Performance of the Self-Q-Switched Cr,Yb:YAG Laser *

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We report on the spectral properties of Cr,Yb:YAG crystal co-doped with 0.025 at.% Cr and 10 at.% Yb are reported. Using a continuous wave Ti:sapphire laser as a pumping source, we have demonstrated the self-Q-switched Cr,Yb:YAG laser at room temperature. We obtained an average output power as much as 75 mW at 1.03 μm with a pulse width (FWHM) as short as 0.4 μs. The laser experiment demonstrated that the Cr,Yb:YAG crystal exactly combines the Cr^{4+} saturable absorber and Yb^{3+} gain medium. The Cr,Yb:YAG crystal can be a most promising self-Q-switched laser crystal for compact and efficient solid-state lasers.

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Passive Q-switching of solid-state lasers is usually accomplished with organic dyes or colour centres as the saturable absorber. Dyes,[1] however, have poor thermal stability and tend to degrade rapidly. To operate in continuous wave (cw) pumped lasers, dyes require a circulation system. Colour centres, such as the colour-centre LiF crystal,[2] exhibit a fading phenomenon. Recently, the chromium-doped host crystals, such as YAG,[3] GSGG,[4] and forsterite,[5] have been used as passive Q-switches for Nd^{3+}-doped crystal solid-state lasers. When YAG and GSGG host crystals are co-doped with Nd and Cr, the functions of the gain medium and the saturable absorber are combined. This result has led to the self-Q-switched operation.[3,6] Compared to Nd ions in laser crystals, the Yb ion matches diode pumping ideally since it has a very simple energy level scheme with desirable properties for a laser system. Yb:YAG has a long storage lifetime (951 μs)[7] and a very low quantum defect (8.6%), resulting in heat generation during lasing which is three times less than comparable Nd-based laser systems.[8] In addition, the absorption at 940 nm makes this material highly suitable for diode pumping using InGaAs diodes which are potentially more robust than AlGaAs diodes used to excite Nd:YAG at 808 nm.[9] Another advantage of using Yb:YAG is that the 940 nm absorption feature is approximately five times broader than the 808 nm absorption feature in Nd:YAG and therefore the Yb:YAG system is less sensitive to diode wavelength specifications.[10] Thus, the Cr–Yb co-doped YAG crystal has been grown and the absorption and luminescence spectra have been reported.[11,12]

Here, for the first time to our knowledge, we report on a self-Q-switching operation in a Cr,Yb:YAG laser pumped by a Ti:sapphire laser. By using the laser host crystal YAG co-doped with saturable absorber Cr^{4+}, the function of the gain medium Yb^{3+} and the saturable absorber Cr^{4+} are combined into one. This can lead to the development of monolithic Q-switched solid-state lasers.

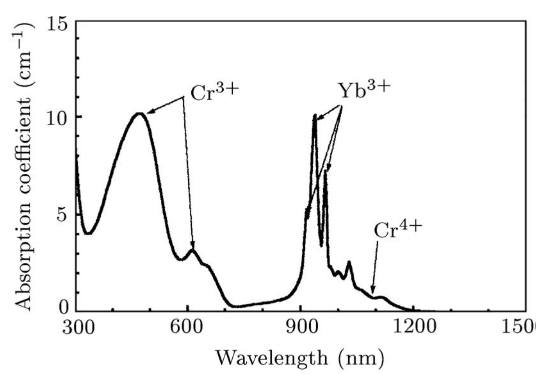

Fig. 1. Room-temperature absorption spectrum of the Cr,Yb:YAG crystal co-doped with 0.025 at.% Cr and 10 at.% Yb.

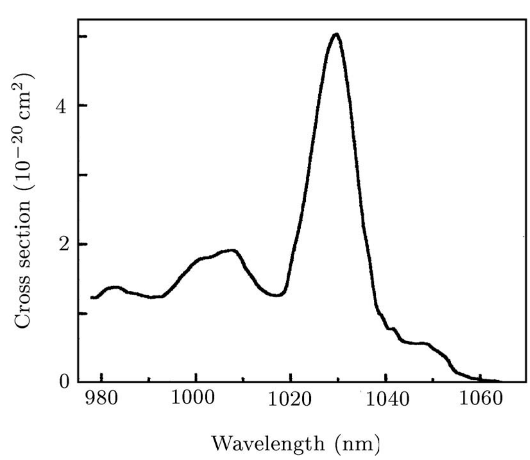

Fig. 2. Emission spectrum of the Cr,Yb:YAG crystal co-doped with 0.025 at.% Cr and 10 at.% Yb at room temperature.

