power corresponding to the transition from the QML state to the stable CML state decreased from 20 °C to 90 °C. However, the pumping power corresponding to the transition between cw operation to the QML state increased from 20 °C to 90 °C as shown in Fig 6. This temperature tuning characteristics indicate that the modulation depth of SBR device decreases as the temperature increases. These results are consistent with the PL measurement shown in Fig. 1. While the temperature of SBR increases, the PL spectrum shifts to longer wavelengths about 0.3 nm per Celsius degree; thus the laser experiences smaller saturable absorption. The transition power is rather insensitive to temperature since the broadened PL spectrum.

3. CONCLUSIONS

The advantage of a relaxed SBR in passively high-power mode-locked Nd:YVO_4 laser has been demonstrated. It remains to study further the amount of appropriate relaxation for applications. The demonstrated experiment using relaxed SBR obtained a high-power mode-locked performance of diode-end-pumped Nd:YVO_4 laser. 23.5 W of average output power with 148 MHz cw mode-locked pulse trains with pulse duration 21.5 ps was achieved at 50 W pumping power. Experimental results show that the insertion loss of the relaxed SBR is fairly small and its uniformity is also sufficient for mode-locked operation. Highly reliability and stability of this laser makes it much interesting for laser applications.

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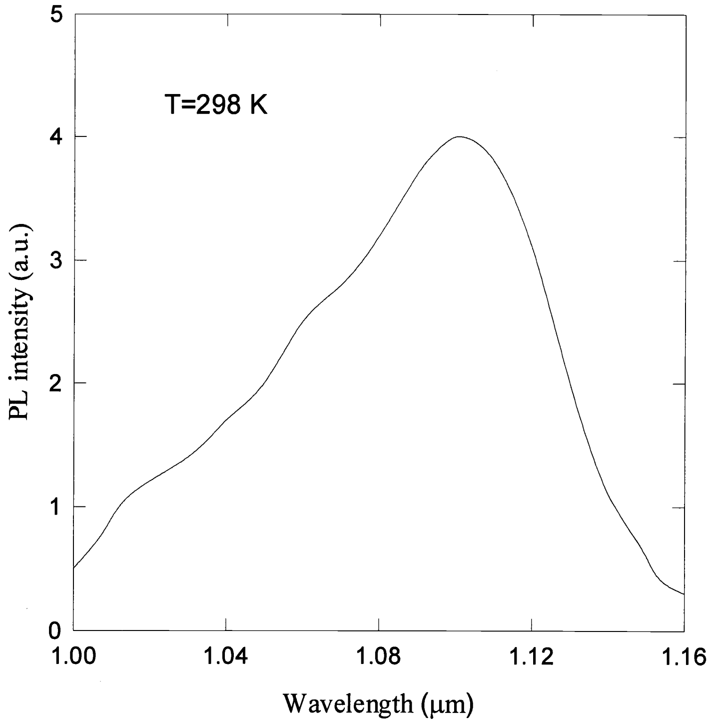

