Continuous-wave and passively mode-locked operation of a cunyite (Cr^{4+}:Ca_2GeO_4) laser

Bing Xu, Jonathan M. Evans, Vladimir Petričević, S. P. Guo, O. Maksimov, Maria C. Tamargo, and R. R. Alfano

Continuous-wave and mode-locked Cr^{4+}:Ca_2GeO_4 lasers that use a fiber laser pump source were demonstrated. The continuous-wave Cr^{4+}:Ca_2GeO_4 laser yielded a maximum output power of 415 mW at 1420 nm and a tuning range of 1335–1492 nm. With a saturable-absorber mirror, 60-ps pulses and 110-mW maximum output power were generated from a passively mode-locked Cr^{4+}:Ca_2GeO_4 laser. © 2000 Optical Society of America

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1. Introduction

During the past several years, a number of Cr^{4+}-based laser crystals have been grown and investigated for laser operation. Only a few of these efforts have produced laser-grade materials. Interest in the development of new lasers activated by Cr^{4+} ions followed the demonstration of the Cr^{4+}:forsterite (Cr^{4+}:Mg_2SiO_4) laser by Petričević *et al.* in 1988.[1] Cr^{4+}:YAG laser operation was also demonstrated in 1988,[2] although at that time the laser action was ascribed only to impurity color centers. Cr^{4+}:Ca_2GeO_4 was demonstrated in 1996 with potential laser tunability in the 1.3–1.6-μm range.[3] Development of new host crystals for the laser active Cr^{4+} ion has been prompted by the deficiencies of the hosts that are now available. In particular, Cr:forsterite suffers from the introduction of Cr^{3+} and Cr^{2+} ions into the crystal lattice, which results in a low figure of merit, typically in the 20–40 range, and of Cr:YAG crystals, which require the presence of a charge-compensating codopant. In addition, nonradiative relaxation of the upper laser level is significant in both Cr:forsterite and Cr:YAG at room temperature. Recently, all-solid-state continuous-wave (cw) Cr^{4+}:Ca_2GeO_4 lasers that use a semiconductor diode device and a fiber laser as the pump sources have been reported.[4,5] The development of a compact, stable, diode- or fiber-pumped ultrashort-pulse laser source in the 1.3–1.6-μm wavelength range has several practical applications in medicine, telecommunication, fiber sensing, and semiconductor devices.

To accomplish stable mode-locked operation in vibronic lasers similar to Cr^{4+}:Ca_2GeO_4, various groups of researchers have used intracavity quantum-well-based semiconductor saturable absorbers. These devices have acquired various names, including saturable-absorber mirror (SAM), semiconductor saturable-absorber mirror, and saturable Bragg reflector. The mode-locked performance of lasers that incorporate such devices has been characterized by high tolerance to cavity perturbations and is an inherently self-starting and sustaining mode-locking technique. Several solid-state lasers including Ti:sapphire,[6] Yb:YAG,[7] Cr:LiSAF,[8] $Nd:YVO_4$, Nd:YLF,[9] and Cr:YAG,[10] have been mode locked by use of such semiconductor devices.

In this paper we report on two modes of Cr^{4+}:Ca_2GeO_4 laser operation: by a cw oscillator and by a passively mode-locked laser. The cw laser was tunable in the 1335–1492-nm spectral range. With a SAM, a passively mode-locked Cr^{4+}:Ca_2GeO_4 was constructed. Stable mode-locked operation has been observed over a tuning range of 1380–1460 nm.

2. Experiments

First we present the results of cw operation of a fiber-pumped Cr^{4+}:Ca_2GeO_4 laser. The cw Cr^{4+}:Ca_2GeO_4 laser resonator consisted of a standard

All the authors are with the Institute for Ultrafast Spectroscopy and Lasers and the New York State Center for Advanced Technology in Ultrafast Photonic Materials and Applications, The City College of the City University of New York, New York, New York 10031. B. Xu (bingxu@scisun.sci.ccny.cuny.edu), J. M. Evans, V. Petricevic, and R. R. Alfano are with the Department of Physics of the latter institution; S. P. Guo and O. Maksimov are with the Department of Chemistry.

