# Sub-50-fs widely tunable Yb:CaYAlO$_4$ laser pumped by 400-mW single-mode fiber-coupled laser diode

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**Abstract:** Yb:CaYAlO$_4$ has been investigated spectroscopically and compared to better known Yb:CaGdAlO$_4$. It turns out that both materials show very similar spectroscopic parameters relevant to ultrafast lasers design. Employing single-mode fiber-coupled 400-mW laser diode at 976 nm we measured pulses as short as 43 fs, and broad tunability of 40 nm with a simple single-prism setup.



**OCIS codes:** (140.3615) Lasers, ytterbium; (140.7090) Ultrafast lasers.

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## 1. Introduction

Yb-doped diode-pumped lasers have attracted a lot of attention since late 1990s and their technology has been proven successful for many applications. Their success is based on a combination of few key aspects: 1) pump laser diodes at 940 - 980 nm have reached a high level of maturity owing to wide-scale telecom applications; 2) the simple electronic structure of $Yb^{3+}$ ions yields very low quantum defect and no parasitic upconversion effects; 3) wide fluorescence bandwidth allows ultrashort pulse generation. While Yb:YAG is generally preferred for ultra-high pulse energy applications [1], tungstate hosts such as Yb:KYW or Yb:KGW are most usually employed in commercial products, offering shorter pulses of few hundreds femtoseconds owing to their larger gain bandwidths. Many alternative Yb-doped materials have been proposed and successfully used for high-power and/or sub-100-fs pulse generation [2]. However, the implementation of reliable and cost-effective growing processes for the most promising of these materials, a most critical step for commercial products development, still needs to be fully demonstrated. Among disordered crystal hosts with multisite structure, Yb:$CaGdAlO_4$ (Yb:CALGO) is perhaps one of the most exciting new materials having emerged in the last decade, owing to a particularly attractive combination of thermo-mechanical and optical properties [3]. Indeed, pulses as short as 32 fs were demonstrated with Kerr-lens mode-locking (KLM) [4] or 40 fs with SESAM mode-locking [5], as well as regenerative amplifiers with output power up to 28 W [6] or pulse energy up to 3 mJ [7] and pulse width as short as 97 fs [8].

A very similar laser crystal, but easier to grow and fabricate, is Yb:$CaYAlO_4$ (Yb:CALYO), which belongs to the tetragonal $ABCO_4$ compounds, where A = Sr, Ca; B = rare earth elements, and C = Ga, Al. In fact there is a difference between $Gd^{3+}$ and $Y^{3+}$ ionic radii (1.20 and 1.02 Å respectively) that can result in a lattice structure stress. This behavior is well evident also in fluoride materials such as $YLiF_4$ (YLF), $LuLiF_4$ (LLF) and $GdLiF_4$ (GLF), which are isomorphic, but YLF and LLF grow congruently while GLF is strongly incongruent. After earlier studies in the 1990s, Yb:CALYO was recently re-discovered and investigated for production of femtosecond pulses [9,10]. Given the promising properties of such material, we have carried out an independent spectroscopic characterization on Yb:CALYO and Yb:CALGO samples, as well as a detailed investigation of low-power Yb:CALYO oscillators. We have found that the spectroscopic properties of Yb:CALYO compare very similarly to those of Yb:CALGO, leading to extremely short pulses of 43 fs with SESAM mode-locking and a broad 40-nm continuous tuning range. These values are in close agreement with our previous experimental results with Yb:CALGO, thus confirming the expectations from our spectroscopy investigation.

## 2. Spectroscopic measurements

In order to compare the performances of CALYO and CALGO hosts, samples of $CaYAlO_4$:2at%Yb and $CaGdAlO_4$:2at%Yb have been investigated with a standard spectroscopic apparatus. Samples under investigation were 4x4x1 $mm^3$, *a*-cut. In particular, room temperature polarized absorption has been measured with a Cary 500 spectrophotometer in the wavelength range 890-1100 nm. The resolution was 1.0 nm. From these absorption spectra, the absorption cross sections have been calculated (shown in Fig. 1) considering an ion density of about $2.5 \times 10^{20}$ ions/$cm^3$. As is evident from Fig. 1 and 2, both materials show very similar behavior. The peak value was obtained for π polarization placed at about 980 nm with a $\sigma = 4.4 \times 10^{-20}$ and $\sigma = 3.4 \times 10^{-20}$ $cm^2$ for CALYO and CALGO respectively. A comparison with the Yb:CALYO absorption cross section reported in Ref [9] shows a difference of about 20% in the maximum values but a similar structure.