Fig 1 the photoluminescence spectrum of the saturable Bragg reflector

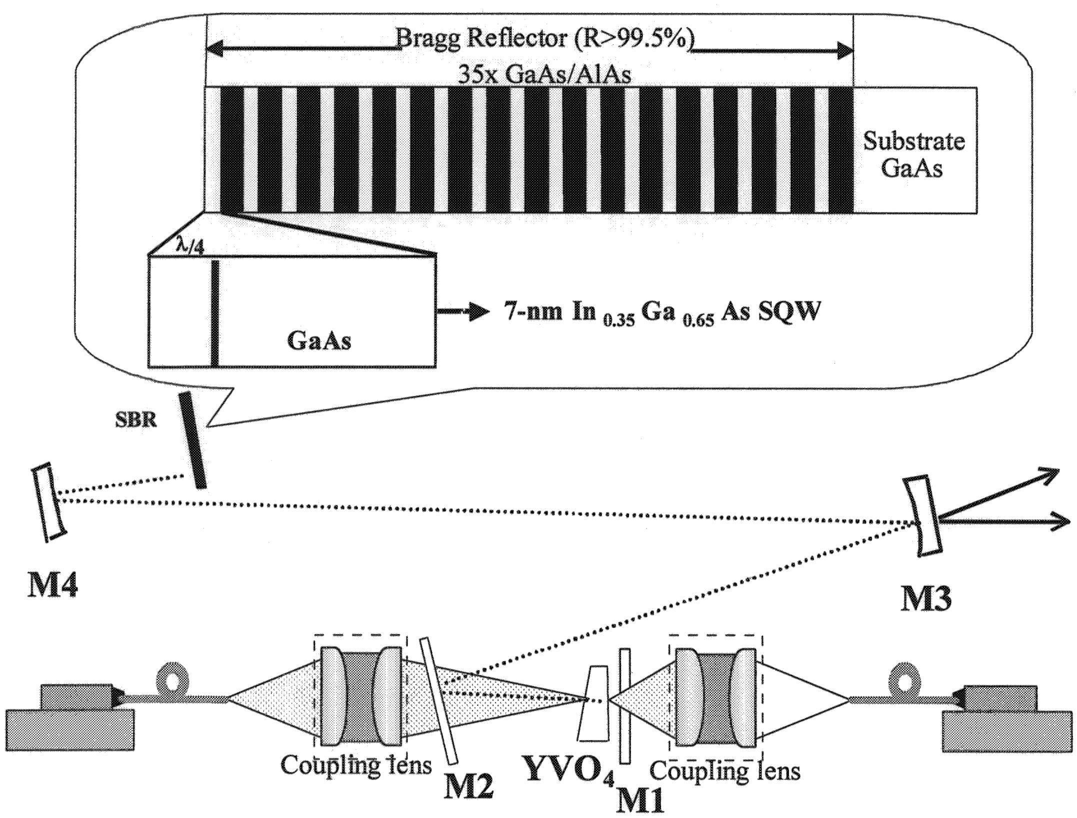

Fig. 2 the laser scheme of the passively mode-locked Nd:YVO4 laser with the saturable Bragg reflector (SBR)

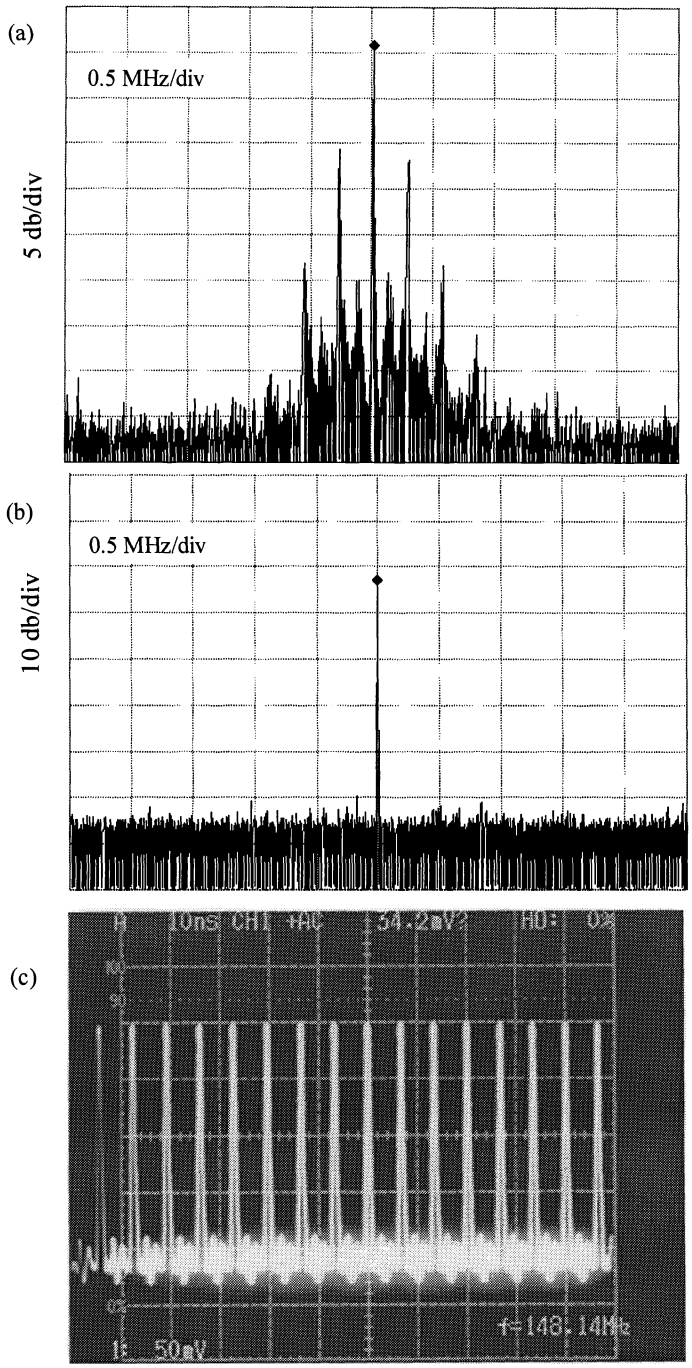

Fig. 3 Power spectrum analyzer signal for the (a) QML and (b) CML states. The oscilloscope signal (c) for the CML state.

