Self-mode-locked Cr:forsterite laser

Y. Pang,* V. Yanovsky,† and F. Wise

Department of Applied Physics, Cornell University, Ithaca, New York 14853

B. I. Minkov

Institute for Single Crystals, Ukraine Academy of Sciences, Kharkov 310141, Ukraine

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We have demonstrated self-sustaining operation of a mode-locked chromium-doped forsterite laser in which short-pulse formation is entirely due to the nonlinearity of the laser crystal. Stable pulse trains are generated for intracavity pulse energies from 35 to 120 nJ. Pulses less than 100 fs in duration are obtained over the range of 1.23–1.28 μm, with a maximum average output power of 700 mW for 9 W of pump power.

Since the first report of self-mode locking of a titanium-doped sapphire (Ti:sapphire) laser,[1] there has been much interest in applying this technique to other solid-state laser materials. In parallel with this, there has been a resurgence of interest in the development of solid-state media.[2] One such material that has attracted much attention recently is chromium-doped forsterite (Cr^{4+}:Mg_2SiO_4; Cr:forsterite). In addition to its high efficiency and output power capabilities when pumped by a Nd:YAG laser, Cr:forsterite is of interest owing to its broad wavelength tunability near 1.25 μm and its potential for generation of ultrashort pulses. The first report of mode locking of a Cr:forsterite laser, in which actively mode-locked operation resulted in the production of picosecond pulses, was by Seas *et al.*[3] An additive-pulse mode-locked Cr:forsterite laser, operating at 77 K and producing as much as 60 mW of power,[4] generated 150-fs pulses. Recently, pulses as short as 60 fs were obtained with an actively mode-locked laser producing 85 mW of average power.[5] A regeneratively mode-locked version produces pulses as short as 48 fs and extends this performance to average powers as high as 380 mW.[6] A synchronously pumped Cr:forsterite laser generated 105-fs pulses with an output power of 45 mW.[7]

The femtosecond pulses produced by active mode locking and synchronous pumping are much shorter than expected theoretically. Seas *et al.* suggest that the Kerr nonlinearity of the gain medium, together with negative group-delay dispersion from an intracavity prism pair, is responsible for production of the shortest pulses.[5] This explanation seems probable based on previous research with self-mode-locked solid-state lasers. The acousto-optic mode locker in the cavity simply provides gain modulation in the initial stages of pulse formation. After the pulses build up to the level at which Kerr nonlinearities in the gain medium are significant, intracavity self-phase modulation and dispersion compensation will support solitonlike pulse formation. In fact, sub-100-fs pulses were observed for as long as 30 s after the rf power to the acousto-optic modulator was disconnected.[5] This was taken as an indication that the Cr:forsterite laser was operating in a self-mode-locked regime, similar to that of Ti:sapphire lasers. Since the nonlinearity and dispersion of Cr:forsterite are unknown, the lack of long-term mode-locking stability hinders a better understanding of the mode locking in Cr:forsterite.

In this Letter we report the generation of 100-fs pulses from a stably self-mode-locked Cr:forsterite laser. The laser produces average powers as high as 700 mW near 1.25 μm, and operation is self-sustaining for hours without an intracavity modulator. The operating and performance parameters of this laser are similar to those of a self-mode-locked Ti:sapphire laser.

The laser resonator is shown schematically in Fig. 1 and is essentially identical to that commonly used for Ti:sapphire lasers. The four-mirror cavity has an X fold for the Cr:forsterite crystal, which is Brewster cut and 20 mm in length. The crystal was grown by the Czochralski method with preferential localization of lasing centers, Cr^{4+}, doped at a level of 0.15% by atomic weight, resulting in a figure of merit $\alpha(1.06\ \mu m)/\alpha(1.2\ \mu m)$ estimated to be ~30.[8] The crystal is mounted in a copper clamp attached to a single-stage thermoelectric cooler that maintains the temperature at 1.0 ± 0.2 °C. A thin layer of indium foil was used between the crystal and the copper

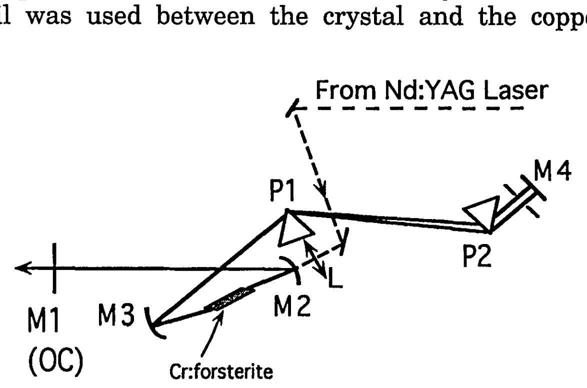

Fig. 1. Schematic of the self-mode-locked Cr:forsterite laser: M's, mirrors; OC, output coupler; P1, P2, intracavity prisms; L, lens.

