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A diode-pumped, self-starting, all-solid-state self-mode-locked Cr:LiSGAF laser

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Abstract

In this paper, a self-starting, diode-pumped self-mode-locked Cr:LiSGAF laser, which produced a stable pulse train of 45 fs duration with about 20 mW-average power at the repeated rate of 90 MHz, was presented. Self-mode-locked operation can be obtained whether there is the semiconductor saturable absorber mirror (SESAM) in the Cr:LiSGAF laser cavity or not, and with the SESAM in the cavity, the self-mode-locked operation could self-start. The shortest pulses, as short as 38 fs, which were not very stable, were obtained with the SESAM in the cavity.

Keywords: All solid-state laser; Cr:LiSGAF; Self-starting; SESAM

There has been a remarkable progress on ultrafast solid-state lasers after the Kerr-lens mode-locking technique for solid-state lasers was exploited in the early 1990s, and this kind of femtosecond lasers is widely used in many research areas. For example, femtosecond OCT [1,2], TeraHz generation and imaging [3,4], Ultrashort laser pulses tackle precision machining [5], etc. At the same time, requirements for femtosecond lasers become higher and higher. The all-solid-state femtosecond lasers, such as self-mode-locked Cr:LiSAF lasers and Cr:LiSGAF lasers, have the characteristics of compactness, small volume, high-efficiency and long lifetime, etc., and exactly meet these requirements. The research on all-solid-state lasers is also one of the highlight in the area of ultrafast laser. Till now, output pulses shorter than 20 fs have been obtained from the krypton-laser-pumped self-mode-locked Cr:LiSAF or Cr:LiSGAF lasers with the double-chirped mirrors in the cavity [6–8], but the shortest pulses were longer than 40 fs from the diode-pumped all-solid-state self-mode-locked lasers without chirped mirrors and with the SESAM. We have reported femtosecond self-mode-locked operation of an argon-ion laser pumped Cr:LiSAF laser and Cr:LiSGAF laser [9,10]. In this letter, we report a diode-pumped, all solid-state femtosecond self-mode-locked operation of Cr:LiSGAF laser with a tighter pump lens compared to the conventional focal length of the pump lens, from which we obtained self-mode-locked operation and self-stating self-mode-locked operation without and with the semiconductor saturable absorber mirror (SESAM), respectively. As a result, the Cr:LiSGAF laser produced a very stable pulse train of 45 fs-pulse-width with about 20 mW-average power at the repeated rate of 90 MHz. The shortest pulses, as short as 38 fs, which were not very stable, were obtained with the SESAM and without the chirped mirrors in the cavity in our experiment.

Fig. 1 shows the structure of the self-mode-locked Cr:LiSGAF laser pumped by two diodes from two opposite directions. Since self-mode-locked operation is the result of combination of the Kerr-lens effect and the gain aperture in the gain medium, collimating of the output beam of the diodes is very important. In the experiment, the optical system to collimate the diode beams is shown in Fig. 1. L_0 is a collimating objective of 8 mm-focal length. L_1 and L_2 are cylindrical lenses of focal lengths of 100

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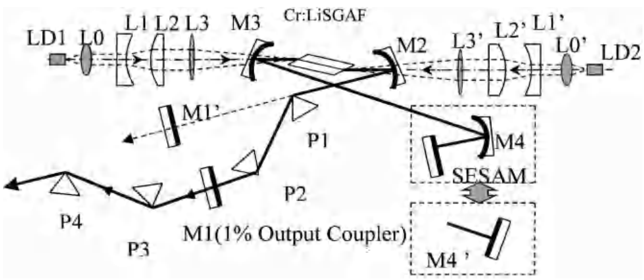

Fig. 1. Schematic of the diode-pumped self-mode-locked Cr:LiSGAF laser.

