

## 8.7-W average power femtosecond Ho:CALGO bulk laser at 2.1 $\mu\text{m}$

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High-power ultrafast solid-state lasers directly emitting in the 2  $\mu\text{m}$  spectral region are an important research topic because of growing demands in spectroscopy, polymer processing, and for efficiently driving secondary sources from the THz to the XUV. So far, Cr:ZnS/Se have mostly dominated the landscape of results in this area, achieving power levels up to the watt-level with <100 fs [1]. Ho<sup>3+</sup>-doped laser gain media are another attractive alternative with largely unexplored potential. In fact, the requirements for high thermal conductivity and a broad gain spectrum is known to be a challenge, and few options for broadband hosts have been explored. In this context, rare-earth doped disordered CaLnAlO<sub>4</sub> (Ln stands for Gd/Y/Lu) crystals are known for high thermal conductivity as well as broad gain profile in both 1  $\mu\text{m}$  and 2  $\mu\text{m}$  regime [2, 3]. However, to date, in addition to a few CW laser results based on Ho:CaYAlO<sub>4</sub> [4], no reports of mode-locking were made based on Ho:CaLnAlO<sub>4</sub>. In this paper, we present first mode-locking results with Ho:CaGdAlO<sub>4</sub> (Ho:CALGO), reaching the highest average power mode-locked laser so far achieved in the bulk geometry in the 2-3  $\mu\text{m}$  wavelength region.

Our experimental setup is presented in Fig. 1(a). A Brewster-cut 15 mm-length Ho:CALGO crystal (3.1 at.% doping concentration) was used to ensure a double-pass absorption  $\sim 80\%$  and access to  $\pi$ -polarization. The laser was in-band pumped by a single-mode 1940-nm Tm-fiber laser with a pump beam radius of 93  $\mu\text{m}$  (sagittal)  $\times$  175  $\mu\text{m}$  (tangential) in the crystal. TEM<sub>00</sub> mode radius in the crystal was 95  $\mu\text{m}$  (sagittal)  $\times$  180  $\mu\text{m}$  (tangential). In CW wave operation (using an HR mirror and an OC as shown in Fig. 1(a)), we could reach up to 10.8 W of output power at an absorbed pump power of 22.8 W, corresponding to an o-o efficiency of 47.4%, as shown in Fig. 1(b). To ensure soliton mode-locking, in addition to the -1800 fs<sup>2</sup> of round-trip group delay dispersion (GDD) from the CALGO crystal, additional -15000 fs<sup>2</sup> GDD was introduced by multiple bounces on dispersive mirrors. A commercial GaSb based SESAM (RefleKron Ltd.) working at 2.1  $\mu\text{m}$  with a saturable fluence of 10  $\mu\text{J}/\text{cm}^2$  and a modulation depth of 0.22% was used to start and stabilize the mode-locking.

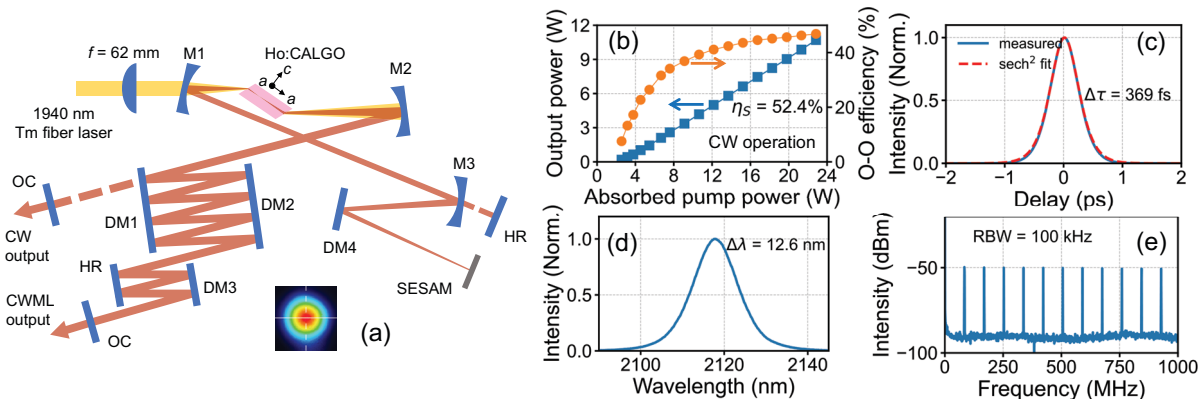


Fig. 1. (a) SESAM mode-locked Ho:CALGO laser. DM1-4 dispersive mirrors. Inset: far-field beam shape during mode-locking at 8.7-W average power. (b) CW operation. (c) Intensity autocorrelation trace with sech<sup>2</sup> fit. (d) Laser spectrum. (e) RF spectra with 1 GHz scanning range.

Applying an output coupler with 10% transmission, mode-locking was stable up to 22.8-W absorbed pump power with a maximum average output power of 8.7 W, corresponding a high optical-to-optical efficiency of 38.1%. Figure 1(c)-(d) show the laser performance at the maximum output power. Laser wavelength was centered at 2118 nm with 12.6-nm full-width half maximum bandwidth. The obtained pulses have a pulse duration of 369 fs assuming a sech<sup>2</sup> pulse shape. Time-bandwidth product of the mode-locked pulses was calculated to be 0.311, indicating near transform-limited soliton pulses. The radio frequency (RF) spectra in Fig.1 (d) indicates 84.4 MHz repetition rate resulting in pulse energy of 103 nJ. In this experiment, we were limited to reach higher powers and shorter pulses by the low modulation depth of the SESAM, giving us a straightforward path to improve these results to >10 W and <100 fs level.

### References

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