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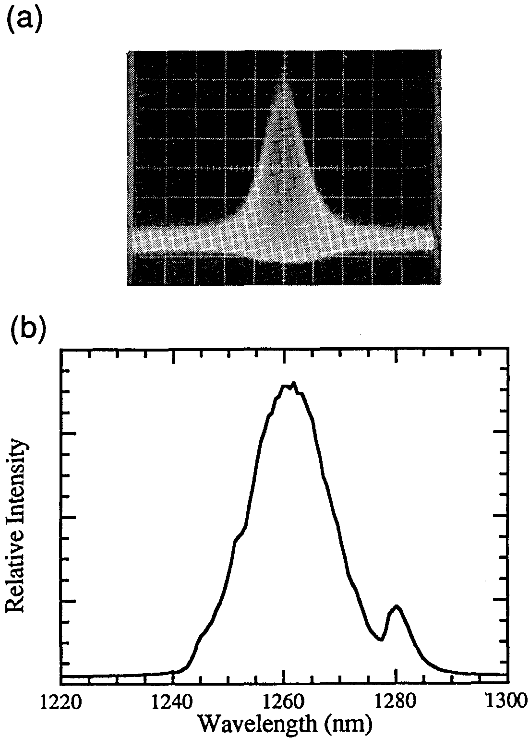

Fig. 2. (a) Measured interferometric autocorrelations, (b) laser spectrum.

clamp to ensure good thermal contact. The mirrors for the gain fold have radii of 10 cm, and the crystal is pumped by as much as 9 W of power from a Nd:YAG laser operated in TEM_{00} mode. The pump beam is focused through a cavity mirror by a lens with a focal length of 88 mm, and the crystal absorbs 80% of the pump power. Both the end high reflector and the output coupler are flat, and the output coupler has 7.5% transmission centered at 1.25 μm. Based on the parameters provided in Refs. 5 and 6, and allowing for the longer crystal in our laser, we use two Schott SF-14 prisms separated by 65 cm to control dispersion in the cavity.

The laser is first aligned to operate cw with a TEM_{00} transverse mode. Under these conditions, the laser has no tendency to pulse, and thus there is no evidence for mode beating. With a slight misalignment of the cavity from TEM_{00} mode, the tendency to pulse is immediately evident on a fast photodiode that monitors the output beam. Mode locking can then be initiated with a moderate mechanical perturbation, such as tapping an end mirror. This alignment technique is commonly used in self-mode-locked Ti:sapphire lasers.[1,9,10] By projecting the expanded output beam onto a screen, we observe the transverse mode of the laser in mode-locked operation to be near TEM_{00}. A slit at the dispersive end of the resonator is used for wavelength tuning and is not required for mode locking. The pulse repetition rate is 80 MHz. As is the case with Ti:sapphire, the self-mode-locked Cr:forsterite laser is generally not self-starting. Similar to what we experienced with Ti:sapphire lasers, spontaneous self-starting at high intracavity power levels (>8 W for Cr:forsterite) is occasionally observed. For intracavity powers below 2 W, stable mode-locked pulse trains are not produced. Between 2 and 2.7 W of power, a pulse train is generated but is sustained for less than 1 min. Mode-locked operation is self-sustaining for intracavity powers above 2.7 W, which corresponds to 200 mW of output power. Stable pulse trains are produced with intracavity powers as high as 9.4 W, which corresponds to 700 mW of output power. At higher intracavity powers, we observe mode-locked operation and higher output powers, but the stability of the pulse train is degraded by the appearance of cw components in the oscillating spectrum. The range of intracavity power levels (2.7–9.4 W, or pulse energies of approximately 35–120 nJ) for stable self-mode-locked operation is comparable with that observed in Ti:sapphire lasers.