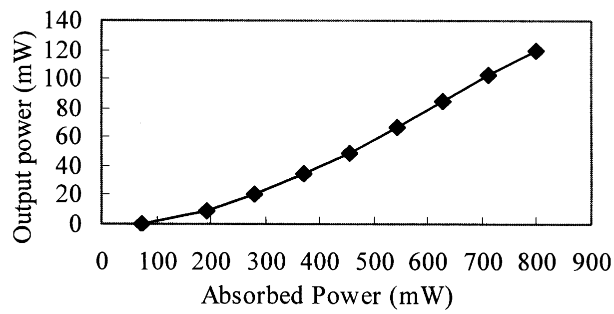

Fig. 2. Variation of output power with absorbed pump power for CW Cr:LiSGAF laser with the 1% output coupler.

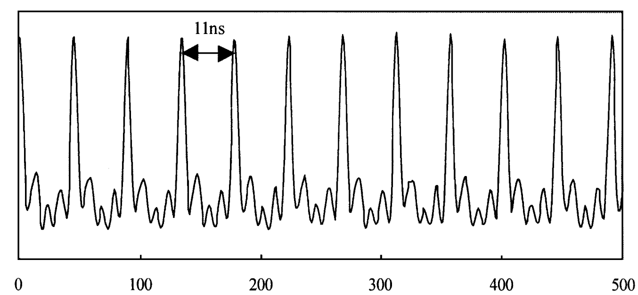

Fig. 3. Pulse train of the self-mode-locked Cr:LiSGAF laser.

and 150 mm, respectively, which were used to compress the divergence angles of the diode laser beams in the tangential plane. L_3 is a pump lens of 75 mm-focal length. A X-style four-mirror astigmatism-compensated folded cavity was used for the Cr:LiSGAF laser in our experiment. The Cr:LiSGAF crystal, which was doped with a Cr^{3+} concentration of 2.5% by weight, was Brewster-angle cut and of 5 mm-path-length. In the astigmatism-compensated cavity, M_3, M_2, M_4 are all spherical reflecting mirrors with a curvature-radius of 100 mm. M_1 and M_1' are output couplers of 1% transmission. M_4' is a high-reflection flat mirror, and was used in the cavity when the SESAM was not inserted. P_1, P_2 were fused silica prisms were used to compensate the intracavity second-order dispersion. The total length of the cavity was about 165 cm, and the astigmatism-compensated angle is about 13°. When the self-mode-locked operation was obtained, a home made real-time interferometric autocorrelator and a spectrum analyzer were used to monitor the pulse-width and the spectrum, respectively.

At first, we examined CW operation, and the M_4' was used to replace M_4 and the SESAM, the prisms P_1, P_2 were removed away from the cavity and M_1' was used as the output coupler. As a result, a threshold of 75 mW-pump power was obtained. When the output power of the two diodes was maximized (500 mW for each diode), 800 mW power of 670 nm laser was absorbed by the Cr:LiSGAF crystal, a maximum output power of 120 mW was achieved. Fig. 2 showed variation of the output power with the absorbed pump power, indicating a maximum efficiency of 15% and a slope efficiency of 18.5%.

On the basis of the above CW experiment, after inserting the prism pair in the cavity, the CW output power was reduced to about 80 mW from 120 mW. By carefully adjusting the state of the laser cavity to be more suitable for the self-mode-locked operation, and by inserting a slit, near mirror M_1 and an aperture near mirror M_4 in the cavity, we obtained a CW output of about 40 mW. At that time, disturbing one of the flat mirrors or one of the prisms would start the self-mode-locked pulse train, the average output power became 45 mW, slightly higher than that of CW operation. Fig. 3 shows the pulse train observed from an oscilloscope. Although the pump beams from the diodes were reshaped and collimated, they were not as high quality as the argon-ion laser beam or the diode-pumped 532 nm green laser beam. Consequently, the pulse train from the diode-pumped self-mode-locked Cr:LiSGAF laser was not as stable as that from self-mode-locked solid-state lasers pumped by argon-ion lasers, and the sustaining time of the pulse train was not as long as that of the lasers pumped by argon-ion lasers either.

