Continuous-wave self-mode-locked operation of a femtosecond Cr^{4+}:YAG laser

Alphan Sennaroglu and Clifford R. Pollock

School of Electrical Engineering, Cornell University, Ithaca, New York 14853

Howard Nathel

Lawrence Livermore National Laboratory, Livermore, California 94551

Received August 16, 1993

Continuous-wave self-mode-locked operation of a chromium-doped YAG laser pumped by a continuous-wave Nd:YAG laser at 20 °C is described. We used both regenerative initiation and continuous-wave self-mode-locking techniques to generate nearly transform-limited pulses of 120-fs (FWHM) duration at 1.52 μm. The TEM_{00} output power was as high as 360 mW. The output of this femtosecond source was tunable from 1.51 to 1.53 μm.

Self-mode-locking,[1] in which gain medium Kerr nonlinearities are utilized to generate femtosecond pulses, has become widely used in a variety of tunable solid-state laser systems operating over different wavelength regimes. The key ingredients of this technique are intracavity negative group-velocity-dispersion compensation to balance the otherwise positively chirped pulses and a starting mechanism to provide the initial intensity conditions necessary for the onset of pulse shaping. Initiation may take various forms, such as synchronous pumping,[2] acousto-optic initiation,[3] regenerative initiation,[4,5] and others discussed elsewhere.[6]

Owing to its broad cw tunability extending from 1.34 to 1.56 μm, the chromium-doped yttrium aluminum garnet (Cr^{4+}:YAG) laser, first demonstrated by Shestakov *et al.*,[7] is a good candidate for the generation of femtosecond pulses. Ultrashort pulses in this spectral range may prove useful for applications in present fiber-optic transmission systems. Furthermore such a femtosecond source could provide a more practical and readily commercializable room-temperature alternative to the cryogenically operated mode-locked NaCl:OH^- laser[8,9] operating over a comparable wavelength range. Recently French *et al.* demonstrated cw acousto-optically mode-locked operation of the Cr^{4+}:YAG laser with 26-ps pulses tunable from 1.40 to 1.48 μm.[10]

In this Letter we describe the self-mode-locked operation of a room-temperature Cr^{4+}:YAG laser pumped by a cw Nd:YAG laser. Both regeneratively initiated and cw self-mode-locked operations have been observed, with the two techniques giving indistinguishable results. The regenerative initiation scheme used in this experiment is similar to the one we recently employed to generate femtosecond pulses from a dispersion-compensated chromium-doped forsterite (Cr:forsterite) laser that produced tunable pulses of 48-fs duration at 1.23 μm.[5] Using the Cr^{4+}:YAG laser operated at 20 °C, we have produced nearly transform-limited pulses having 120-fs (FWHM) duration at 1.52 μm with as high as 360 mW of TEM_{00} output power.

A schematic of the experimental setup that we used to observe self-mode locking of the Cr^{4+}:YAG laser is shown in Fig. 1. A folded, astigmatically compensated Z cavity with approximately equal arm lengths and a total length corresponding to a 81.27-MHz cavity repetition rate was used. The gain medium was placed slightly off center between two curved high reflectors (M1 and M2), each having a 10-cm radius of curvature and a reflectivity exceeding 99.9% from 1.35 to 1.55 μm. A flat wedged output coupler (O.C.) having 1% transmission in the same wavelength region was used throughout the experiment. All the optics used in the setup were obtained from the optics division of Spectra-Physics Lasers, Inc. A 1-cm-long Brewster-cut quartz acousto-optic cell (A.O.M.) was used for regenerative initiation, and a pair of Brewster-angled synthetic fused-silica prisms (P1 and P2) placed at minimum deviation on the high reflector (H.R.) side provided intracavity negative group-velocity-dispersion compensation. The Nd:YAG pump beam was focused into the Cr^{4+}:YAG crystal with an antireflection-coated mode-matching