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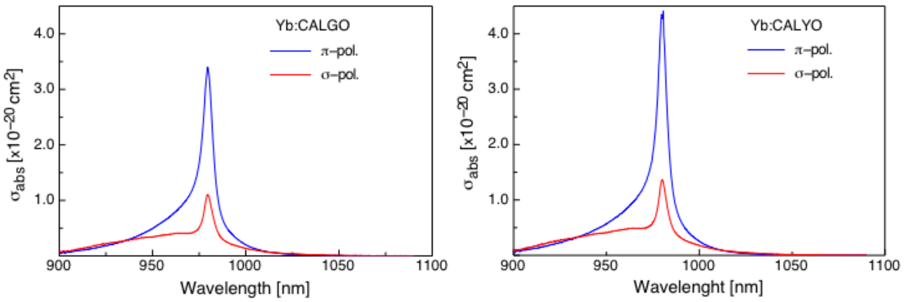


Fig. 1. Room temperature absorption cross sections for Yb:CALGO and Yb:CALYO samples.

Fluorescence measurements have been performed at room temperature exciting the sample with a diode laser tuned at 930 nm, at the shortest wavelength of emission spectrum of Yb:CALGO and Yb:CALYO. The exciting beam was focused onto the sample by a lens having a focal length of 10 cm. Luminescence was chopped and focused on the entrance slit of a 320 mm focal length monochromator equipped with a 600 lines/mm grating, blazed at 1 μm. To record polarized spectra of the sample we used a Glan-Thomson polarizer in front of the input slit of the monochromator and an InSb detector, cooled at liquid nitrogen temperature. The fluorescence signals, corresponding to the well-known $^2F_{5/2} \rightarrow {}^2F_{7/2}$ transition, were acquired by a SR830 Lock-in Amplifier in the wavelength range 890-1090 nm with a resolution of 0.53 nm and subsequently stored on a PC. The spectra were normalized for the optical response of the system using a black-body source at 3000 K. Further information on experimental setup can be found in Ref [11]. The fluorescence decay-time for $^2F_{5/2}$ manifold has been measured at room temperature with the same experimental apparatus but pumping with a pulsed tunable Ti:$Al_2O_3$ laser with 10 Hz repetition rate and 30 ns pulse width [11]. In lifetime measurements the excitation wavelength was about 930 nm.

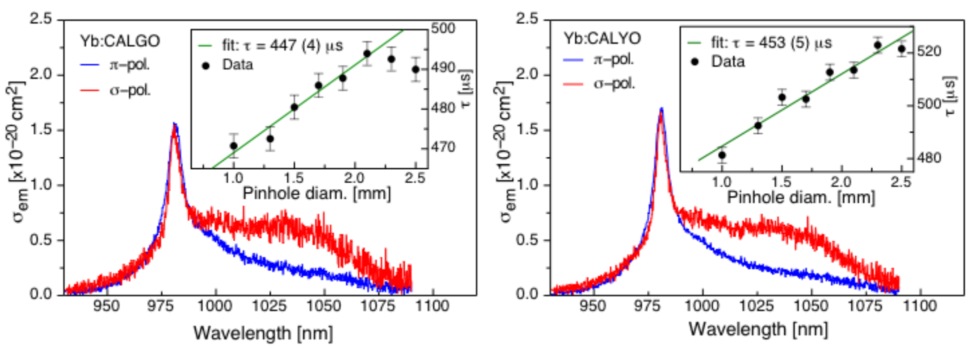


Fig. 2. Room temperature emission cross sections for Yb:CALGO and Yb:CALYO samples. Insets: Lifetime measurements obtained with the pinhole method. The error value (in brackets) corresponds to the standard deviation of the fit result.

