Passively Q-switched $Yb^{3+}:YCa_4O(BO_3)_3$ laser with InGaAs quantum wells as saturable absorbers

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A diode-pumped Yb:YCOB laser at 1086 nm is passively Q switched by using InGaAs quantum wells as saturable absorbers and utilizing the Bragg mirror structure as an output coupler. With an absorbed pump power of 9.2 W the laser produces pulses of 100 ms duration with average pulse energy of as much as 165 μJ at a pulse repetition rate of 7 kHz. © 2007 Optical Society of America

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1. Introduction

In the past few years, ytterbium (Yb^{3+})-doped lasers have attracted a great deal of interest because of their practical applications in diode-pumped solid-state lasers.[1–10] Despite the quasi-three-level nature, the Yb^{3+}-doped gain media have numerous advantages in comparison with their Nd^{3+} counterparts. The main advantages of the Yb ion include the availability of high doping levels without concentration quenching, very small quantum defects, and a simple electronic structure that prevents undesired effects such as upconversion and excited-state absorption. Another important advantage of Yb^{3+}-doped gain media is their long upper-laser-level lifetimes that enhance the energy-storage capabilities for the Q-switching operation.

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. Most of the work on passively Q-switched Yb^{3+}-doped lasers has been performed with Cr^{4+}:YAG crystals as saturable absorbers.[11–16] In addition to Cr^{4+}:YAG crystals, the semiconductor saturable absorber mirror (SESAM) has been successfully used in a passively Q-switched Yb:YAG laser to generate pulses with 1.1 μJ energy, 1.9 kW peak power, and a repetition rate of 12 kHz.[17] Even so, to the best of our knowledge, SESAMs have never been applied to other Yb^{3+}-doped lasers. Among Yb-doped hosts, Yb-doped calcium oxyborate crystals, $Yb^{3+}:Ca_4YO(BO_3)_3$ (Yb:YCOB) and $Yb^{3+}:Ca_4GdO(BO_3)_3$ (Yb:GdCOB), posses longer upper-level lifetimes.[5] The upper-level lifetimes of Yb:YCOB and Yb:GdCOB crystals have been found to be more than twice that of Yb:YAG crystal. In this work we present a passively Q-switched operation using InGaAs quantum wells (QWs) as the saturable absorbers in a diode-pumped Yb:YCOB laser. With an absorbed pump power of 9.2 W, the compact laser cavity produces an average output power of 1.15 W at 1086 nm with a repetition rate of 7 kHz and a pulse width of 100 ns. The corresponding pulse energy and peak power are up to 165 μJ and 1.65 kW, respectively.

2. Experimental Setup

Figure 1 shows the experimental configuration for the passively Q-switched 1086 nm Yb:YCOB laser with InGaAs QWs used as saturable absorbers and an output coupler (SESAMOC). The concept of combining the SESAM with an output coupler has been realized in passively Q-switched lasers.[18] The present SESAM structure was monolithically grown on an undoped GaAs substrate by metalorganic chemical vapor deposition (MOCVD) to simultaneously serve as a saturable absorber and an output coupler in the passively Q-switched laser at 1086 nm. The Bragg mirror structure consists of 12 AlAs/GaAs quarter-wavelength layers, designed for a reflectivity of 97.5%

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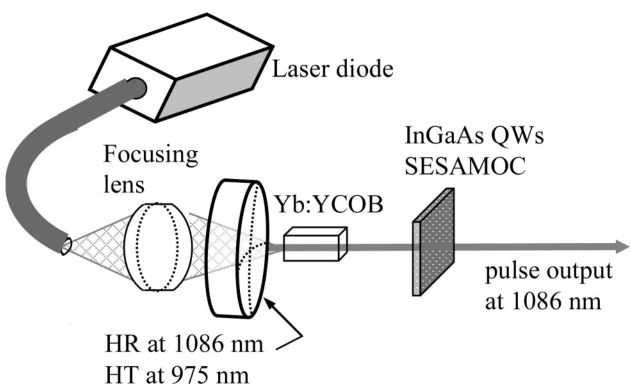

Fig. 1. Schematic of a diode-pumped passively Q-switched Yb: YCOB laser at 1086 nm: HR, high reflection; HT, high transmission.

at 1086 nm. The saturable absorber region was grown to comprise two 8 nm thick $In_{0.34}Ga_{0.66}As$ QWs separated by a 10 nm thick GaAs layer. It was experimentally found that the SESAM device has a modulation depth of 1.5% and a saturation fluence of 20 $\mu J/cm^2$. The saturation measurements were performed using nanosecond Q-switched laser pulses to coincide with the present Q-switched experiment. The thickness of the GaAs substrate was 350 μm. The back side of the GaAs substrate was coated for antireflection at 1086 nm ($R < 2\%$). The SESAM device was surface mounted in a water-cooled copper block without any transparent heat spreader on the surface.

