Passively Q-switched ceramic Nd^{3+}:YAG/Cr^{4+}:YAG lasers

Yan Feng, Jianren Lu, Kazunori Takaichi, Ken-ichi Ueda, Hideki Yagi,
Takagimi Yanagitani, and Alexander A. Kaminskii

Passively *Q*-switched ceramic Nd^{3+}:YAG lasers with ceramic Cr^{4+}:YAG saturable absorbers are demonstrated. When the lasers are pumped by a 1-W cw laser diode, optical–optical efficiency as great as 22% is obtained with Cr^{4+}:YAG of initial transmission ranging from 94% to 79%. The results are similar to those in their crystalline counterparts. The operation of Brewster's angle and the polarization state of the laser output are also investigated. © 2004 Optical Society of America

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Ceramic laser materials have shown great potential in recent years, since high-optical-quality ceramic laser materials are now available, such as YAG, Y_2O_3, and Lu_2O_3, because of improved fabrication methods.[1–5] Ceramics as laser material have several remarkable advantages over single crystals. For example, samples with high doping concentration and of large sizes can be more easily fabricated, whereas this is usually difficult for crystals. The cost of ceramic laser materials can be potentially much lower than their single-crystal counterparts because of their faster fabrication process and possibility of mass production. Moreover, the rigid bonding of multiple samples is easy with these materials; thus the design flexibility for novel laser devices is greatly enhanced. Progress in this field is impressive. The first ceramic Nd:YAG laser with an output of 70 mW was reported in 1995,[6] the 1.46-kW cw ceramic Nd: YAG laser. The Nd:Y_2O_3, Yb:Y_2O_3, Nd:Lu_2O_3 ceramic lasers are demonstrated now.[2–5,7,8]

Besides laser gain media, ceramic material as a saturable absorber has also been explored.[9] Diode-pumped passively *Q*-switched solid-state lasers that employ solid-state saturable absorbers have attracted much attention because they can be compact, simple, and low in cost. Several solid-state saturable absorber materials have been reported, such as Cr^{4+}:YAG, LiF:F_2, GaAs, and semiconductor saturable absorber mirrors. Among them, Cr^{4+}:YAG is widely used for *Q*-switching Nd^{3+}-doped lasers for a low saturable intensity at 1064 nm and a high damage threshold.[10–13] We are now able to fabricate good-quality ceramic Cr^{4+}:YAG lasers. In this paper, progress in the ceramic Nd^{3+}:YAG/Cr^{4+}:YAG passively *Q*-switched laser is reported.

Figure 1 shows the experimental setup schematically. A laser diode with a maximum power of ~1 W was used as the pump source. A pair of lenses focused the pump beam onto a rectangular spot measuring approximately 70 μm × 50 μm. The gain medium was a $\phi 3 \times 5\ mm^3$ 1-at.% ceramic Nd^{3+}:YAG that had a 1.06-μm coating for high transmission on one side. The other side was antireflection coated at a pump wavelength of 808 nm and highly reflection coated at 1.06 μm. Several output couplers with different curvatures and transmissions were used. The saturable absorbers used in the experiments were uncoated ceramic Cr^{4+}:YAG samples with initial transmissions of 94%, 85%, and 79%. Both normally incident and Brewster's angle operations were investigated. The dynamics of the laser output were detected by a fast PIN and recorded by a 500-MHz digital oscilloscope.

Continuous-wave operations were investigated first. A cavity length of ~15 mm was used. Output couplers had transmissions of 3% and 5% and a curvature of 50 and 250 mm. With such cavity configurations the fundamental mode diameters at the gain medium were approximately 180 and 280 μm, respectively, which are much larger than the waist of the

Y. Feng, J. Lu, K. Takaichi, and K. Ueda are with the Institute for Laser Science, University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan (e-mail for Y. Feng, feng@ils.uec.ac.jp). H. Yagi and T. Yanagitani are with the Takuma Works, Konoshima Chemical Company, Ltd., 80 Koda, Takuma Mitoyo-gun, Kagawa 769-1103, Japan. A. A. Kaminskii is with the Crystal Laser Physics Laboratory, Institute Crystallography, Russian Academy of Sciences, Leninsky Prospekt 59, Moscow 117333, Russia.

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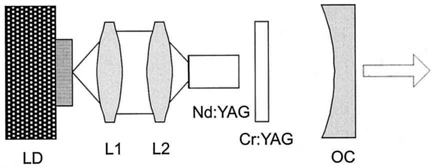

Fig. 1. Schematic of experimental setup: L1, L2, two lenses with $f = 8$ mm; OC, outcoupler. When we investigated Brewster's angle operation, the Cr^{4+}:YAG samples were tilted at an angle of 61°.

pump beam. However, the highest output power was obtained with a curvature of 250 mm and a transmission of 5%. This is due to the high divergence of the diode laser: The effective pump spot in the gain medium was much larger than the pump beam waist. At an incident pump power of 910 mW, a maximum 470-mW output was generated that corresponds to an optical–optical efficiency of 51.6% and a slope efficiency of 55.0%.