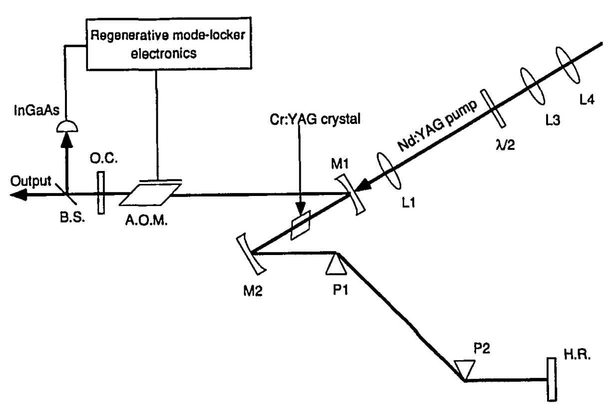

Fig. 1. Schematic of the cw self-mode-locked Cr^{4+}:YAG laser.

0146-9592/94/060390-03$6.00/0

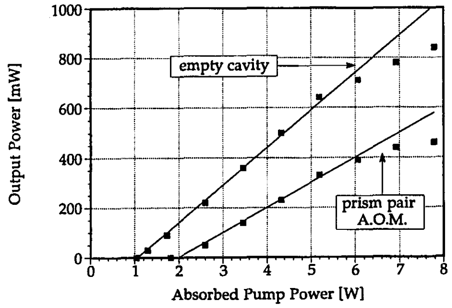

Fig. 2. Efficiency curves for the cw Cr^{4+}:YAG laser in the case of an empty cavity and with the intracavity elements.

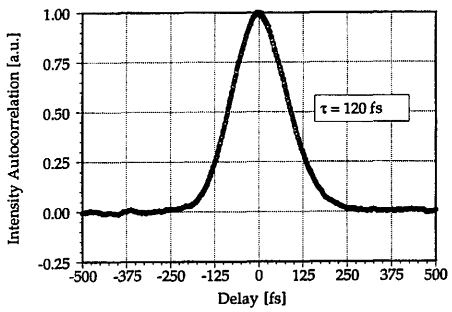

Fig. 3. Background-free autocorrelation of the mode-locked pulses. The pulse duration (FWHM) is 120 fs, assuming a sech^2 intensity profile.

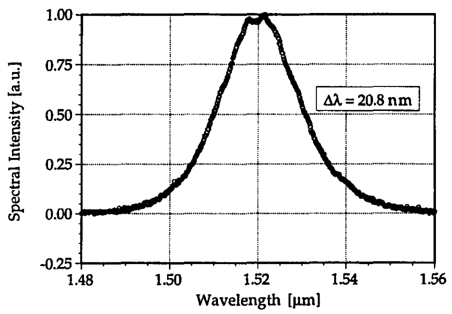

Fig. 4. Spectrum of the mode-locked pulses. The spectral bandwidth (FWHM) of 20.8 nm gave a time–bandwidth product of 0.327.

lens (L1) with a 10-cm focal length through M1, which had 93% transmission at 1.064 μm. To facilitate mode matching of the pump and laser cavities, we used a telescope consisting of two 5-cm focal-length antireflection-coated lenses (L3 and L4) with adjustable separation together with L1. We could readily obtain optimum mode matching by changing the separation of L3 and L4 and readjusting the position of L1. A half-wave plate ($\lambda/2$) at 1.06 μm was also used to adjust the pump-beam polarization to optimize the output power of the Cr^{4+}:YAG laser further.

The gain medium was a cylindical Brewster-cut Cr^{4+}:YAG rod, 20 mm in length and 5 mm in diameter, obtained from IFC, Inc. At the operating temperature of 20 °C, the differential absorption coefficient of the crystal was measured to be 1.33 cm^{-1} at 1.06 μm. The Cr:YAG crystal was surrounded with indium foil to improve the thermal contact and tightly clamped between copper holders connected to a thermoelectric cooler having 5-W heat-removal capacity. Using a feedback control loop for active stabilization of the crystal holder temperature, we maintained the gain medium at 20 °C with peak temperature fluctuations of less than 0.2 °C. Operating the crystal above the dew point of water eliminated the need for purging the crystal with dry nitrogen because no water condensation took place on the crystal surfaces.