The active medium was 20 at. % Yb:YCOB crystal with a length of 4 mm. Both sides of the laser crystal were coated for antireflection at 1086 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 15 W 975 nm fiber-coupled laser diode with a core diameter of 400 μm and a NA of 0.20. A focusing lens with a 12.5 mm focal length and 90% coupling efficiency was used to reimage the pump beam into the laser crystal. The pump spot radius was approximately 150 μm. The input mirror was a 500 mm radius-of-curvature concave mirror with antireflection coating at the pump wavelength of 975 nm on the entrance face ($R < 0.2\%$) and high-reflection coating at 1086 nm ($R > 99.8\%$) and high-transmission coating at 975 nm ($T > 85\%$) on the other surface. The cavity length was approximately 20 mm. The spectral information of the laser was monitored by an optical spectrum analyzer (Advantest Q8381A, Japan). The spectrum analyzer employing diffraction lattice monochromator can be used for high-speed measurement of pulse light with a 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 Yb:YCOB laser at 1086 nm was studied first. For this investigation an output

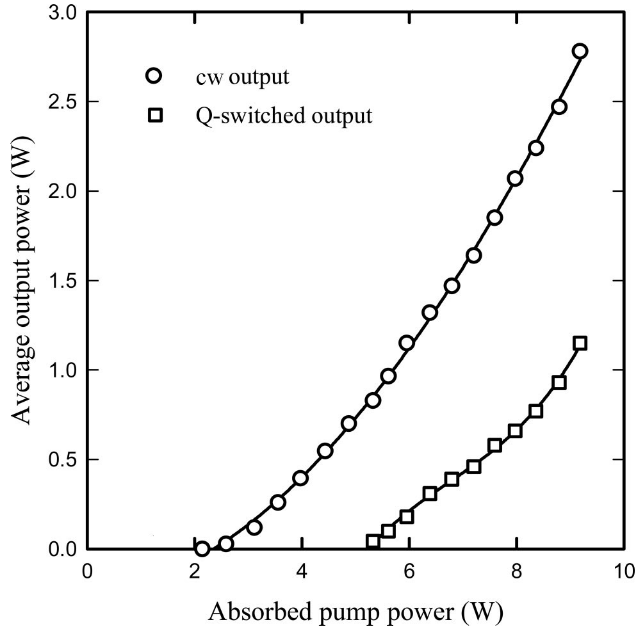

Fig. 2. Average output powers at 1086 nm with respect to the absorbed pump power in cw and passively Q-switching operations.

coupler with partial reflection at 1086 nm was used instead of the above-mentioned InGaAs SESAM. The optimum reflectivity of the output coupler was found to be approximately 98%. The optimum cw performance at 1086 nm provides the baseline for evaluating the passively Q-switched efficiency. Figure 2 shows the average output powers at 1086 nm with respect to the absorbed pump power in cw and passively Q-switching operations. In the cw regime the laser had a slope efficiency of 40%; the output power reached 2.8 W at an absorbed pump power of 9.2 W. The beam-quality factor M^2 was found to be less than 1.5 for all pump powers. In the passively Q-switching regime an average output power of 1.15 W was obtained at an absorbed pump power of 9.2 W. The Q-switching efficiency (the ratio of the Q-switched output power to the cw one at the maximum pump power) was found to be up to 41%. This Q-switching efficiency is comparable to those of Yb-doped lasers with Cr^{4+}:YAG crystals as saturable absorbers.[11–16] Here the output power is limited by the available absorbed pump power not by the cracking of the laser crystal. Figures 3(a) and 3(b) depict, respectively, the experimental results for the lasing spectra in the cw and passive Q-switching operations at an absorbed pump power of 9.2 W. It can be seen that the spectral bandwidth of the Q-switching mode is nearly similar to that of the cw mode. In other words, the present SESAM device does not limit the lasing bandwidth, and it should be a practical saturable absorber to mode lock Yb-doped lasers.

