Passive mode locking and dispersion measurement of a sub-100-fs Cr\textsuperscript{4+}:YAG laser

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We report the passive mode locking of a Cr\textsuperscript{4+}:YAG laser by use of a moving mirror and the generation of pulses as short as 70 fs by use of Kerr-lens mode locking. The intracavity dispersion has been measured, and the laser performance has been related to water absorption lines.

The rapid development of solid-state lasers promises to deliver high-average-power sources of picosecond and femtosecond pulses over a broad tuning range. Powerful passive mode-locking techniques based on the optical Kerr effect were developed by use of Ti-doped sapphire lasers (see, for example, Refs. 1–5), yielding pulses as short as 11 fs.

These mode-locking techniques were successfully applied to other new laser media including Cr\textsuperscript{3+}:LISAP,\textsuperscript{6} for which diode-pumped femtosecond operation was demonstrated,\textsuperscript{7} indicating the potential for relatively convenient and compact femtosecond laser systems. Recently this trend was extended to the near-infrared spectral region with the generation of femtosecond pulses from Cr\textsuperscript{4+}:forsterite lasers by use of additive-pulse mode locking\textsuperscript{8} and Kerr-lens mode locking\textsuperscript{9} (KLM), yielding pulses as short as 25 fs.\textsuperscript{10}

To extend further the spectral coverage of ultrafast solid-state lasers, Cr\textsuperscript{4+}:YAG is of particular interest in the region from 1.34 to 1.58 \(\mu\)m, an important window for optical communications and switching. Diode pumping of this laser was demonstrated with 970-nm diodes,\textsuperscript{11} and the potential exists for a compact diode-pumped Cr\textsuperscript{4+}:YAG laser system delivering tunable femtosecond pulses with watts of average power. In time, cryogenic color-center lasers will be replaced by convenient room-temperature (diode-pumped) solid-state lasers operating in these spectral regions. Cr\textsuperscript{4+}:YAG was demonstrated as a cw laser at room temperature, pumped by a Nd:YAG laser in spite of significant excited-state absorption,\textsuperscript{12} and we previously reported what we believed was the first mode-locked Cr\textsuperscript{4+}:YAG laser\textsuperscript{13} with an acousto-optic modulator. This medium’s upper-state lifetime of \(\sim 4\ \mu s\) and its net peak gain cross section of \(\sim 4 \times 10^{-19}\ \text{cm}^2\) are similar to those of Ti:sapphire, and so one may expect that it will deliver similar laser performance. This projection is supported by the recent report of a high-average-power cw Cr\textsuperscript{4+}:YAG laser and KLM operation successfully generating pulses as short as 120 fs.\textsuperscript{14} We now describe the passive mode locking of this laser by a moving mirror and the generation of sub-100-fs pulses for what we believe is the first time by KLM.\textsuperscript{3} We report the performance of mode-locked Cr\textsuperscript{4+}:YAG lasers with mirror sets covering spectral regions below and above 1.5 \(\mu\)m.

Initially the Cr\textsuperscript{4+}:YAG laser cavity shown in Fig. 1 was set up. The Brewster-angled laser crystal was grown at the IRE-POLUS Institute and was 20 mm in length. The laser rod absorbed 70% of the 1.064-\(\mu\)m Nd:YAG laser pump power. Unless otherwise stated, the experimental parameters of this laser were the same as those reported in Ref. 14.

Our initial single-stack dielectric mirror set was centered on 1.45 \(\mu\)m. Mirror M3 was a 1% or 3% output coupler, and the other mirrors were all high reflectors. We tuned the laser from 1.37 to 1.51 \(\mu\)m, using a 0.8-mm-thick quartz birefringent filter. Figure 2 shows the output power as a function of wavelength. The laser threshold was 3 W of absorbed pump power with the 1% output coupler.

We achieved mode locking across this tuning range, using a lead molybdate acousto-optic modulator, and pulses as short as 10 ps at 125 MHz were obtained with mode-locked output powers of as high as 40 and 130 mW with the 1% and 3% output couplers, respectively. This performance is slightly better than that obtained in Ref. 14 because the rod

Fig. 1. Schematic of the cw Cr\textsuperscript{4+}:YAG laser cavity. M1–M4, mirrors.
was water cooled to \(-5\,^\circ C\) rather than operated at room temperature. It was noticed that the shortest pulses (<30 ps) were always obtained at specific discrete wavelengths. No femtosecond pulses were observed, in spite of attempts to achieve KLM. Synchronous mode locking was also demonstrated with as much as 9 W of average mode-locked pump power at 1.06 \(\mu\m\), and pulses in the range of 20–30 ps were generated for pump pulses of \(-100\)-ps duration.