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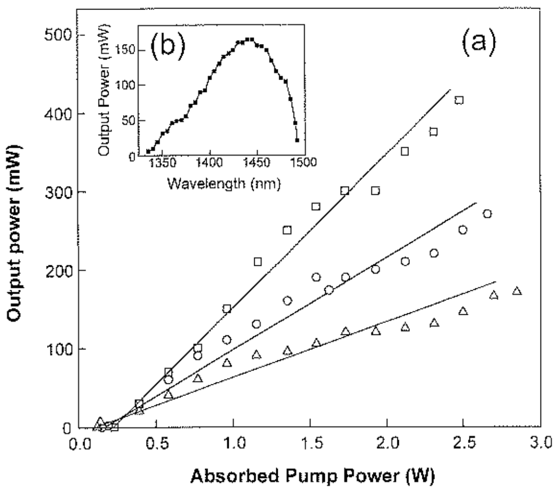

Fig. 1. Output characteristics of the Cr^{4+}:Ca_2GeO_4 laser: (a) slope efficiency for 7.5% (squares), 2.5% (circles), and 1% (triangles) output coupling; (b) tuning range with the 1% output coupler.

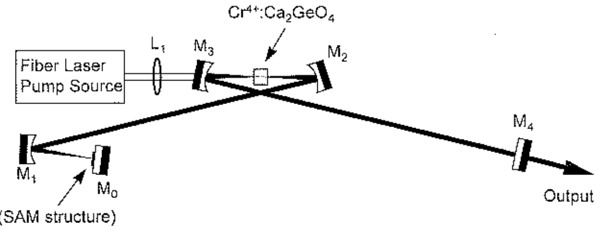

Fig. 2. Schematic diagram of the passively mode-locked Cr^{4+}:Ca_2GeO_4 laser cavity incorporating the SAM device (M_0). M's, mirrors; L_1, lens.

three-mirror L-fold cavity formed by two 10-cm radius-of-curvature mirrors and a flat output coupler. The crystal used in our investigation was 6 mm long, with a rectangular cross section. It was cut for light propagation along the crystal *a* axis, with polarization parallel to the *b* axis. The faces of the crystal were polished parallel flat–flat and were coated with a broadband antireflection layer centered at 1.45 μm. This Cr^{4+}:Ca_2GeO_4 crystal absorbed 90.5% of the pump light. To achieve a good match between pump spot size and cavity mode size we used a 10-cm focal-length lens to focus the pump beam. To improve laser efficiency, we implemented thermoelectric cooling of the laser crystal, reducing the operating temperature of the active region of the crystal to −15 °C. N_2 gas was passed over the crystal's faces to prevent moisture condensation. A single birefringent crystalline quartz plate was inserted into the cavity for tuning purposes. A fiber laser (SDL FL-10-3911) capable of delivering a maximum of 9 W of power at 1.1 μm in a near-diffraction-limited beam was used as a pump source that falls within the broad absorption band of Cr^{4+}:Ca_2GeO_4.

The cw Cr^{4+}:Ca_2GeO_4 laser operated at 1430 nm without a tuning element inserted into the cavity, and a maximum output power of 415 mW was obtained for an absorbed pump power of 2.5 W by use of an output coupler with 7.5% transmission at 1.43 μm. The lowest measured threshold was 120 mW of absorbed pump power when a 1% output coupler was implemented. The threshold increased to 0.15 and 0.23 W for 2.5% and 7.5% output couplers, respectively. The maximum optical slope efficiency of 21% was obtained for a 7.5% output coupler.