Passively Q-switching experiments with normally placed Cr^{4+}:YAG samples were carried out. The best results were also obtained with output mirrors of 250-mm curvature. Figure 2 shows the average output power versus pump power with different saturable absorbers. For initial transmissions of 94%, 85%, and 79%, outputs of 204, 121, and 72 mW, respectively, were produced at an incident pump power of 910 mW, which corresponds to an optical–optical efficiency of 22.4%, 13.3%, and 7.7%, respectively. These results were similar to those reported for crystalline counterparts.

However, the pulsed output fluctuated strongly. We thought it was a result of the saturable absorber samples being uncoated. To verify this, a coated crystalline Cr^{4+}:YAG sample was used for the same experiments, much better pulsing stability (fluctuations, <10%) was observed. A Fresnel reflection of 0° at YAG (refractive index, 1.82) and the air surface was ~8.6%. Therefore the laser resonators were actually four-mirror compound ones[14]; the component resonators hardly matched one another. The saturable absorber sample acted as an intracavity Fabry–Perot with a time-varying spectral response for a saturable absorption and heat-induced refractive-index change. Thus the longitudinal mode structure in those resonators varied with time too. In such complicated resonators, external noise can be magnified to make the system chaotic.

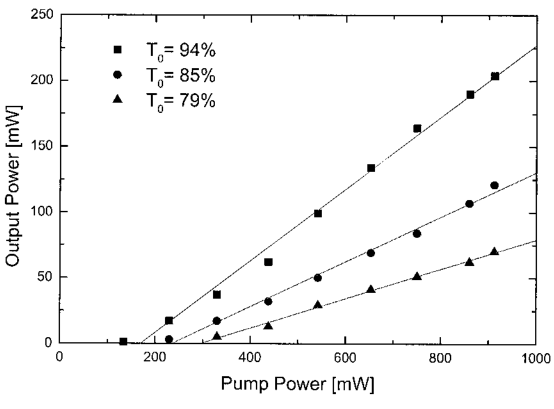

Fig. 2. Average output power versus laser-diode pump power with ceramic Cr^{4+}:YAG samples of different initial transmission. The curvature and transmission of the output mirror are 250 mm and 5%, respectively.

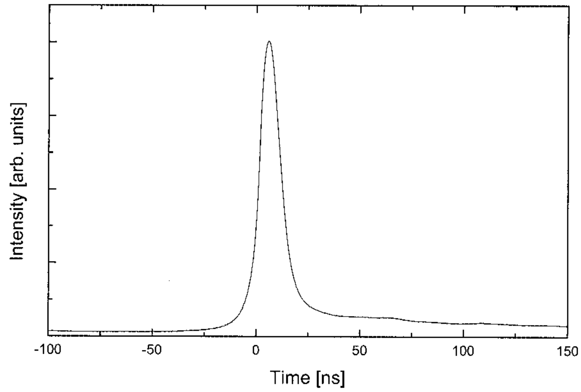

Fig. 3. Average pulse waveform taken at a pump power of 910 mW and a saturable absorber initial transmission of 79%. The FWHM pulse width is ~14 ns.

Despite that, we estimated pulse widths and repetition rates by averaging over a long period. For the maximum available power of our laser diode, 910 mW, {14 ns, 18 kHz}, {23 ns, 33 kHz}, and {42 ns, 45 kHz} were measured for initial transmissions of 79%, 85%, and 94%, respectively. A maximum average energy of 4 μJ and an average peak power of 286 W were obtained in the configuration of an initial transmission of 79% and an outcoupling of 5%. Figure 3 shows an averaged pulse waveform obtained at a pump power of 910 mW and an initial transmission of 79%, the FWHM pulse width is ~14 ns.

All observations of the behaviors of pulse energy, width, and repetition are consistent with the established theory for passive Q switching.[15] With a lower initial transmission the pulse energy became smaller and the width became larger. It is obvious that passively Q-switched crystalline and ceramic lasers have the same physics in these properties.

It is natural to investigate the Brewster's angle operation for uncoated samples. To do this, the cavity length was adjusted to ~25 mm. Note that the cw wave output remained almost unchanged. Figure 4 shows the results for the Brewster's angle operation with an outcoupling of 5%. A lower average power was obtained. However, much more stable pulsing was observed, which was understandable because the problem of the compound resonator no longer existed. The polarization was measured to be linear with a ratio of >100:1. But the pulse became very long with a minimum width of ~80 ns, which can be understood when one is considering the larger beam spot and the longer light path in a saturable absorber in the Brewster's angle operation. For YAG, the Brewster's angle is ~61°.