The room-temperature absorption spectrum of Cr,Yb:YAG co-doped with 0.025 at.% Cr and 10 at.% Yb is shown in Fig. 1. The broad absorption bands centered at 440 nm and 605 nm are attributed to the $^4A_2 \rightarrow {}^4T_1$ and $^4A_2 \rightarrow {}^4T_2$ transitions of Cr^{3+} ions,

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the absorption feature in the visible region is similar to that of Cr:YAG.[13] The absorption bands centred at 913, 940 and 968 nm are attributed to the $^2F_{7/2} \rightarrow {}^2F_{5/2}$ transition of Yb^{3+}. The absorption band centred at 1.064 μm is believed to be caused mainly by the $^3A_2 \rightarrow {}^3T_1$ transition of Cr^{4+} ions. The absorption band of Cr^{4+} has a full width at half maximum (FWHM) of ~250 nm so that an appreciable absorption exists near the 1.03 μm line of Yb:YAG. There is also an absorption peak at 1.03 μm of the absorption of Yb^{3+}. The absorption coefficient is 10.05 cm^{-1} at the pumping wavelength of 940 nm and it is 1.1 cm^{-1} at 1064 nm. The absorption coefficient is 2.61 cm^{-1} at the lasing wavelength of 1.03 μm which is higher than that of 1.064 μm for the existence of Yb^{3+} at 1.03 μm, so that the absorption coefficient of Cr^{4+} near 1.03 μm is approximately 1.1 cm^{-1}. Using 968 nm LD as the pump source, the measured fluorescence spectrum of the Cr,Yb:YAG crystal co-doped with 0.025 at.% Cr and 10 at.% Yb is from 980 to 1055 nm (Fig. 2), the strong emission peak centred at 1030 nm is attributed to the $^2F_{5/2} \rightarrow {}^2F_{7/2}$ transition of Yb^{3+}, and the emission cross section of the Cr,Yb:YAG crystal is greater than that of the Yb:YAG crystal ($(5.5\pm0.5)\ 10^{-20}\ cm^2$ for the Cr,Yb:YAG crystal co-doped with 0.025 at.% Cr and 10 at.% Yb and $2.0 \times 10^{-20}\ cm^2$ for the 10 at.% Yb:YAG crystal). However, the fluorescence lifetime of the Cr,Yb:YAG crystal is shorter than that of the Yb:YAG crystal (520 μs versus 951 $\pm$ 15 μs).

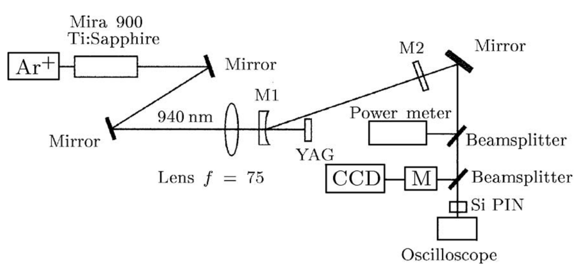

Fig. 3. Schematic diagram of the Cr,Yb:YAG self-*Q*-switched laser pumped by a Ti:sapphire laser: M1 and M2 are cavity mirrors, M is a monochromator, and CCD is a charge-coupled device array.

The set-up of the Ti:sapphire laser-pumped Cr,Yb:YAG crystal self-*Q*-switched laser is shown in Fig. 3. The Mira 900 tunable Ti:sapphire laser with an output power up to 1 W was used as a pump source. The optical pump system was composed of a spherical lens (= 75 mm) for focusing the pump beam to a circular spot with a diameter of about 50 μm. After the focusing system, the pumping power was measured to be up to 920 mW. The laser cavity was configured to be semispherical, and was formed by the 50 mm curvature radius mirror M1 and the flat mirror M2. One face of mirror M1 was coated for high transmission (HT) at 940 nm and the other was coated for HT at 940 nm and total reflection (TR) at 1.03 μm. Mirror M1 was placed in front of the input facet of the Cr,Yb:YAG crystal. The Cr,Yb:YAG crystal was polished to a planar–planar geometry. One surface of the $10 \times 10 \times 1\ mm^3$ Cr,Yb:YAG laser crystal was HT-coated at 940 and 1030 nm, the other surface of the crystal was TR-coated at 940 and 1030 nm. Mirror M2 was TR-coated at 940 nm and had a reflectivity of 97% at 1.03 μm acting as an output coupler. The overall cavity length was 23 cm. More than 90% of the laser pumping power was absorbed by the Cr,Yb:YAG crystal. The laser operation was performed at 278 K by using a thermostat. The *Q*-switched pulses were recorded using a fast Si PIN detector with a 1.5 ns rise time and a Tektronix TDS 380 digitizing oscilloscope with a 400 MHz sampling rate in the single-shot mode. The output power was measured using a laser power meter.