Figure 2 shows the cw performance of the Cr:YAG laser with the 1% output coupler at 20 °C. With no intracavity elements present, an absorbed pump power slope efficiency of 15% with threshold absorbed pump power of 1.04 W was measured with the output of the laser centered at 1.45 μm. As much as 840 mW of power was obtained in this case. For absorbed pump powers greater than 5 W, the efficiency began to level off because of thermal overloading of the thermoelectric cooler. With the inclusion of the intracavity elements (the A.O.M. and the prism pair) that had losses as a result of wavelength-dependent absorptions and scattering from surface imperfections, the slope efficiency dropped to 10% and the output of the laser shifted to 1.49 μm. It is important to note that the Cr^{4+}:YAG laser system, having low round-trip gain, is extremely susceptible to even small amounts of intracavity loss. The threshold absorbed pump power also increased to 1.82 W in this case. The output wavelength of the laser was measured with a Jarrel-Ash 0.25-m monochromator having 25-μm slits and 0.2-nm resolution. The linewidth of the Cr^{4+}:YAG laser operated in this cw mode was measured to be 0.8 nm.

To study the characteristics of the mode-locked output, we used a scanning spectrometer (Monolight Model 6000) with 2-nm resolution and an autocorrelator having a 2-mm-thick type I phase-matched-cut lithium iodate crystal. A high-speed InGaAs detector monitored the pulse train, and a Hewlett-Packard Model 5328A 500-MHz frequency counter was used to register the pulse repetition rate. The obtained spectrum and autocorrelation data were then acquired from a storage sampling oscilloscope with an interfaced computer.

For regenerative initiation of the self-mode locking, 4% of the beam was sent by a beam splitter (B.S., Fig. 1) to an InGaAs detector to pick up the cavity mode beating signal, which was then frequency divided and amplified with an adjustable phase shift to drive the intracavity acousto-optic mode locker, which had an approximately 0.4% modulation depth. The intracavity negative group-velocity-dispersion compensation was provided by the synthetic fused-silica prism pair, which had 39-cm tip-to-tip separation. On adjustment of the positions of M1 and M2 to optimize the self-focusing in the gain medium, the femtosecond pulse train was readily initiated. Shown in Figs. 3 and 4 are the background-free intensity autocorrelation and the spectrum, respectively, of the mode-locked output of the Cr^{4+}:YAG laser. Assuming a sech^2 intensity profile, we measured the pulse width (FWHM) to be 120 fs. A simultaneous measurement of 20.8-nm spectral bandwidth gave a time–bandwidth product of 0.327, verifying that the pulses were nearly transform limited. With the onset of self-mode locking, the peak wavelength shifted to 1.52 μm, resulting in a reduction of the maximum output power from 460 mW (for the cw case) to 360 mW. With an aperture between P2 and the H.R., the output wavelength could be tuned over a narrow range, from 1.51 to 1.53. The operation on the longer-wavelength side was impaired by the optics coatings. On the lower-wavelength side, tuning resulted in the collapse of the broad femtosecond spectral bandwidth, giving approximately 20-ps-long pulses. We suspect that the losses introduced by the prism pair together with possible excited-state absorption are the dominant factors inhibiting femtosecond pulse formation on this lower-wavelength side. The possible role of excited-state absorption as a net negative saturable absorber to quench self-mode-locked operation was earlier suggested by other authors.[10] The cavity repetition rate was measured to be 81.272 MHz, with less than 20-Hz fluctuation in the frequency. With the mode locker off, self-sustained operation for as much as an hour was observed. The measured peak power and the energy per pulse were 37 kW and 4.43 nJ, respectively. A threshold output power of ~100 mW was required for observation of the onset of femtosecond pulse formation, corresponding to ~1 MW of intracavity peak power per pulse.

