Laser-diode-pumped Cr^{4+},Nd^{3+}:YAG with self-Q-switched laser output of 1.4 W

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Received May 18, 2000

By use of a laser diode as a pump source, a self-Q-switched laser from a Cr,Nd:YAG crystal is demonstrated. The output Q–switched traces are very stable, the threshold pump power is 3.5 W, the pulse duration is 50 ns, and the slope efficiency is as high as 20%. In addition, the pulse width remains constant while the pulse repetition rate varies with pump power. © 2000 Optical Society of America

OCIS codes: 140.0140, 140.2020, 140.3380, 140.3480, 140.3540, 140.3580.

Pulses in the nanosecond and subnanosecond regimes with high power and a high repetition rate have wide applications in micromachining, ranging, remote sensing, microsurgery, and so on. Laser-diode- (LD-) pumped passively Q-switched lasers can supply this kind of pulse and have the advantages of simplicity, compactness, low cost, and high efficiency. Therefore LD-pumped passively Q-switched lasers have attracted a great deal of attention in recent years. Saturable absorbers that have been successfully used for passively Q-switched lasers include dyes,[1] LiF:F_2 color-centered crystals,[2] and Cr^{4+}-doped crystals.[3–10] Among these absorbers, Cr^{4+}-doped crystals that have been developed in recent years, such as Cr^{4+}:YAG,[3–7] Cr^{4+}:Mg_2SiO_4,[8] Cr^{4+}:GSGG,[9] and Cr^{4+}:YSO,[10] have the advantages of good photochemical and thermal stability, large absorption cross section, low saturable intensity, and high damage threshold. In addition, Cr^{4+} can be doped into a gain medium to form self-Q-switched lasers.[4,7] As a result of the above advantages, Cr^{4+}-doped crystals have become the most promising saturable absorbers for passively Q-switched lasers. So we grew a Cr,Nd:YAG crystal and studied the self-Q-switched laser properties with a LD as the pump source.

A Cr,Nd:YAG crystal was grown by use of the standard Czochralski method. We constructed the hot zone of the growth station with stabilized zirconia ceramics to maintain the high temperature required for growth of Cr and Nd codoped YAG crystal (MP, 1970 °C). The crystal was pulled at a rate of 1 mm/h and rotated at 15 rpm. Cr^{4+} is regarded as being substituted into the distorted tetrahedral Al site in the garnet lattice; therefore a charge compensator is required, and divalent calcium was added as a charge compensator. Samples for spectroscopic measurements were cut out of boules, and the surfaces perpendicular to the $\langle 111 \rangle$ growth axis were measured with a Lambda Perkin-Elmer 9 UV–visible–near-IR spectrometer at room temperature. A schematic of the LD-pumped Cr,Nd:YAG self-Q-switched laser cavity is shown in Fig. 1. The pump source was a fiber-coupled AlGaAs–GaAs single-quantum-well laser emitting at 808 nm. A Cr,Nd:YAG crystal was polished to a planar–concave geometry. The concave mirror had a radius of curvature of 80 mm and was coated for high transmission at 808 nm and total reflection at 1064 nm. The planar surface was coated for 95% reflection at 1064 nm as the output coupler and total reflection at 808 nm. The misalignment of the axes of the two mirrors was measured to be less than 0.3°. We operated the laser at 278 K, using constant-temperature water-cooled circulation with a copper surface. The Q-switched pulses were recorded with a fast Si p–i–n detector with a 1.5-ns rise time and a Tektronix TDS 380 digitizing oscilloscope with a 400-MHz sampling rate in single-shot mode. The output power was measured with a laser powermeter. The LD output, after beam shaping with a focal lens, was focused onto a spot with a diameter of 100 μm. The LD was operated in the cw mode, and after the focal lens the loss was approximately 8%.