Because of the levels structure of $Yb^{3+}$, there is always a reabsorption contribution at room temperature, where the higher Stark sublevels of the $^2F_{7/2}$ ground state are appreciably populated. This results in an artificial lengthening of the fluorescence lifetime. To avoid this spurious effect the fluorescence lifetime was measured according to the pinhole method described in Ref [12]. Measurements were performed utilizing eight pinholes width diameters ranging from 2.5 to 1.0 mm and the result is shown in Fig. 2. The extrapolated lifetimes were $\tau$ = 453 μs and $\tau$ = 447 μs for CALYO and CALGO, respectively. The CALGO lifetime is in fair agreement with the one measured in Refs [9,13]. Fluorescence spectra and lifetimes were utilized to calculate the emission cross section with the β-τ method [14] and are plotted in Fig. 2. It is evident from Fig. 1 and 2 that the optical behavior of the two hosts is very similar. Comparing our data with literature, there is a significant discrepancy to Ref [9], where the π-

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polarized emission cross section spectrum shows a broad dip centered at 1025 nm, which we do not observe at all. Data reported in the present work are in very good agreement with the cross sections reported in Ref [13] relative to Yb:CALGO.

### 3. Laser experiments

Initially we used a 400-mW, single-mode fiber-coupled (FC) laser diode (JDSU S27-7602-400) emitting at 976 nm as pump source. By properly coiling the diode laser fiber pig-tail we were able to induce a strongly elliptical polarization with a ratio about 13:1 between the two axes. The diode laser beam was collimated by means of an aspherical lens (L1, see Fig. 3) and focused on a w ≈12 μm spot in the active medium by a spherical lens (L2 in Fig. 3). A half-wave plate (HWP) at 976 nm was used to adjust the pump beam polarization principal axis along theYb:CALYO crystal *c*-axis. Considering the optical transmission of the pump lenses, the HWP and cavity pump mirror M1 (see Fig. 4), the maximum incident pump power on the Yb:CALYO sample was 390 mW, of which about 360 mW were polarized along the *c*-axis. The X-folded resonator for both Continuous Wave (CW) and Mode-Locked (ML) operations is shown in Fig. 3. The active medium was a 2-mm-long, 5%-doped, *a*-cut Yb:CALYO sample, antireflection (AR) coated for both the pump and laser wavelength. The crystal was simply placed on a metallic plate and oriented with a small tilt angle with respect to the normal incidence in order to avoid unwanted etalon effects. Given the diffraction-limited pump beam quality and the Yb:CALYO refractive index n = 1.85, the pump beam confocal parameter was $2z_R$ ≈1.7 mm, fairly well matched to the crystal length. In order to minimize the cavity mode astigmatism in the active medium, the resonator curved mirror folding angles were kept as small as possible. Given the mechanical constraints, this corresponded to an angle of incidence on M1, M2 of about 2.2°. In both CW and ML operation, we exploited the 2nd stability region of the resonator (corresponding to larger separation M1-M2). Therefore, we could control the cavity mode waist on the HR mirror by properly adjusting the distance M2-HR and M1-M2 separation. The cavity arm lengths were as follows: M2-HR = 180 mm; M1-M2 = 99 mm; M1-OC = 400 mm both in CW and ML experiments. Through ABCD modeling of the resonator we could estimate a fundamental cavity mode radius in the active medium ranging from 12 to 15 μm within the stability region.

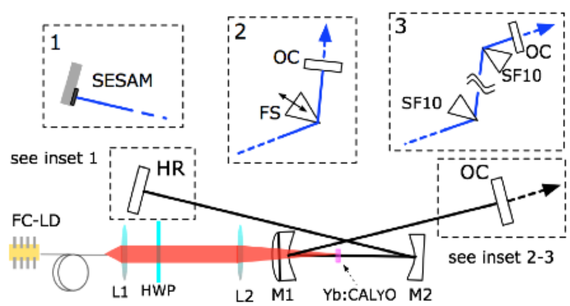


Fig. 3. Resonator layout: FC-LD: Single-mode fiber-coupled laser diode; L1: Aspherical lens (f = 15.3 mm, NA 0.16); HWP: Half-wave plate AR coated at 976 nm; L2: Spherical lens (50 mm focal); M1: Concave mirror, R = 50 mm, high reflectivity (HR) at 1000–1100 nm, high transmissivity at 940–980 nm; M2: Concave mirror, 100 mm radius of curvature; HR: Flat mirror HR between 1000 and 1100 nm; OC: Output coupler, 30’ wedge; SF10 and FS: Dispersive prisms; SESAM: Semiconductor saturable absorber mirror.