Adjusting the dispersion of the laser will easily produce pulse durations of ~100 fs. A typical interferometric autocorrelation is shown in Fig. 2(a). The FWHM is 180 fs, from which we infer a pulse duration of 96 fs, assuming a sech^2 intensity profile (the deconvolution factor for the interferometric autocorrelation of a sech pulse is 1.89). The power spectrum corresponding to this pulse is shown in Fig. 2(b). Assuming that the phase is constant across the spectrum, we inverse Fourier transform the measured spectrum and obtain a pulse duration of 95 fs, in good agreement with the assumption of a sech pulse shape. The origin of the feature on the long-wavelength side of the spectrum is under investigation. However, the result of the Fourier analysis suggests that the effect of this feature on the pulse shape is negligible. With a pulse energy of 8.5 nJ, the peak power is 85 kW.

The long-term stability of the laser is very good. The output power varies less than 3% during a 4-h period. However, some short-term fluctuations are evident on the mode-locked pulse train. Figure 3 shows a typical pulse train as recorded by a fast photodiode and an oscilloscope. The power fluctuates by approximately 1–3% rms owing to fluctuations of the pump power. We expect that the fluctuations would be much smaller with a quieter pump laser.[11] Unattended, self-mode-locked operation is sustained continuously for hours at a time, despite the relatively large fluctuations of the Nd:YAG pump laser.

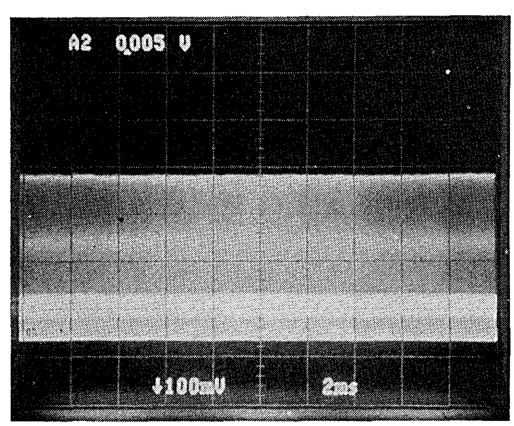

Fig. 3. Mode-locked pulse train recorded by a fast photodiode. The time scale is 2 ms/division.

By translation of the intracavity slit and prism P2, the wavelength of the mode-locked output can be tuned from 1.23 to 1.28 μm. Pulses less than 100 fs in duration are generated throughout this range, and the output power does not vary significantly. The tuning range is limited by the coatings of the mirrors that were available at the time of this research.

We observe a weak dependence of pulse duration on intracavity power. At levels moderately above the threshold for self-mode locking (2.7–5.4 W), the pulse duration decreases from 200 to 100 fs with increasing intracavity power if the cavity dispersion is kept constant. However, at any intracavity power above 2.7 W, the pulse duration can be reduced to the lowest value obtained (96 fs) by adjustment of the intracavity dispersion. For intracavity powers between 5.4 and 9.4 W, the pulse duration is constant, ~96 fs.

The similarity between the operation of this laser and that of mode-locked Ti:sapphire lasers suggests that existing theoretical models of Kerr lens mode locking[12,13] ought to be applicable to Cr:forsterite. It is likely that Cr:forsterite will satisfy the conditions for strong solitonlike pulse shaping,[14] assuming typical material properties. However, comparison of the experimental results with theoretical predictions is currently hampered by the fact that neither the dispersion nor the nonlinear index of Cr:forsterite is known. Based on the observation that self-mode locking occurs at intracavity powers similar to those in operating Ti:sapphire lasers, we can only make the qualitative statement that the nonlinearity of forsterite is probably comparable with that of sapphire. Once the material parameters are available for Cr:forsterite, a detailed comparison with theory will be helpful for a better understanding of the laser.

In conclusion, we have demonstrated stable self-mode locking of a Cr:forsterite laser. Self-mode locking occurs over a wide range of intracavity powers. A useful output power of 700 mW is obtained with 100-fs pulses. Overall, the performance and behavior of this laser are similar to those of now-standard mode-locked Ti:sapphire lasers. Cooling the laser crystal to 77 K should make multiwatt operation of this laser possible.[15]

In addition to the output near 1.26 μm, it will be possible to obtain useful power in a synchronized pulse at the second-harmonic wavelength by using this laser. In a preliminary experiment we have generated and measured 80-fs pulses tunable from 615 to 640 nm with average powers of 10 mW. Thus we obtain performance comparable with that of a colliding-pulse mode-locked dye laser in a solid-state system. We expect the combination of wavelengths generated with this laser to be useful in time-resolved spectroscopic studies.

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*Permanent address, Clark Instrumentation, Inc., Rochester, New York 14618.

†Permanent address, Institute of General Physics of the Russian Academy of Sciences, Moscow 117942, Russia.

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