In our experiments, stable self-mode locking was most readily achieved for prism separations in the neighborhood of 40 cm. With index-of-refraction data for YAG,[11] the estimated net second-order cavity dispersion for 39-cm prism separation at 1.52 μm was -3300 fs^2, comparable with what is observed in Ti:sapphire lasers operating with similar pulse widths.[4] In addition, the fused-silica prism pair at this wavelength has positive third-order dispersion, like the gain medium, thus providing no cancellation. Therefore shorter pulses may be obtainable by use of other prism materials that are transparent in this wavelength region and have the correct sign of third-order dispersion.

In a separate experiment, the intracavity A.O.M. was removed from the laser, and self-mode locking was initiated solely from cw fluctuations without application of any periodic perturbation to the cavity round-trip gain. In this case we maximized the mode beating signal detected by the high-speed InGaAs detector by adjusting curved mirrors M1 and M2, and the cavity was slightly misaligned to initiate the femtosecond pulse train. Alternatively, one of the prisms could be slightly translated to initiate the pulse train. Even though results indistinguishable from those of the regeneratively initiated case were obtained, cw self-mode-locked Cr^{4+}:YAG laser did not have the same long-term stability, hence making the former technique more favorable for applications requiring reliable operation over prolonged periods.

In conclusion, cw self-mode-locked operation of the Cr^{4+}:YAG laser was demonstrated for the first time to our knowledge. Using two alternative initiation schemes, regenerative initiation and cw self-mode locking, we obtained pulses of 120-fs duration (FWHM) at 1.52 μm with TEM_{00} output powers as much as 360 mW. This femtosecond source should find various applications in the characterization of fiber-optic communication systems designed at 1.55 μm.

We thank Spectra-Physics Lasers, Inc., for technical assistance. This research was supported by the Rome Laboratories (grant F30602-93-L-0003), the Joint Services Electronics Program, the Materials Science Center at Cornell University, and the U.S. Department of Energy under the auspices of contract W-7405-Eng-48.

References

1. D. E. Spence, P. N. Kean, and W. Sibbett, Opt. Lett. **16,** 42 (1991).
2. F. Krausz, Ch. Spielmann, T. Brabec, E. Wintner, and A. J. Schmidt, Opt. Lett. **17,** 204 (1992).
3. P. F. Curley and A. I. Ferguson, Opt. Lett. **16,** 1016 (1991).
4. J. D. Kafka, M. L. Watts, and J. J. Pieterse, IEEE J. Quantum Electron. **28,** 2151 (1992).
5. A. Sennaroglu, C. R. Pollock, and H. Nathel, Opt. Lett. **18,** 826 (1993).
6. F. Krausz, M. E. Fermann, T. Brabec, P. F. Curley, M. Hofer, M. H. Ober, Ch. Spielmann, E. Wintner, and A. J. Schmidt, IEEE J. Quantum Electron. **28,** 2097 (1992).
7. A. V. Shestakov, N. I. Borodin, V. A. Zhitnyuk, A. G. Ohrimtchyuk, and V. P. Gaponstev, in *Conference on Lasers and Electro-Optics,* Vol. 10 of 1991 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1991), paper CPDP11.
8. C. P. Yakymyshyn, J. F. Pinto, and C. R. Pollock, Opt. Lett. **14,** 621 (1989).
9. G. T. Kennedy, R. S. Grant, and W. Sibbett, Opt. Lett. **18,** (1993).
10. P. M. W. French, N. H. Rizvi, J. R. Taylor, and A. V. Shestakov, Opt. Lett. **18,** 39 (1993).
11. W. L. Bond, J. Appl. Phys. **36,** 1674 (1965).