Comparative studies for Cr^{4+}:YAG crystal and AlGaInAs semiconductor used as a saturable absorber in Q-switched Yb-doped fiber lasers

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Abstract: We demonstrate comparative studies for Cr^{4+}:YAG crystal and AlGaInAs quantum-well (QW) used as a saturable absorbers in passively Q-switched Yb-doped fiber lasers. Both saturable absorbers were designed to be possessed of nearly the same initial transmission. Under a pump power of 24 W, the average output powers were up to 14.4 W and 13.8 W obtained with the AlGaInAs QWs and with the Cr^{4+}:YAG crystal, respectively. The maximum pulse energies obtained with the Cr^{4+}:YAG crystal and with the AlGaInAs QWs were found to be 0.35 mJ and 0.45 mJ, respectively.

OCIS codes: (140.3510) Lasers, fiber; (140.3480) Lasers, diode-pumped; (140.3540) Lasers, Q-switched.

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1. Introduction

The rapid development of double-clad rare-earth doped fibers and high-power laser diodes spirits the generation of high-power and high-brightness light sources [1–3]. Pulsed fiber lasers have attracted a great deal of attentions in applications owing to their higher peak power than in CW operation. Passive Q-switching (PQS) is a sophisticated and an efficient technique to create high-pulse-energy and high-peak-power pulses. Besides, PQS lasers are more compact and lower cost than the active Q-switching cause of that they utilize saturable absorbers (SAs) in replace of acoustic-optic or electro-optic modulators as the Q-switch.

Fiber-type SA [4–6] offers the in-line configuration, nevertheless they are restricted by modulation depth to deliver high-pulse-energy laser. Crystal-based and semiconductor-based SAs are other choices of passive Q-switch. Their high mechanical robustness and well-developed fabrication process make them more common in Q-switched fiber lasers [7–11]. In the spectral region of 1.0~1.1 μm, Cr^{4+}:YAG crystals [7] and InGaAs/GaAs quantum wells (QWs) [10] have been adopted to Q-switch fiber lasers. However, the output pulse energy with InGaAs SESAMs in passively Q-switched lasers are limited by the lattice mismatch with the substrate GaAs for the spectral region of above 1.0 μm. Alternatively, AlGaInAs material has the advantages of lattice match with the substrate InP and better electron confinement in the 0.84-1.65 μm spectral region than AlGaInP materials [12,13]. We have recently utilized AlGaInAs periodic QWs to Q-switch a Nd:YVO4 laser [14] and an Yb fiber laser [15], they could emit pulse energy up to 40 and 300 μJ, respectively. Furthermore both of them delivered pulse peak power ≧ 10 kW. Consequently, AlGaInAs semiconductor QWs is comparable with Cr^{4+}:YAG crystal in the region of 1.0~1.1 μm.

Here we report on comparative studies for Cr^{4+}:YAG crystal and AlGaInAs semiconductor used as a SA in Q-switched Yb-doped fiber lasers. The two SAs were designed to be possessed of nearly identical small-signal transmission of ~28%. Experimental results reveal that the maximum transmissions are 85% and 96% for the Cr^{4+}:YAG crystal and the AlGaInAs QWs, respectively. Under a pump power of 24 W, the average output powers were up to 14.4 W and 13.8 W obtained with the AlGaInAs QWs and with the Cr^{4+}:YAG crystal, respectively. The maximum pulse energies obtained with the AlGaInAs QWs and with the Cr^{4+}:YAG crystal were found to be 0.45 mJ and 0.35 mJ, respectively.

2. Characteristics of saturable absorbers

The Cr^{4+}:YAG crystal has thickness of 3 mm and was highly doped with a small signal transmission of 28%. Both sides of the Cr^{4+}:YAG crystal were coated for antireflection at 1030 ~1080 nm (R<0.2%). The AlGaInAs absorber was designed with 50 groups of three QWs as described in Ref [15]. Both sides of the semiconductor SA were coated for anti-reflecting to reduce back reflections and the couple-cavity effects. Figure 1 shows the saturation transmission of the SAs, where the pump source was a nanosecond Nd:YAG Q-switched laser. The saturation energy density of AlGaInAs QWs and Cr^{4+}:YAG crystal are estimated to about 1 mJ/cm^2 and 300 mJ/cm^2, respectively. The deduced absorption cross-section of the Cr^{4+}:YAG crystal is in the order of 10^{-19} cm^2 and agrees approximately with Ref. [16~18]. Besides, the cross-section for the AlGaInAs QWs was obtained in the order of 10^{-15} cm^2. The 95% final transmission of AlGaInAs reveals the low nonsaturable loss induced