The results obtained in CW regime for a set of different Output Couplers (OCs) are shown in Fig. 4. With the optimum T = 5% OC we obtained up to 157 mW at an absorbed pump power of 350 mW (45% optical-to-optical efficiency). A maximum slope efficiency of 58% was measured with the 10% transmission OC. In order to assess the total (cavity + crystal) losses δ, and the intrinsic slope efficiency $\eta_0$, we performed a Caird slope analysis fitting the measured slope efficiencies as a function of the output coupling with the following equation [15] (pump and laser wavelengths determine the upper limit for laser efficiency):

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$$\eta = \eta_0 \frac{\lambda_p}{\lambda_l} \frac{-\ln(R_{OC})}{\delta - \ln(R_{OC})} \tag{1}$$

The best fit yields an intrinsic slope efficiency (accounting for mode-matching efficiency and quantum efficiency) of $\eta_0 = 0.7$ and total resonator losses, excluded the reabsorption losses in the Yb-doped crystal, of $\delta = 1.1\%$. Given the 4 mirrors resonator design and the AR coated crystal facets, the relatively low cavity losses we estimated suggest a good optical quality of the Yb:CALYO sample.

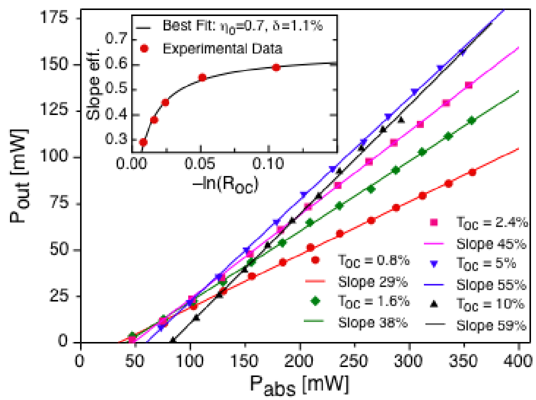


Fig. 4. CW performance with different OCs. Inset: slope efficiency as function of output coupler mirror reflectivity is shown.

For the CW-ML experiments, we modified the resonator as depicted in Fig. 3. The HR flat mirror was replaced by a semiconductor saturable absorber mirror (SESAM) having 3% modulation loss and a saturation fluence of ~140 µJ/cm$^2$ . For group delay dispersion (GDD) compensation we used a pair of SF10 prisms separated by a distance of about 230 mm (tip to tip), corresponding to a maximum negative dispersion of about −1700 fs$^2$. CW-ML regime was readily obtained. Optimizing the cavity alignment and the prisms insertion with $T_{OC}$ = 0.4% output coupler, we obtained optical spectra as wide as about 29 nm. The corresponding pulse duration of 43 fs was close to Fourier transform limit for sech$^2$ shaped pulses ($\Delta\nu\Delta\tau$ = 0.33). In these operating conditions the average output power was about 20 mW and the ML regime was self-starting. The autocorrelation trace and optical spectrum of the shortest pulses are shown in Fig. 5(a). In order to explore the tuning range of the center wavelength in the ML regime, we also performed experiments employing a single prism for GDD compensation. In order to limit the spatial filtering of the spectral components in the active medium [16], we opted for a single fused silica (FS) prism in this setup. By ABCD modeling of the resonator we found that the virtual prism was positioned about 55 mm away from mirror M1 [17]. The optimal distance between virtual and real prism was in this case about 500 mm (corresponding to a maximum negative dispersion of about −1100 fs$^2$). For shorter distances, the intracavity net negative dispersion was not sufficient to sustain soliton ML. With the same T = 0.4% OC employed in the previous experiments, the shortest pulse duration we obtained was about 45 fs, with an average output power of 30 mW and a 29.5 nm FWHM wide spectra (time-bandwidth product $\Delta\nu\Delta\tau$ = 0.36). This is to the best of our knowledge the shortest pulse duration ever reported for a single-prism, mode-locked laser resonator. By simply rotating the OC around its vertical axis we were able to tune the center wavelength in the soliton ML regime from 1035 to 1075 nm. It is worth noticing that in a wide portion of this spectral region extending from 1040 to 1070 nm, the pulse duration was always below 65 fs. The tuning range and shortest pulse autocorrelation trace are shown in Fig. 5(b).