We achieved passive mode locking by vibrating one of the end mirrors of the cw laser cavity.\(^{16,17}\) Pulse lengths of approximately 20-ps duration were obtained at a repetition rate of approximately 100 MHz across most of the tuning range, with 3–5 ps pulses again produced at certain discrete wavelengths. On a millisecond time scale the pulse train was flat but had periodic dropouts corresponding to those portions of the vibrating mirror's cycle when the mirror moved too slowly. The amplitude of the mirror oscillation was measured, and, using the vibration frequency of 50 Hz, we measured the minimum average speed required for stable mode locking to be \(-17\) cm/s.

For the passively mode-locked lasers we attempted to optimize the cavity for KLM but never achieved femtosecond pulse generation. In attempting to understand our observations, we made a study of the dispersion of a synchronously pumped Cr\(^{4+}\):YAG laser, using a simple technique similar to that in Ref. 18. When any actively mode-locked-laser cavity length is adjusted to optimize the mode locking, there is a well-defined matching point for which the cavity round-trip time bears a fixed relationship to the applied modulation frequency. As the actively mode-locked laser is tuned in wavelength, the cavity length must then be adjusted to restore the matching condition. It is therefore straightforward to measure the change of total cavity group delay as a function of wavelength. This technique may be used with any actively mode-locked tunable laser system, including those that are synchronously pumped or that incorporate a modulator. Following Ref. 18, the cavity round-trip time \(T\) is given by

\[
T = \frac{2}{c} (L - 1) + \frac{2I}{v_g},
\]

where \(L\) is the total cavity length and \(I\) is the length of the dispersive medium of the cavity (all dispersive elements are considered to be lumped together). When \(T\) is held constant, rearrangement of this equation and differentiation with respect to wavelength yields

\[
\frac{dL}{d\lambda} = -cI \frac{d}{d\lambda} \left( \frac{1}{v_g} \right) = -cID,
\]

where \(D\) is the dispersion parameter per unit length. Thus differentiation of the relative change in cavity length (i.e., group-delay data) with respect to wavelength yields the net cavity dispersion.

This dispersion measurement was made for the laser cavity of Fig. 1 when it was synchronously pumped. Using the original mirror set, we obtained the data corresponding to the filled circles of Fig. 3. Figure 3(a) shows the relative variation in matched cavity length as a function of wavelength and Fig. 3(b) shows the wavelength dependence of the total cavity group-velocity dispersion (GVD), as calculated by differentiation of the data of Fig. 3(a), which was predominantly positive (i.e., normal). The narrow features correspond to contributions to the GVD from water-vapor absorption lines,\(^9\) as indicated in Fig. 3(b). There are corresponding dips in the output power versus wavelength curve of Fig. 2. We note that these water absorption lines may also have an effect on the performance of cw optical parametric oscillators operating in this spectral region. The discrete wavelengths at which the shortest pulses were obtained correspond to those wavelengths at which the cavity GVD was most neg-
the intracavity dispersion, using the same technique laser to tune to as long as 1.58 μm. We measured for wavelengths longer than 1.5 μm, and so we substituted a new dielectric mirror set that permitted the laser to tune to as long as 1.58 μm. We measured the intracavity dispersion, using the same technique as above and, for this second mirror set, obtained the data shown in Fig. 3 as open circles. These data indicated that the cavity dispersion for wavelengths longer than 1.5 μm was indeed suitable for femtosecond pulse generation. Using the same cavity as described above, we attempted KLM with the second mirror set and obtained sub-100-fs pulses from 1.49 to 1.58 μm, with the shortest pulses of 70-fs duration and a time–bandwidth product of 0.34. Figure 4 shows the autocorrelation trace and the spectral profile of these pulses. Average output powers of as high as 50 mW were obtained with a 0.5% output coupler for ~9 W of pump power.

In conclusion, we report the passive mode locking of a cw Cr<sup>4+</sup>:YAG laser by moving-mirror mode locking. We also report what we believe is the first sub-100-fs Cr<sup>4+</sup>:YAG laser tuning from 1.49 to 1.58 μm with transform-limited pulses as short as 70 fs generated by KLM. We have measured the dispersion of the Cr<sup>4+</sup>:YAG laser for the first time to our knowledge, using a technique that may be applied to any actively mode-locked laser. This Cr<sup>4+</sup>:YAG laser provides sub-100-fs test pulses at wavelengths suitable for telecommunications experiments (~1.53–1.55 μm) and for eye-safe applications (1.54 μm). We note that a diode-pumped version of this laser should be achievable.

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