#116739 - $15.00 USD Received 3 Sep 2009; revised 15 Oct 2009; accepted 18 Oct 2009; published 29 Oct 2009

by the facet reflection and absorption by the substrate. On the other hand, the final transmission of the Cr^{4+}:YAG was only 85%, the lossy phenomenon was attributed mainly to the excited-state absorption (ESA) [19]. The final transmission influenced by the ESA effect could be express approximately as $T_f = T_i^{\beta}$, *where* T_f and T_i are the final transmission and the parameter β is the ratio of the absorption cross-section of the excited-state and the ground-state, i.e. $\beta = \sigma_{es} / \sigma_{gs}$. The values of β derived from Ref [16–18]. ranges from 0.1~0.28 and is 0.128 in our experiment. The modulation depth could be found to be 68% for AlGaInAs QWs and 57% for the Cr^{4+}:YAG crystal. Furthermore, the relaxation time of the AlGaInAs QWs the Cr^{4+}:YAG crystal were estimated to be on the order of 100 ns and 3 µs respectively.

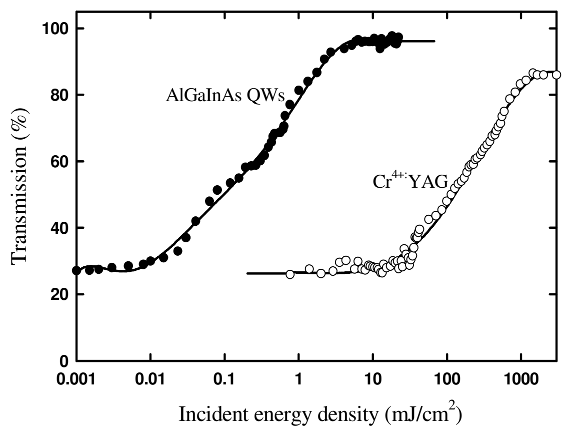

Fig. 1. Saturation transmission of the AlGaInAs QWs and the Cr^{4+}:YAG crystal.

3. Experimental setup

The cavity consists of a 3-m Yb-doped fiber and an external feedback cavity with a SA. Figures 2 (a) and (b) show the setups for PQS fiber lasers by use of a Cr^{4+}:YAG crystal and a AlGaInAs semiconductor, respectively. The fiber has an absorption coefficient of 10.8 dB/m at 976 nm and a double-clad structure with a 350 µm octagonal outer cladding, a 250 µm inner cladding with a numerical aperture (NA) of 0.46, and 30µm circular core with a NA of 0.07. The use of the large-mode-area fiber with low NA is beneficial for storing higher pulse energies and sustaining excellent beam quality simultaneously. The external cavity in Fig. 2 (a) consists of a focusing lens of 25-mm focal length to focus the fiber output into the Cr^{4+}:YAG crystal, a re-imaging lens to re-image the beam on a highly reflective mirror for feedback, and a thin film filter for controlling the resonant wavelength. The SA was wrapped with indium foil and mounted in a copper block without active cooling. Here we used a tight focusing configuration to enhance the energy inside the Cr^{4+}:YAG crystal. The beam waist was about 20 µm and a translation stage was used to adjust the longitudinal position of the Cr^{4+}:YAG saturable absorber for minimizing the beam volume inside the crystal and achieving the lowest Q-switching threshold. On the other hand, the low saturation energy density of the AlGaInAs QWs could allow a simple external cavity, as shown in Fig. 2 (b), where the beam spot diameter was approximately 300 µm. And the peak optical intensity allowed on the AlGaInAs QWs is estimated to be 300 MW/cm^2 without damage. The SA was tilted slightly to avoid facet reflection back to the gain fiber, which usually incurs parasitic fluctuation in pulse stability in high gain fiber lasers.

The pump source was a 35-W 976-nm fiber-coupled laser diode with a core diameter of 400 µm and a NA of 0.22. Focusing lens with 25 mm focal length and 92% coupling

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efficiency was used to re-image the pump beam into the fiber through a dichroic mirror with high transmission (>90%) at 976 nm and high reflectivity (>99.8%) within 1030~1100 nm. The pump spot radius was approximately 200 µm. With launching into an undoped fiber, the pump coupling efficiency was measured to be approximately 80%.