Figure 1 shows the laser output power as a function of absorbed pump power for the Cr^{4+}:Ca_2GeO_4 laser operating with 1%, 2.5%, and 7.5% output couplers. The output polarization parallel to the crystal *b* axis is the result of the strongly polarization-dependent gain of Cr^{4+}:Ca_2GeO_4. At approximately 1.5 W of absorbed pump power the output laser mode changed from TEM_{00} to multimode. The maximum TEM_{00} output power generated was 305 mW. With the insertion of a birefringent plate, a tuning range of 1335–1492 nm was measured for the Cr^{4+}:Ca_2GeO_4 laser shown in the inset of Fig. 1. This laser operated with a 1% output coupler, and the absorbed pump power was 3.0 W.

The broad tunability of Cr^{4+}:Ca_2GeO_4 lasers indicates their potential as sources of ultrafast light pulses. If the entire laser bandwidth of Cr^{4+}:Ca_2GeO_4 were utilized, pulses as short as 13 fs would potentially be attainable. To investigate mode-locked operation we used a SAM in the Cr^{4+}:Ca_2GeO_4 resonator, as shown schematically in Fig. 2. For mode-locked operation, an X-fold cavity was built that was similar to that of a standard Ti:sapphire laser with a cavity waist of 40 μm inside the Cr^{4+}:Ca_2GeO_4 crystal. The active crystal was the same as that used in the cw investigation. A 1% output coupler (M_4) was used in this Cr^{4+}:Ca_2GeO_4 laser. To obtain sufficient bleaching of the saturable absorber for pulse formation we used a concave mirror (M_1) with a 20-cm radius of curvature to reduce the incident beam size to approximately 80 μm upon the SAM. The separation between the mirror and the SAM was ~9.5 cm. The total cavity length was 98 cm, yielding a pulse repetition rate of 153 MHz.

The SAM structure used in our experiment was similar in design to that used by Hayduk *et al.*,[11] with a modified geometry for operation at a center wavelength of 1.43 μm. Grown by molecular-beam epitaxy upon an undoped (100) GaAs substrate, the SAM consists of a distributed Bragg reflector with 24.5 periods of 123-nm AlAs low-index–104.9-nm GaAs high-index quarter-wave layers for 1.43 μm. A 21.9-nm-thick $Al_{0.48}In_{0.52}As$ buffer layer was grown between the partial Bragg stack and a double quantum well. The double quantum well in the saturable-absorber region follows the buffer layer and has the following structure: 6.5-nm $Ga_{0.47}In_{0.53}As$ well–8-nm $Al_{0.48}In_{0.52}As$ barrier–6.5 nm $Ga_{0.47}In_{0.53}As$ well. The entire structure is capped by a 65.8-nm-thick $Al_{0.48}In_{0.52}As$ layer, so the total thickness of the buffer–double quantum well–cap layer was a 1.43-μm quarter-wave layer completing the Bragg reflector. Two 10 mm × 10 mm SAM samples were used in our investigations. One was cut from the center of a wafer, and a second was taken

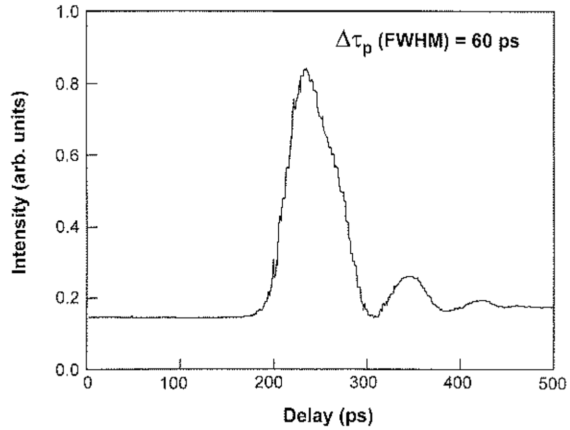

Fig. 3. 60-ps mode-locking pulse generated by a passively mode-locked Cr^{4+}:Ca_2GeO_4 laser measured by a combination of a fast photodiode and a sampling oscilloscope.