For the reasons above, we inserted a broadband semiconductor saturable-absorber mirror (SESAM) [11] in the Cr:LiSGAF laser cavity, as shown in Fig. 1. The average output power was reduced to almost half of the original value because of the loss of 1–2% due to the SESAM. Carefully changing the position of SESAM, we obtained the self-starting self-mode-locking operation of the Cr:LiSGAF laser, and the average power of the pulse train was about 20 mW. In the experiment, the shortest stable pulse duration was 45 fs. Fig. 4 shows the interferometric autocorrelation trace and the corresponding spectrum of the pulse train. The time-bandwidth product was $\Delta\nu \cdot \Delta\tau = 0.33$, close to the Fourier-transform limit. Pulses as short as 38 fs were also obtained with the SESAM and without chirped-mirrors, but they were not very stable due to the central absorbed wavelength of the SESAM, and we are presently improving the SESAM.

What should be pointed out is that the alignment of a diode-pumped self-mode-locked Cr:LiSGAF or Cr:LiSAF laser is much more difficult than that of a Ti:sapphire laser pumped by an argon-ion laser or a diode-pumped 532 nm green laser. There are two key factors: the first is that the nonlinear refractive index n_2 of Cr:LiSGAF or Cr:LiSAF crystals is smaller than that of the Ti:sapphire crystal, and

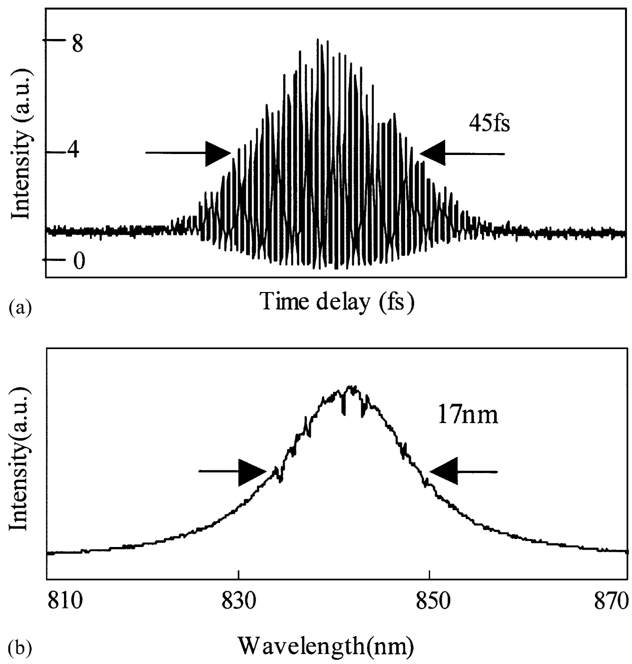

Fig. 4. (a) Interferometric autocorrelation and (b) associated spectrum of the pulse train from the Cr:LiSGAF laser.

so the Kerr-lens effect in the Cr:LiSGAF or Cr:LiSAF crystals as the laser beam passed through the gain medium is relatively weaker, consequently, it is not very easy to mode-lock a Cr:LiSGAF or Cr:LiSAF laser. Secondly, the qualities of the beams directly from semiconductor diodes are too poor, although they could be reshaped and collimated with optical systems. Their qualities (i.e. divergence angle, radius of the beam, intensity distributing across the beam cross-section, etc.) are not comparable to that of the argon-ion laser or 532 nm green laser beam quality yet. As a result, the gain aperture formed in the gain medium (Cr:LiSGAF or Cr:LiSAF crystal) does not work as well as that in the Ti:sapphire crystal. Therefore, a SESAM is needed to compensate for these defects.

In conclusion, we obtained self-starting, self-sustaining, self-mode-locked operation of a Cr:LiSGAF laser, which produced a stable pulse train of 45 fs with about 20 mW-average power at a repetition of 90 MHz, by using the semiconductor saturable absorber mirror to start the self-mode-locking. Pulses as short as 38 fs were also obtained in the experiment.

Acknowledgements

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