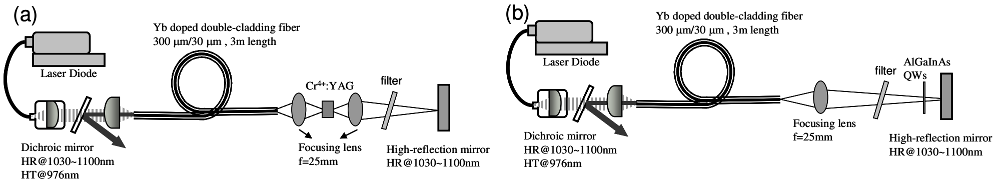

Fig. 2. Schematic of diode-pumped PQS Yb-doped fiber lasers. (a) with Cr^{4+}:YA crystal (b) with AlGaInAs QWs. HR: high reflection; HT: high transmission.

4. Results and discussions

Figure 3 shows the average output powers with respect to the launched pump power in cw and PQS operations. The cw operation was performed with an external cavity only comprising a re-imagining lens and a reflective mirror. In the cw regime, the laser had a slope efficiency of 74% and the output power reached 15.8 W at a launched pump power of 24 W. In the PQS regime, the maximum average output powers at a launched pump power of 24 W were up to 14.4 W and 13.8 W with the AlGaInAs QWs and with the Cr^{4+}:YAG crystal, respectively.

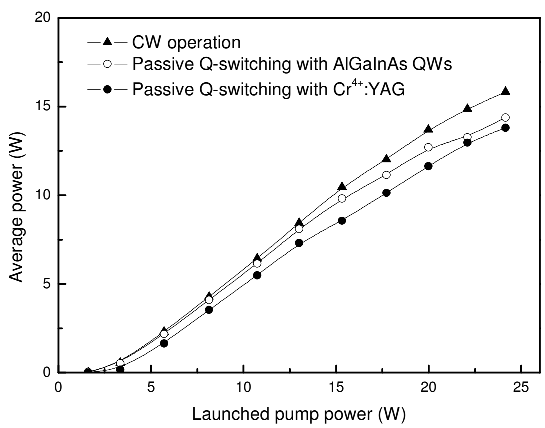

Fig. 3. Dependence of the average output power on the launched pump power for the cw and passive Q-switching operations.

The Q-switching efficiencies were 91% and 87% for the lasers with with the AlGaInAs QWs and with the Cr^{4+}:YAG crystal, respectively.

The pulse temporal behavior was recorded by a Leroy digital oscilloscope (Wavepro 7100; 10G samples/sec; 4 GHz bandwidth) with a fast InGaAs photodiode. Figure 4 shows the pulse characteristics including the pulse repetition rate and the pulse energy. Figure 4 (a) shows the pulse repetition rate versus the launched pump power. The repetition rates of both lasers increased monotonically with the pump power. At a launched pump power of 24 W, the repetition rates were 38 kHz and 30 kHz for using the Cr^{4+}:YAG crystal and the AlGaInAs QWs, respectively. Figure 4 (b) shows the pulse energy versus the launched pump power. The pulse energy with the Cr^{4+}:YAG crystal was almost constant at 0.3 mJ for the pump power less than 20 W and slightly increased up to 0.35 mJ at a pump power of 24 W. On the other hand, the pulse energy with the AlGaInAs QWs increases gradually, from 0.25 mJ at the threshold to 0.45 mJ at a pump power of 24 W.

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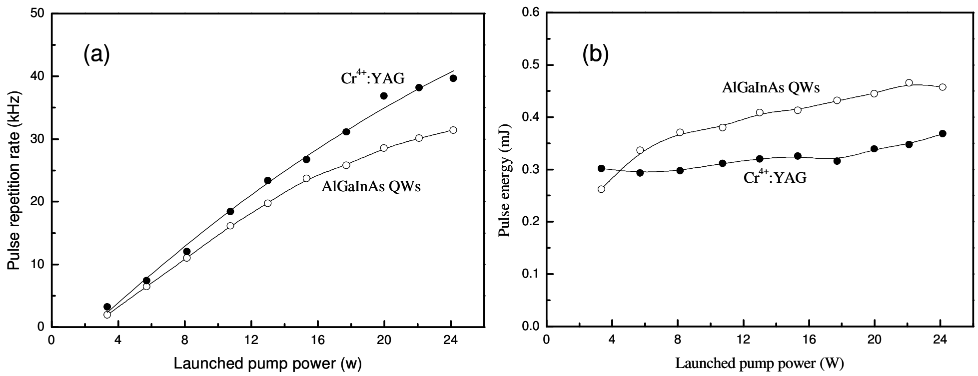

Fig. 4. (a) Pulse repetition rate and (b) pulse energy versus the launched pump power.