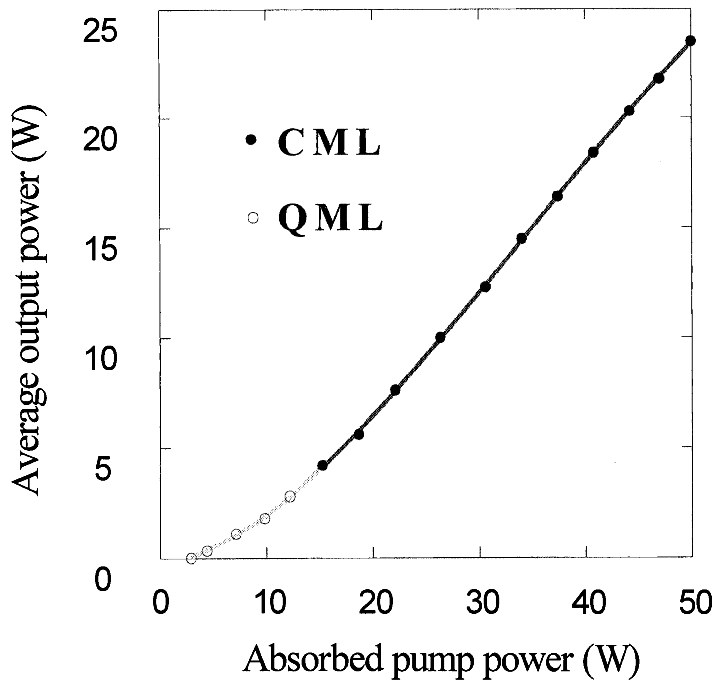

Fig. 4 the dependence of average output power on the absorbed pumping power.

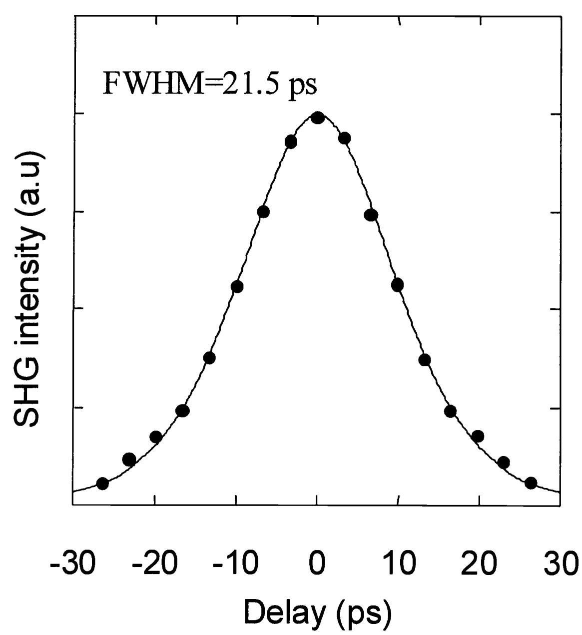

Fig. 5 the autocorrelation trace of the pulse duration 21.5-ps at 20-W output power.

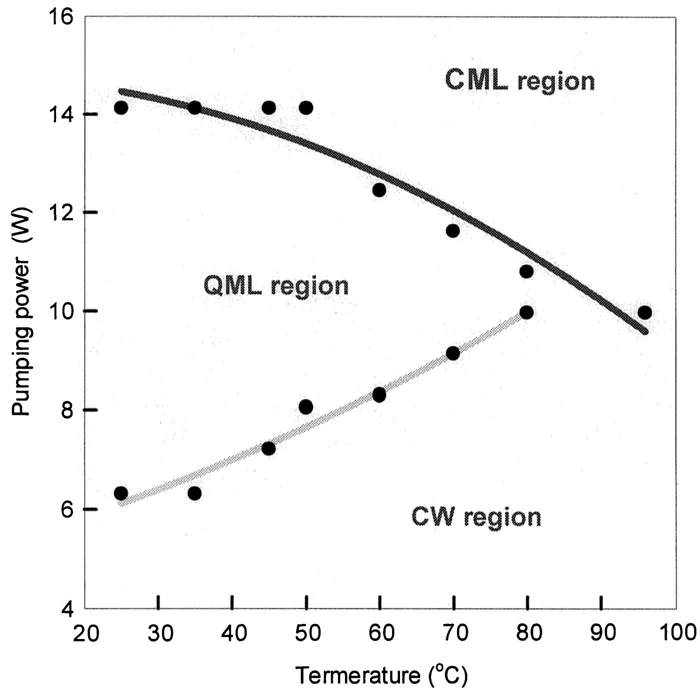

Fig. 6 the transition points for varying temperature of SBR