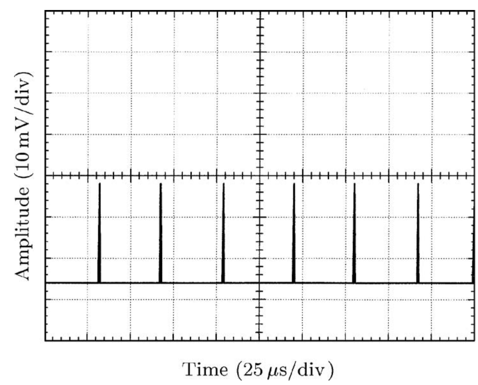

Fig. 4. Oscilloscope trace of a train of self-*Q*-switched pulses.

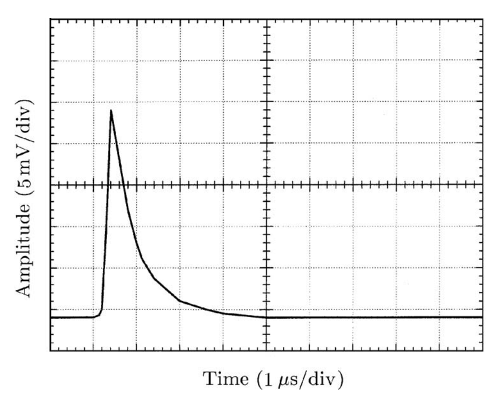

Fig. 5. Oscilloscope trace of a single *Q*-switched pulse with a pulse duration of 400 ns.

First, we performed the laser experiment with Cr,Yb:YAG crystal co-doped with 0.1 at.% Cr and 10 at.% Yb[11,12] as the laser gain medium using the laser set-up shown in Fig. 3, but we did not obtain the laser output. This might be because the absorption of the highly doped Cr^{4+} caused the oscillation of Yb^{3+} ions in the laser cavity to be suppressed. From the above results, we think that the reduction of Cr in Cr,Yb:YAG is necessary for the performance of the self-*Q*-switched laser. The Cr,Yb:YAG crystal co-doped with 0.025 at.% Cr and 10 at.%Yb was grown.

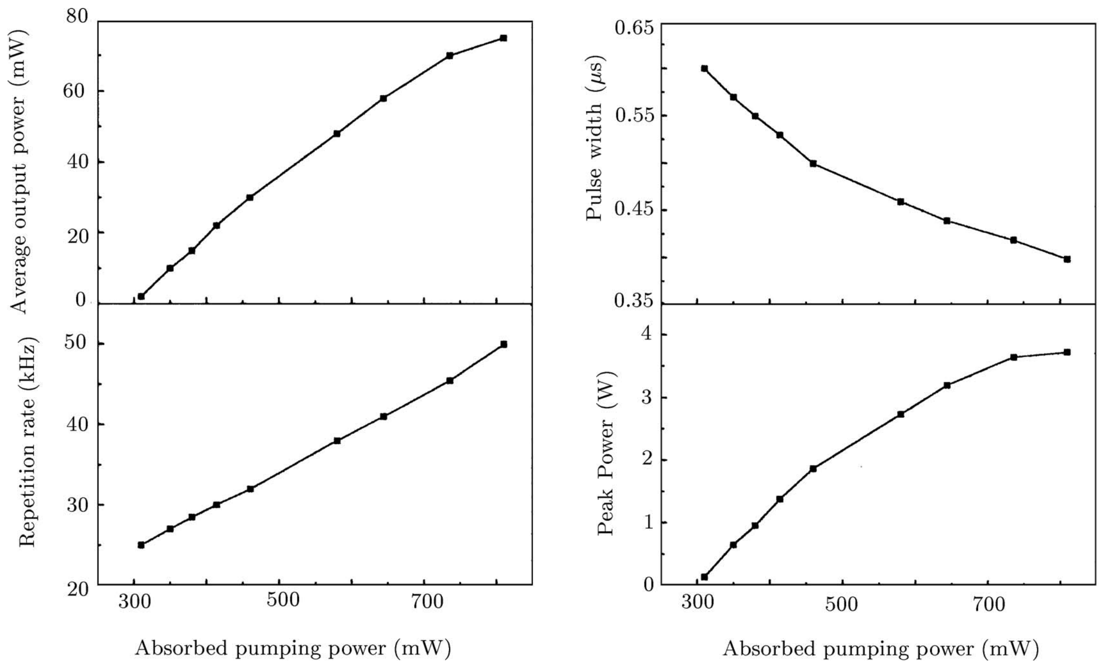

Fig. 6. Average output power, repetition rate, pulse width and peak power as functions of the absorbed pumping power for the Cr,Yb:YAG self-Q-switched laser.