The beam area and light path are ~1.8 times larger

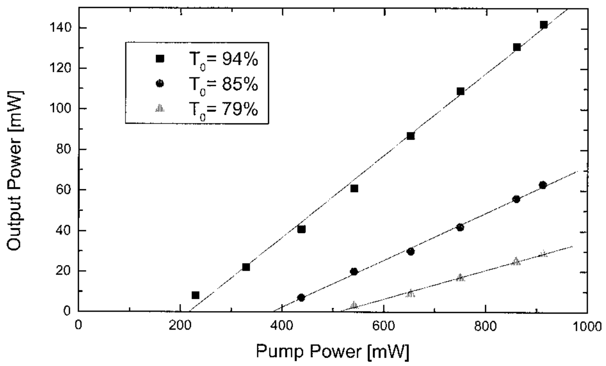

Fig. 4. Average output power versus laser-diode pump power in Brewster's angle operation for a different initial transmission with an output mirror with a transmission of 5% and a curvature of 250 mm.

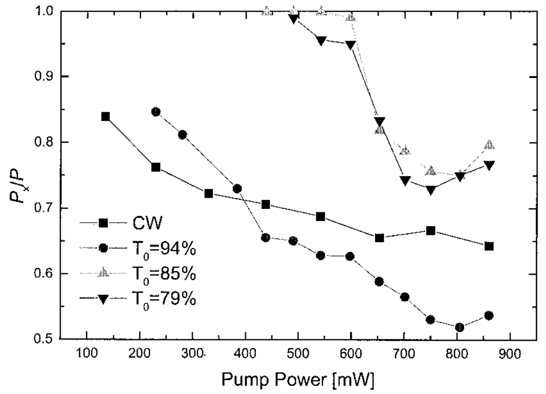

Fig. 5. Ratio of the horizontal polarized component to the total output, P_x/P, versus pump power for different operation conditions.

and 1.14 times longer, respectively, than those in the case of normal incidence. So the lasers were closer to the second threshold condition, which is[15]

$$\frac{\ln\left(\frac{1}{T_0^{\,2}}\right)}{\ln\left(\frac{1}{T_0^{\,2}}\right)+\ln\left(\frac{1}{R}\right)+L} > \frac{\sigma}{\sigma_{gs}}\frac{A_s}{A} \tag{1}$$

for the four-level system, without consideration of the excited-state absorption in the saturable absorber. T_0 is the initial transmission of the saturable absorber, A_s/A is the ratio of the effective area in the saturable absorber and in the gain medium, R is the reflectivity of the output mirror, L is the nonsaturable intracavity round-trip loss, and σ_{gs} and σ are the ground-state absorption cross section of the saturable absorber and the stimulated emission cross section of the gain medium. The physical meaning of this threshold condition is that for good passive Q switching the saturation in the absorber must occur before the saturation in the gain medium.

There was a long and inconclusive discussion of the self-polarization phenomena in crystalline Nd^{3+}:YAG/Cr^{4+}:YAG passively Q-switched lasers.[13,16,17] One mechanism is the anisotropy in the saturation power of the Cr^{4+}:YAG crystal,[18] which is generally accepted. There is a second mechanism of unknown nature[17] that relates to pump properties. For all ceramic Nd^{3+}:YAG/Cr^{4+}:YAG passively Q-switched lasers the former mechanism should no longer have an effect. Therefore it is interesting to investigate the polarization properties of these lasers.

We took some measurements of the polarization of the laser output, as shown in Fig. 5 where the ratio of the horizontal component to the total output versus pump power is plotted for a different operation condition. When the laser was in cw operation the polarization state ranged from near linear to a 2:1 ratio with an increase in pump power from threshold to 18 times threshold. When the laser was used in the Q-switched operation, the polarization state can range from linear (>100:1) to random depending on the initial transmission of the saturable absorber and pump power. The preferred axis was always parallel to the slow axis of the laser diode, which was the same as that in the literature.[17] The steep transition of the polarization state with pump power was observed in the experiments, which indicates competition between differently polarized modes. We figured that this polarization effect relates to pump beam profiles. The presence of a saturable absorber altered the competition conditions inside the laser cavity. A detailed study of this effect will be reported in the future.

In summary, passive Q-switching of ceramic Nd^{3+}:YAG lasers with a ceramic Cr^{4+}:YAG saturable absorber has been demonstrated. The results are similar to their crystalline counterparts. Brewster's angle operation and the polarization state of the output were also investigated. The ceramic Cr^{4+}:YAG is a promising alternative to crystalline Cr^{4+}:YAG.

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