The room-temperature absorption spectrum of Cr,Nd:YAG crystal, after correction of the surface reflection losses, is displayed in Fig. 2. The absorption feature in the visible region is similar to that of chromium-doped YAG.[11] The absorption bands peaked at 0.53, 0.59, 0.75, 0.81, and 0.88 μm are attributed to Nd^{3+} ions. The broad absorption bands centered at 0.43 and 0.59 μm are attributed to the ${}^4A_2 \rightarrow {}^4T_1$ and ${}^4A_2 \rightarrow {}^4T_2$ transitions of Cr^{3+}. The band from 900 to 1200 nm is believed to be caused by Cr^{4+} ions.[12] The absorption coefficient is 2.6 cm^{-1} at the pump wavelength of 808 nm and is 0.15 cm^{-1} at 1064 nm. With Cr,Nd:YAG crystal as the active medium, the laser Q switches, and the threshold pump power is 3.5 W. Figure 3 shows a typical Q–switched

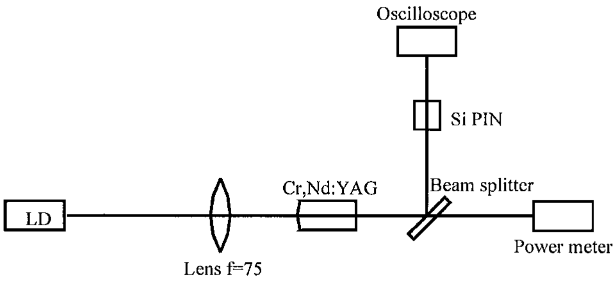

Fig. 1. Schematic of the LD-pumped Cr,Nd:YAG self-Q-switched laser.

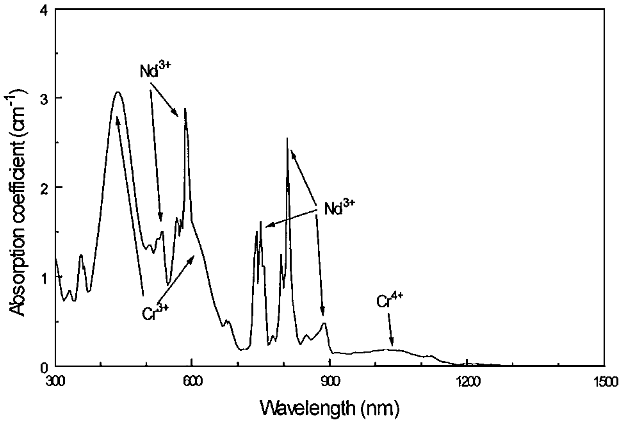

Fig. 2. Room-temperature absorption spectrum of Cr,Nd:YAG crystal.

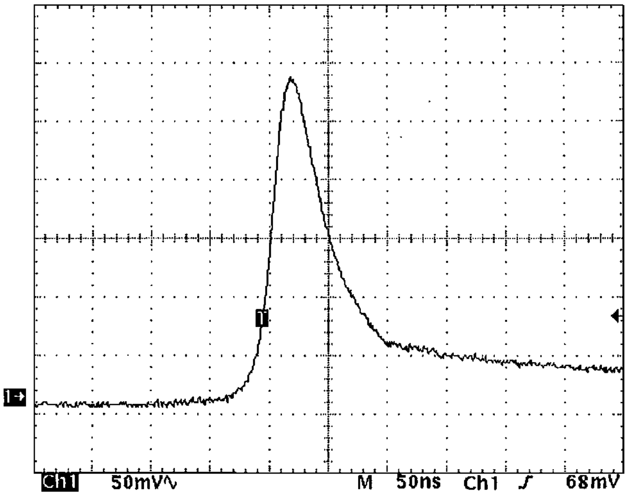

Fig. 3. Oscilloscope trace of the self-Q-switched Cr,Nd:YAG laser, with a FWHM duration of 50 ns.

pulse shape with output energy of 5 μJ and a FWHM duration of 50 ns. The peak power is estimated to be 100 W.