The initial transmission at 1.03 μm of the Cr^{4+} saturable absorber in the Cr,Yb:YAG crystal co-doped with 0.025 at.% Cr and 10 at.% Yb was 90%. When the Cr,Yb:YAG crystal co-doped with 0.025 at.% Cr and 10 at.% Yb was used as the gain medium, we obtained the self-Q-switched laser. Figure 4 shows a typical self-Q-switched pulse train; the amplitudes of the pulses are very stable. Figure 5 shows a typical self-Q-switched pulse with an energy of 1.5 μJ and a FWHM of 0.4 μs. The average output power, repetition rate and pulse width were measured as functions of the pump power. The pulse energy was determined from the average output and the repetition rate. The peak power was determined from the pulse energy and the pulse width. We obtained the 1.5 μJ pulse with a pulse width of 0.4 μs, resulting in a peak power of 3.75 W at a repetition rate of 50 kHz at 810 mW absorbed pumped power (Fig. 6). The threshold for self-Q-switched operation was about 300 mW of absorbed pumped power with an output coupler of 3%. The slope efficiency was 15%. The maximum average output power was 75 mW when the absorbed pumping power was 810 mW. A spectral width (FWHM) of the self-Q-switched Cr,Yb:YAG laser output was measured as approximately 1 nm. The average output power increased slowly with the increasing pumping power when the input power was greater than 750 mW. The fact that the pumping threshold is higher than that of a Yb:YAG laser is due to the absorption of Cr^{4+} in the laser wavelength of Yb^{3+} at 1.03 μm. Compared with Yb:YAG lasers, the lower slope efficiency may be caused by the concentration ratio of Cr/Yb in the Cr,Yb:YAG crystal. The absorption of Cr^{4+} is too high to limit the output power of Yb^{3+}. It is vital to select a suitable Cr/Yb ratio in order to obtain high efficiency and high power for the Cr,Yb:YAG laser. The laser cavity is too long to obtain a short pulse width.

In conclusion, the operation of a Ti:sapphire laser-pumped Cr,Yb:YAG self-Q-switched laser has been demonstrated, for the first time to our knowledge, at room temperature. By optimizing the Cr/Yb ratio in the crystal, increases in the output power and conversion efficiency are expected. The Cr,Yb:YAG crystal provides another potential self-Q-switching laser medium for compact, efficient, and solid-state lasers.

References

[1] Kochner W 1992 *Solid State Laser Engineering* 3rd edn (Berlin: Springer-Verlag) chap 8 p 437

[2] Morris J A and Pollock C R 1990 *Opt. Lett.* **15** 440

[3] Stokowski S E, Randles M H and Morris R C 1988 *IEEE J. Quantum Electron.* **24** 934

[4] Danilov A A, Evstigneev V L, Il'ichev N N, Malyutin A A, Nikol'shii Y M, Umyskov A F and Shcherbakov I A 1987 *Sov. J. Quantum Electron.* **17** 573

[5] Demchuk M I, Mikhailov V P, Zhavoronkov N I, Kuleshov N V, Prokoshin P V, Yumashev K V, Livshits M G and Minkov B I 1992 *Opt. Lett.* **17** 929

[6] Zhou S, Lee K K and Chen Y C 1993 *Opt. Lett.* **18** 511

[7] Sumida D S and Fan T Y 1994 *Opt. Lett.* **19** 1343

[8] Fan T Y 1993 *IEEE J. Quantum Electron.* **29** 1457

[9] Yellin S L, Shepard A H, Dalby R J, Baumaum J A, Serreze H B, Guide T S, Solarz R, Bystrom K J, Harding C M and Walters R G 1993 *IEEE J. Quantum Electron.* **29** 2058

[10] Bruesselbach H W, Sumida D S, Reeder R A and Byren R W 1997 *IEEE J. Sel. Top. Quantum Electron.* **33** 105

[11] Dong J, Deng P and Xu J 1999 *J. Cryst. Growth.* **203** 163

[12] Dong J, Deng P and Xu J 1999 *Opt. Commun.* **170** 255

[13] Angert N B, Borodin N I, Garmash V M, Zhitnyuk V A, Okhrimchuk A G, Siyachenko O G and Shestakov A V 1988 *Sov. J. Quantum Electron.* **18** 73