Figure 4 shows the pulse repetition rate and the pulse energy versus the absorbed pump power. The pulse repetition rate initially increases with pump power, and it is approximately up to 7 kHz at an absorbed pump power of 9.2 W. Like typically pas-

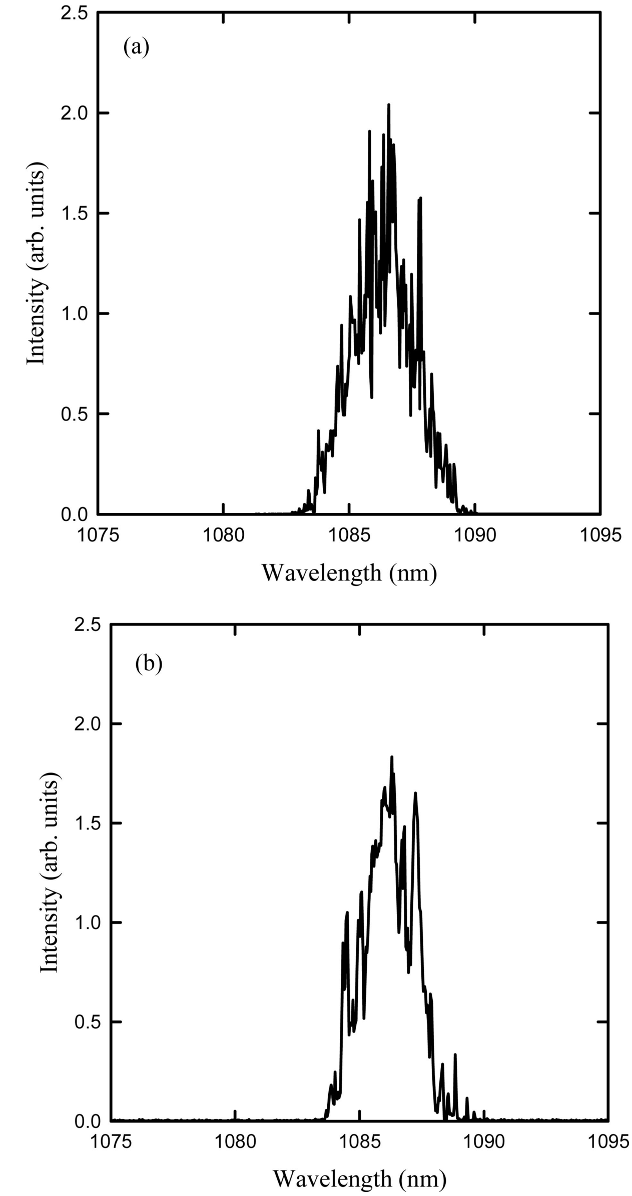

Fig. 3. Experimental results for the lasing spectra at an absorbed pump power of 9.2 W. (a) cw operation, (b) passive Q-switching operation.

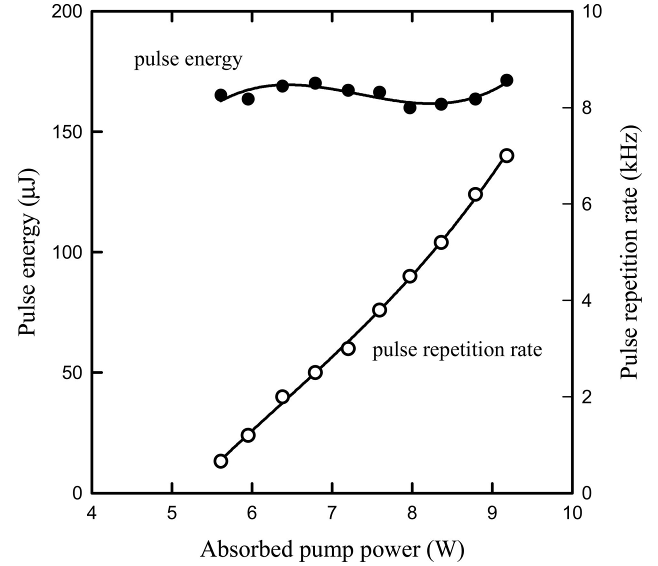

Fig. 4. Experimental results for pulse repetition rate and pulse energy versus absorbed pump power.

sively Q-switched lasers, the pulse energy is almost unrelated to the pump power, and its value is 165 μJ on average. On the whole, the pulse width remains approximately constant at 100 ns. With the measured pulse energy and pulse width, the peak power can be found to be higher than 1.6 kW. 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 ±10%.