Figure 4 shows the output power versus input pump power of the self-Q-switched Cr,Nd:YAG laser. The performance of the self-Q-switched laser was corrected for Fresnel losses. From Fig. 4 we can see that the threshold pump power is approximately 3.5 W, and the slope efficiency is as high as 20% when the input pump power is less than 10.8 W. When the input power is greater than 11 W, the output power drops dramatically; this may be caused by thermal-lens effects and aberrations between the thermal lens and the pump beam. The origin of thermal lensing in a solid is the nonuniform change in refractive index that is induced in the sample as it is traversed by a laser beam, as well as the physical expansion of the sample faces. Both of these effects result in a position-dependent change in the optical path length of the beam as it traverses the materials. In Cr,Nd:YAG laser gain media, there is nonradiative relaxation from the pump bands to the upper metastable level and from the lower laser level to the ground state. There is also nonradiative relaxation from nonradiative sites, which are Nd^{3+} ions that absorb pump photons but do not contribute to inversion,[13,14] and nonradiative relaxation that is due to concentration quenching. The quantum defect (the difference between the pump and the laser photon energies) is the primary source of heating, and thus laser materials with a smaller difference between the pump wavelength and the laser output wavelength may be expected to be heated less as long as effects such as nonradiative sites, concentration quenching, excited-state absorption, and upconversion are weak. Nd:YAG lasers are pumped at 0.81 μm and oscillate at 1.06 μm, which has a bigger difference between the pump and the laser output wavelengths than Yb:YAG, so the efficient way to lessen thermal lensing is to choose gain media that generate less heat. There is also another absorption process that can heat the crystal without contributing to pumping of the $^4F_{3/2}$ level of the Nd ions: absorption by impure atoms, which do not transfer their energy to Nd ions. In particular, there are Cr ions in Cr,Nd:YAG crystal, so the absorption of Cr^{4+} ions can have a great effect on heat generation in Cr,Nd:YAG crystal. There are other impurities such as OH$^-$, CR^{3+}, and CA^{2+}in Cr,Nd:YAG crystal, and the efficient way to reduce the heat generated in Cr,Nd:YAG crystal is to grow high-quality Cr,Nd:YAG crystal with minimal defects. At the same time, the alignment of the pump beam and the focal lens has a great influence on the heat generated in laser media.[15] This work is in progress. We expect to get better laser output data by improving the focal-lens system and growing high-quality Cr,Nd:YAG crystals. Although Q-switched lasers generally have larger intensity fluctuations, we have found that the Q-switched pulse amplitude is extremely stable. The pulse-to-pulse intensity fluctuation is less than the instrument resolution of 0.25%, which merely reflects the small fluctuation of the baseline of the oscilloscope traces. This unprecedented stability is attributed to the stable pump beam of the diode laser and to the cavity's being free from mechanical vibrations. No deterioration in intensity stability was detected over a continuous 3-h testing period.

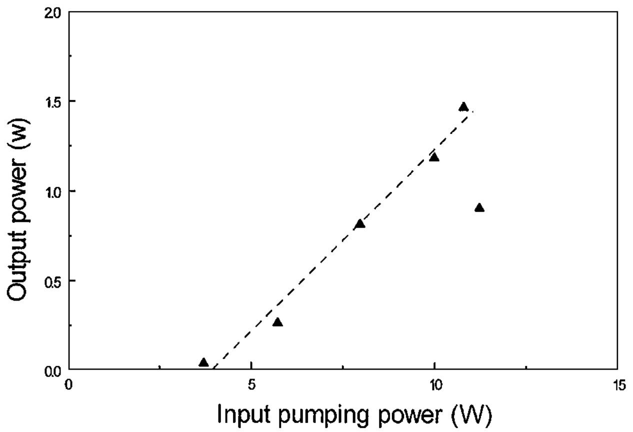

Fig. 4. Relation between the output power and the input pump power. The dashed line is the best fit to the experimental points when input power is less than 10.8 W. The output power dropped dramatically when the input power was greater than 11 W because of thermal-lens effects.