Another interesting characteristic of saturable absorbers is the wavelength-dependent absorption. In this investigation the thin film filter was tilted for controlling the lasing wavelength from 1055 nm to 1083 nm. Figure 5 shows the pulse energy versus the lasing wavelength at a pump power of 24 W. Since the absorption bandwidth of the AlGaInAs QWs was rather narrower, the variation of the pulse energy with the AlGaInAs QWs was more significant than that with the Cr^{4+}:YAG crystal. Therefore, the Cr^{4+}:YAG crystal is more suitable than the AlGaInAs QWs for using in tunable operation.

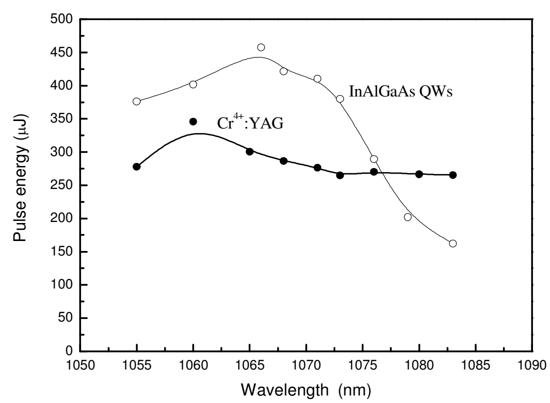

Fig. 5. Pulse energy versus the resonant wavelength.

The temporal shapes of the Q-switched pulses for the maximum pulse energy were depicted in Fig. 6. The top of Fig. 6 shows the single Q-switched envelops. The pulse durations were 70 ns and 60 ns for using the Cr^{4+}:YAG crystal and the AlGaInAs QWs, respectively. The bottom of Fig. 6 show the typical oscilloscope traces of Q-switched pulse train with the optimum alignment. The pulse-to-pulse stability was found to be noticeably better with the AlGaInAs QWs than with the Cr^{4+}:YAG crystal under 30 °C because of the proper cooling ability by the copper sink. Without any cooling mechanism, the pulse-to-pulse stability and the laser output energy will be reduced.

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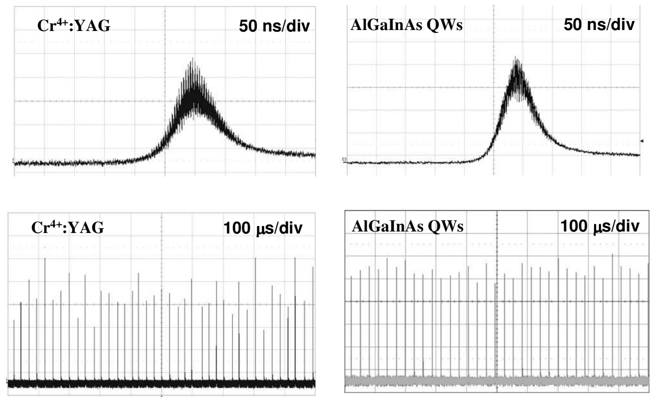

Fig. 6. Top: Oscilloscope traces of a typical Q-switched envelope; Bottom: Oscilloscope traces of a train of Q-switched pulses.

5. Conclusion

In conclusion, we have demonstrated comparative studies for the Cr^{4+}:YAG crystal and the AlGaInAs QWs used as a SA in efficient high-pulse-energy PQS Yb-doped fiber lasers. The two SAs were designed to exhibit nearly identical small-signal transmission of ~28%. Under a pump power of 24 W, the average output powers were up to 14.4 W and 13.8 W obtained with the AlGaInAs QWs and with the Cr^{4+}:YAG crystal, respectively. The maximum pulse energies obtained with the AlGaInAs QWs and with the Cr^{4+}:YAG crystal were 0.45 mJ and 0.35 mJ, respectively. The pulse-to-pulse stability was found to be noticeably better with the AlGaInAs QWs than with the Cr^{4+}:YAG crystal. Nevertheless, the Cr^{4+}:YAG crystal has a broader absorption band that is beneficial to the tunable operation. It is believed that the efficient Q-switched fiber lasers should be useful light sources for technical applications because of its high average power as well as high pulse energy.

Acknowledgments

The authors thank the National Science Council and the Industrial Technology Research Institute for their financial support of this research under Contract No. NSC-97-2112-M-009-016-MY3 and No. B200-97EL4, respectively.

#116739 - $15.00 USD Received 3 Sep 2009; revised 15 Oct 2009; accepted 18 Oct 2009; published 29 Oct 2009