4. Analysis

The coupled rate equations have been used to model a passively Q-switched laser in many investigations.[19,20] Here we analyze the experimental result with the following coupled rate equations:

$$\frac{d\phi}{dt} = \frac{\phi}{t_r}\left[2\sigma n l - 2\sigma_s n_s l_s - \ln(1/R_c) - L\right], \tag{1}$$

$$\frac{dn}{dt} = r_p - \gamma c\sigma\phi n - \frac{n}{t_f}, \tag{2}$$

$$\frac{dn_s}{dt} = -\frac{A}{A_s}c\sigma_s\phi n_s + \frac{(n_{so} - n_s)}{t_s}, \tag{3}$$

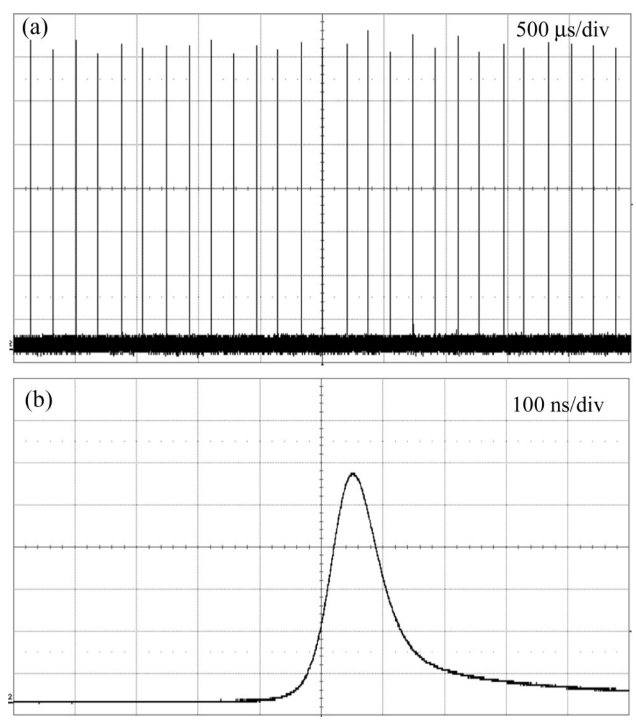

Fig. 5. (a) Typical oscilloscope trace of a train of output pulses and (b) expanded shape of a single pulse.

where ϕ is the intracavity photon density with respect to the effective cross-sectional area of the laser beam in the gain medium, n is the population density of the gain medium, n_s is the ground-state population density of the saturable absorber, n_{so} is the initial ground-state population density in the saturable absorber, σ is the stimulated emission cross section of the gain medium, σ_s is the absorption cross section in the saturable absorber, l is the length of the gain medium, l_s is the length of the saturable absorber, A/A_s is the ratio of the effective beam area in the gain medium to the beam area in the saturable absorber, γ is the inversion reduction factor, r_p is the rate of the