During the Q-switched laser experiment, the pulse width remains constant with variation of the input pump power, and the pulse repetition rate varies with the variation of the input pump power; with increasing pump power, the pulse repetition rate increases, as was reported by Zayhowski and Dill.[3] The pulse width of passively Q-switched laser is determined by the saturable-absorber parameters.[16] The reason that the pulse width remains constant with increasing pump power is due to the dependence of the pulse width on the parameters of the saturable absorber Cr^{4+} in Cr,Nd:YAG crystal; the saturable absorber used here is fully bleached by the pulse energy. By changing the saturable-absorber concentration in YAG crystal, we can vary the modulation depth, and an appropriate pulse width can be achieved. We also found that the Q-switched laser pulse is linearly polarized along either of the mutually orthogonal axes, with an extinction ratio of 200:1. By rotation of the polarization of the pump beam, the laser's polarization between the two axes is switched. The crystal used in this experiment exhibits neither birefringence nor anisotropic transmission for low levels of light intensity. The polarized laser output of Cr,Nd:YAG is probably caused by the existence of a finite number of laser modes, owing to the short laser resonator length, and the high Q value resulting from anisotropy in the saturation power of the absorber-induced[17] passive Q switch lets the stronger mode oscillate preferentially. Although polarized output of Nd:YAG lasers with Cr^{4+}:YAG as a saturable absorber has been reported,[18,19] Yankov[18] attributed this polarization to the resonator alignment and gave no detailed explanation for it. According to Ref. 17, there is anisotropic behavior after the onset of saturation, which leads to polarized output of passively Q-switched Nd:YAG lasers with Cr^{4+}:YAG as a saturable absorber.

In conclusion, by use of a LD as a pump source, self-Q-switched lasing from a Cr,Nd:YAG crystal is demonstrated, and the output Q-switched traces are found to be very stable. The threshold pump power is 3.5 W, the pulse duration is 50 ns, and the slope efficiency is as high as 20%. In addition, the pulse width remains constant, and the pulse repetition rate varies with the pump power. By improving the focal-lens system of the LD source and the growth of high-quality Cr,Nd:YAG crystals, we expect to get better laser output data in the future. This improvement may lead to the development of LD-pumped monolithic self-Q-switched solid-state lasers.

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References

1. W. Kochner, *Solid State Laser Engineering,* 3rd ed. (Springer-Verlag, Berlin, 1992), Chap. 8.
2. J. A. Morris and C. R. Pollock, Opt. Lett. **15,** 440 (1990).
3. J. J. Zayhowski and C. Dill III, Opt. Lett. **19,** 1427 (1994).
4. P. Wang, S. H. Zhou, K. K. Lee, and Y. C. Chen, Opt. Commun. **114,** 439 (1995).
5. I. Freitag, A. Tunnermann, and H. Welling, Opt. Lett. **22,** 706 (1997).
6. Y. Bai, N. Wu, J. Zhang, J. Li, S. Li, J. Xu, and P. Deng, Appl. Opt. **36,** 2468 (1997).
7. H. Liu, S. Zhou, and Y. C. Chen, Opt. Lett. **23,** 451 (1998).
8. M. I. Demchuk, V. P. Mikhailov, N. I. Zhavoronkov, N. V. Kuleshov, P. V. Prokoshin, K. V. Yumashev, M. G. Livshits, and B. I. Minkov, Opt. Lett. **17,** 929 (1992).
9. W. Chen, K. Spariosu, and R. Stultz, Opt. Commun. **104,** 71 (1993).
10. Y. K. Kuo, M. F. Huang, and M. Birnbaum, IEEE J. Quantum Electron. **31,** 657 (1995).
11. N. B. Angert, N. I. Borodin, V. M. Garmash, V. A. Zhitnyuk, A. G. Okhrimchuk, O. G. Siyuchenko, and A. V. Shestakov, Sov. J. Quantum Electron. **18,** 73 (1988).
12. V. Petricevic, S. K. Gayen, and R. R. Alfano, Appl. Phys. Lett. **53,** 2590 (1988).
13. D. P. Devor and L. G. DeShazer, Opt. Commun. **46,** 97 (1983).
14. D. P. Devor, L. G. DeShazer, and R. C. Pastor, IEEE J. Quantum Electron. **25,** 1863 (1989).
15. B. Bendow and P. D. Gianino, Appl. Phys. **2,** 1 (1973).
16. B. Braun, F. X. Kärtner, G. Zhang, M. Moser, and U. Keller, Opt. Lett. **22,** 381 (1997).
17. H. Eilers, K. R. Hoffman, W. M. Dennis, S. M. Jacobsen, and W. M. Yen, Appl. Phys. Lett. **61,** 2958 (1992).
18. P. Yankov, J. Phys. D **27,** 1118 (1994).
19. Y. Shimony, Z. Burshtein, A. B. Baranga, Y. Kalisky, and M. Strauss, IEEE J. Quantum Electron. **32,** 305 (1996).