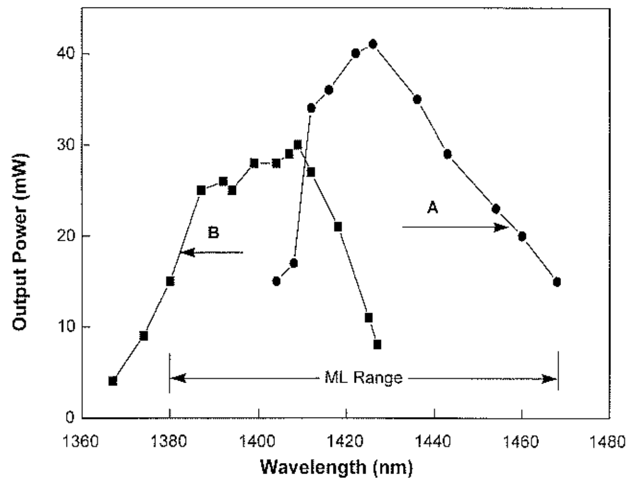

Fig. 4. Tuning range of a fiber-laser-pumped mode-locked Cr:Ca_2GeO_4 laser with corner-cut (squares) and center-cut (circles) SAM samples. ML Range, the wavelength range over which stable mode locking was observed.

from the corner of the same wafer. The measured reflectance for the center-cut sample was more than 99% from 1407 to 1475 nm, and the peak reflectivity of 99.6% was centered at 1440 nm. A peak reflectivity at 1420 nm was observed for the corner-cut sample from the same SAM wafer. The observed difference in center wavelength is due to in-plane thickness variation across the area of the SAM created during the molecular-beam expitaxial growth.

The mode-locked Cr^{4+}:Ca_2GeO_4 laser with the center-cut piece of the SAM generated pulse widths of 60 ps with 1-nm bandwidth for a long period (more than 4 h) and low-amplitude noise fluctuations (less than 2%). Pulse duration measurements were made with a fast photodiode (New Focus Model 1417) and a sampling oscilloscope (Tektronix Model 11801B) combination that had a minimum pulse resolution of 20 ps. A sampling scope oscillogram of a 60-ps pulse is shown in Fig. 3. This mode-locked Cr^{4+}:Ca_2GeO_4 laser operated at 1416 nm without a tuning element inserted into the cavity, and a maximum output power of 110 mW was obtained for 2.4-W absorbed pump power with 1% output coupling. The cw lasing threshold was at 300 mW of absorbed pump power. The onset of mode-locked operation was observed for an absorbed pump power of 760 mW, and an optical slope efficiency of 5.0% was recorded. The beam profile was TEM_{00} for stable mode-locked operation. For an absorbed pump power of 1.33 W we measured a tuning range of 1404–1468 nm by using an intracavity birefringent plate. These data are summarized in Fig. 4 (curve A). Curve B of Fig. 4 is the tuning measured with the corner-cut SAM instead of the center-cut piece. The range is shifted to shorter wavelengths, extending the tuning to 1365 nm. Stable mode-locked operation was observed over the 1380–1460-nm wavelength range with variation of the pulse duration from 60 to 75 ps.

3. Summary

In summary, the operation of a direct fiber-pumped mode-locked Cr:Ca_2GeO_4 laser with a SAM has been described. By utilizing a fiber-laser pump source, we have built an all-solid-state cw Cr:Ca_2GeO_4 laser with a maximum output power of 410 mW at 1410 nm. The fiber-laser-pumped Cr:Ca_2GeO_4 laser is a practical all-solid-state compact source of radiation in the 1335–1492-nm wavelength region. Passive mode locking of a Cr:Ca_2GeO_4 laser has been achieved with an intracavity SAM device that routinely generates pulses as short as 60 ps in the 1380–1460-nm tuning range. Improvements in Cr:Ca_2GeO_4 crystal growth will lead to larger output powers, and subpicosecond pulses may be generated with the implementation of intracavity group-velocity-dispersion compensation.

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