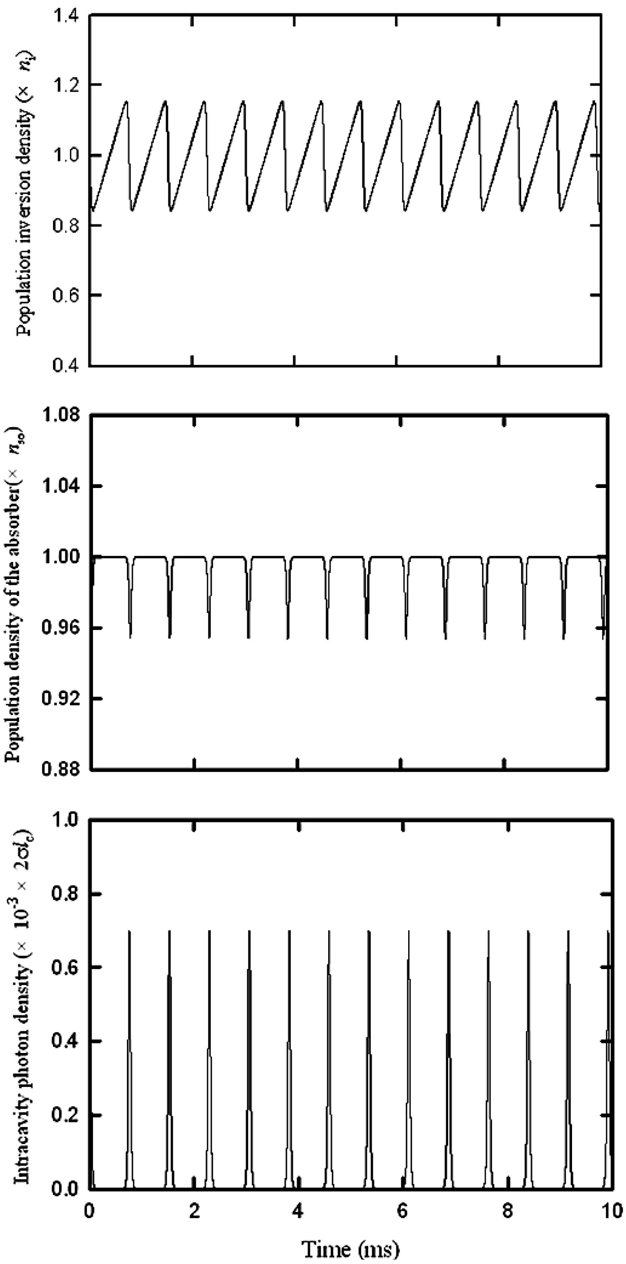

Fig. 6. Numerical results for the population density of the gain medium, the ground-state population density of the saturable absorber, and the intracavity photon density. The results correspond to the absorbed pump power of 6 W.

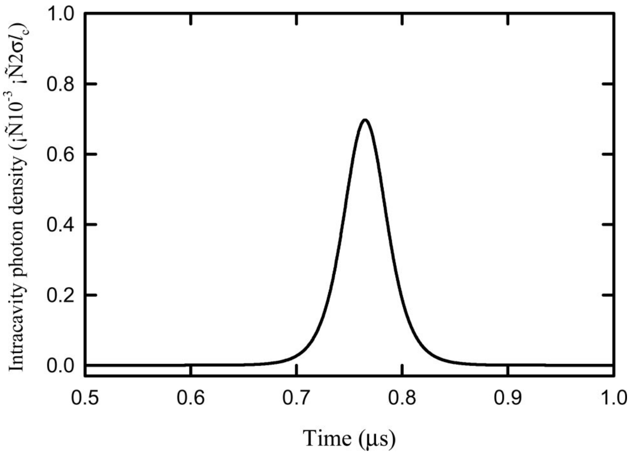

Fig. 7. Numerical result for the single Q-switched pulse shape.

pump density, t_r is the round-trip transit time of light in the cavity, c is the speed of light, t_f is the lifetime of the upper-level state of the gain medium, t_s is the lifetime of the excited state of the saturable absorber, R_c is the reflectivity of the output mirror, and L is the nonsaturable intracavity round-trip dissipative optical loss.

The values of the parameters used in the calculation are as follows: $\sigma = 3.3 \times 10^{-21}\,\text{cm}^2$ (Ref. 5), $t_f = 2.28$ ms,[5] $\sigma_s = 4.6 \times 10^{-19}\,\text{cm}^2$, $t_s = 0.1$ ns, $T_o = 0.985$, $R_c = 0.975$, $L = 0.03$, $t_r = 0.2$ ns, $l = 0.4$ cm, $r_p = 7000\,\text{cm}^{-3}/\text{s}$, and $\gamma = 2$. Figure 6 depicts the numerical results for the population density of the gain medium, the ground-state population density of the saturable absorber, and the intracavity photon density. The condition of the numerical analysis corresponds to the absorbed pump power of 6 W. It can be seen that the repetition rate agrees very well with the experimental results. Furthermore as shown in Fig. 7, the theoretical pulse shape is in good agreement with the experimental data. With the numerical integration, the theoretical output pulse energy is found to 170 μJ, which is also close to the experimental result. The general agreement indicates that the simple model of the coupled rate equations is adequate for a first-order prediction of the low-gain laser characteristics.

5. Conclusions

A diode-pumped Yb:YCOB laser operating at 1086 nm was passively Q switched by using InGaAs QWs as semiconductor saturable-absorber output couplers. An average output power of 1.15 W with a Q-switching efficiency of 41% was obtained at an absorbed pump power of 9.2 W. Stable Q-switched pulses of 100 ns duration with a repetition rate of 7 kHz were generated. The present result indicates the possibility of using the InGaAs QW structure to mode lock a Yb:YCOB laser at 1086 nm.

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