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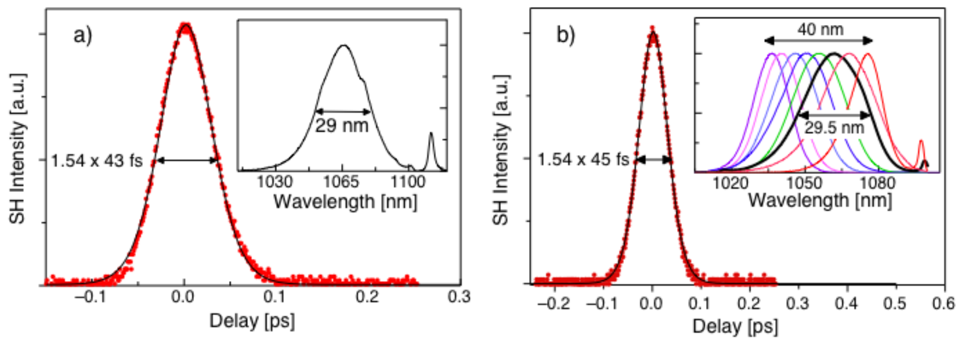


Fig. 5. a) Autocorrelation trace and optical spectrum (inset) of the shortest pulses obtained with the T = 0.4% OC; b) Autocorrelation trace of the shortest pulses obtained with the single-prism setup. In the inset, the tuning range of the output spectrum is shown; the highlighted spectrum (bold black line) corresponds to the autocorrelation shown in the main graph.

We also took advantage of the lower intracavity losses granted by the single-prism setup to explore the maximum output power of our setup in mode-locking regime. Best results were obtained employing a T = 3% OC, which yielded stable pulses trains with 91 mW average output power (26% optical-to-optical conversion efficiency) and 75 fs pulse duration.

In order to investigate the potential power-scaling of the laser, we carried out some preliminary tests in a different resonator pumped by a 10-W, 100-μm fiber-coupled single-emitter pump laser diode. In this experiment, GDD compensation was realized by means of GTI mirrors providing −55 $fs^2$ per bounce. In order to achieve the necessary net negative GDD for soliton ML, we arranged multiple bounces on the GTI mirrors. Best results were obtained for a total number of bounces equal to 10, corresponding to −1100 $fs^2$ per roundtrip. At about 3.7 W of absorbed pump power, employing an OC mirror with 2.5% transmission, we obtained 67-fs stable mode-locked pulses with an average output power of 410 mW at the repetition rate of 67 MHz. The corresponding optical spectrum was centered at 1055 nm and was 17.5 nm at FWHM, resulting in a time-bandwidth product ≈0.32 close to the Fourier transform limit.

## 4. Conclusions

We have reported a detailed spectroscopic comparison of Yb:CALYO and Yb:CALGO, showing that these two promising laser crystals can perform very similarly. Indeed, we have provided strong evidence that ultrafast oscillators based on either such crystal perform very much alike, yielding extremely short pulses of 43/40 fs with 400/350-mW single-mode pump laser diodes and SESAM mode-locking. This represents a nearly four-times pulse width reduction with respect to the earlier report on femtosecond Yb:CALYO oscillators [10]. It is not clear whether the emission spectrum differences reported Ref [9] can explain this significant difference in mode-locked performance, although the relevant *σ*-polarized emission spectrum appears to be similar in both cases.

It is known that the intrinsically faster pulse dynamics of KLM allows even shorter pulses, as well as higher pump power allowing higher pulse energy [4]. Therefore, our research suggests that further significant improvements might be achieved in this direction. We have also reported output power of ≈400 mW with multimode diode pumping, and sub-100-fs pulses, proving the easy power scalability of the oscillator, necessary for expanding the application range beyond the low-power seeding of amplifiers (direct use in ultrafast nonlinear imaging systems, or pumping of ultrafast OPOs, for example). Further power scaling of Yb:CALYO oscillators should also be possible, as we already demonstrated for Yb:CALGO where up to 12.5 W with 94-fs pulses was reported [18]. Like Yb:CALGO, we also expect that also Yb:CALYO will be an extremely interesting laser material for development of high-power ultrafast amplifiers.

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