

## Sub-40 fs Kerr-lens mode-locked Tm,Ho:CALGO laser

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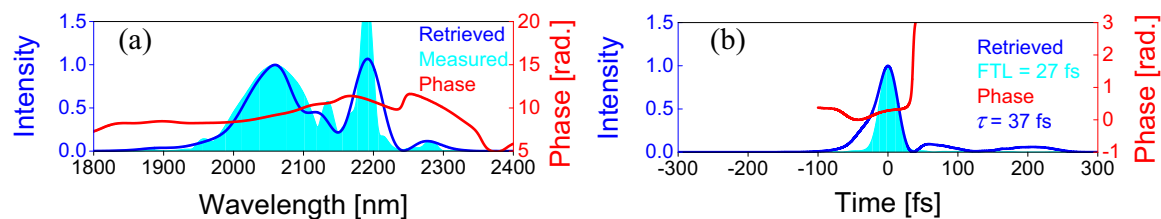
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Tetragonal calcium rare-earth (RE) aluminates, CaREAlO<sub>4</sub>, where RE = Gd or Y (abbreviated CALGO and CALYO), represent a laser host crystal family characterized by strong inhomogeneous spectral line broadening due to the pronounced structural disorder when doped with laser-active RE<sup>3+</sup> ions (e.g., Yb<sup>3+</sup>, Tm<sup>3+</sup> and/or Ho<sup>3+</sup>), which is favorable for sub-100-fs pulse generation from mode-locked (ML) lasers. Despite the disordered structure, they feature relatively high thermal conductivity with moderate dependence on the RE<sup>3+</sup> doping level [1], which is advantageous for power scaling when pumped with high-power diode lasers. Tm<sup>3+</sup> and Ho<sup>3+</sup> co-doped CaREAlO<sub>4</sub> crystals exhibit extremely broad, flat and smooth spectral gain profiles extending beyond 2 μm which originate from overlapping gain profiles of the two ions. In the first sub-100-fs ML laser of this type, a Tm,Ho:CALYO crystal was employed. Mode-locked by a Semiconductor Saturable Absorber Mirror (SESAM), this laser delivered 87-fs pulses at 2043 nm with an average output power of only 27 mW [2]. Subsequently, a shorter pulse duration of 52 fs was achieved from a SESAM ML Tm,Ho:CALGO laser at 2015 nm with an average output power of 376 mW [3]. Very recently, sub-50-fs pulses at ~2 μm were reported using a compositionally “mixed” Tm,Ho:Ca(Gd,Lu)AlO<sub>4</sub> crystal (Tm,Ho:CALGLO) as a gain medium. Pulses as short as 46 fs were achieved by the SESAM ML Tm,Ho:CALGLO laser at 2033 nm with an average output power of 121 mW [4]. In the present work, we explored further shortening of the pulse duration in ML Tm,Ho:CALGO laser via soft-aperture Kerr-lens mode-locking (KLM). A transmission-type single-walled carbon-nanotube saturable absorber (SWCNT-SA) was implemented to stabilize the KLM.

The shortest pulses of the Tm,Ho:CALGO laser were achieved with a 0.2% output coupler (OC) through strong bleaching of the SWCNT-SA. KLM operation was not self-starting but required a slight perturbation. The total intracavity round-trip group-delay dispersion of the four dispersive mirrors (DMs) used amounted to -1375 fs<sup>2</sup>. The pulses were characterized by second-harmonic generation (SHG) frequency-resolved optical gating (FROG).



**Fig. 1** SHG-FROG characterization of the KLM Tm,Ho:CALGO laser with a 0.2% OC. (a) Measured and retrieved optical spectrum and spectral phase; (b) retrieved intensity and phase and Fourier-transform-limited (FTL) pulse.

The directly measured spectrum was centered at 2061.3 nm spanning from 1870 to 2337 nm, in reasonably good agreement with the one reconstructed from the SHG-FROG trace, see Fig. 1(a). After an external linear chirp compensation with a 5-mm thick ZnSe plate, the retrieved pulse had a duration (FWHM) of 37 fs (~5 optical cycles), still ~36% above the Fourier limit, see Fig. 1(b). The average output power amounted to 55 mW at an absorbed pump power of 2.85 W and a pulse repetition rate of ~76 MHz.

### References

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