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SESAM mode-locked Yb:SrLaAlO₄ laser

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Abstract: We report on a detailed investigation of continuous-wave and SESAM mode-locked (ML) laser operation of an Yb:SrLaAlO₄ laser. Pumped with a high-brightness fiber laser at 976 nm, the ML Yb:SrLaAlO₄ laser delivered soliton pulses as short as 38 fs at 1071 nm with an average output power of 86 mW and a pulse repetition rate of ~59 MHz. The maximum average output power reached 1.05 W at 1054 nm for longer pulses (94 fs), corresponding to a peak power of 146 kW and an optical efficiency of 38.6%. To the best of our knowledge, this is the first demonstration of SESAM ML operation of the Yb:SrLaAlO₄ laser.

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1. Introduction

Ytterbium ion (Yb³⁺) doped tetragonal aluminates, e.g., Yb:CaGdAlO₄ (abbreviated Yb:CALGO) and Yb:CaYAlO₄ (abbreviated Yb:CALYO), represent a type of broadband, structurally disordered laser gain media which are extremely suitable for the generation of high-power femtosecond pulses from passively mode-locked (ML) lasers in the spectral region of ~1 μm [1-4]. Yb:CALGO and Yb:CALYO crystals belong to the ABCO₄ crystal family, where A = Ca or Sr, B = Y, Gd, La, etc., and C = Al or Ga. Due to the inhomogeneous spectral broadening originating from their local structure disorder, Yb:CALGO and Yb:CALYO crystals exhibit extremely broad, smooth and flat gain spectral profiles which, combined with attractive thermo-optical properties [5], such as relatively high thermal conductivity and nearly “athermal” behavior, determine their successful applications in the generation of high-average power sub-100 fs soliton pulses at ~1 μm [6-12]. The shortest pulse duration (<30 fs) were achieved via the soft-aperture Kerr-lens mode locking (KLM) technique from Yb:CALGO and Yb:CALYO lasers [13-16].

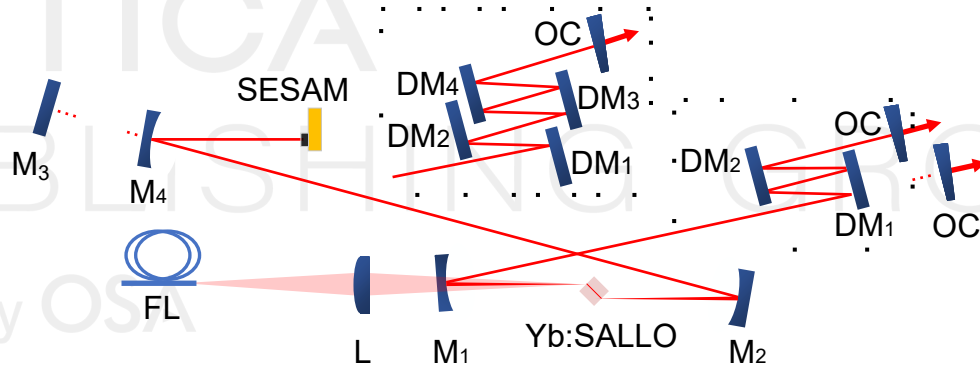
The success of the Yb:CALGO and Yb:CALYO crystals paves the way to further explore other Yb³⁺-doped disordered aluminate crystals as femtosecond laser gain media. Very recently, we developed a novel Yb³⁺-doped strontium lanthanum aluminate crystals grown by the Czochralski method, i.e., Yb:SrLaAlO₄, abbreviated Yb:SALLO [17]. It is also an ABCD₄-type compound belonging to the tetragonal system with a K₂NiF₄ structure (space group *I4/mmm*). The Yb:SALLO crystal exhibits relatively large absorption bandwidths of 24 nm for π- and 14 nm for σ-polarization (full width half maximum, FWHM). The broadband absorption releases the requirement of wavelength stabilization for the pump sources and facilitates power scaling by using commercially available high-power InGaAs laser diodes. The lattice disorder in the structure of the Yb:SALLO crystal provides a variation of the local crystal field around

48 the Yb³⁺ dopants ions resulting in a considerable inhomogeneous spectral broadening. As a
 49 result, Yb:SALLO exhibits also broad, flat and smooth spectral gain profiles supporting sub-
 50 50 fs pulse generation from ML lasers. Recently, we demonstrated the first passively ML
 51 operation of an Yb:SALLO laser with soliton pulses as short as 44 fs via soft-aperture KLM
 52 technique [18]. Compared to its Yb:CALGO and Yb:CALYO counterparts, Yb:SALLO
 53 features: (i) lower melting point (~1650°C) [19], (ii) higher crystallinity and better optical
 54 quality and (iii) slightly broader spectra of Yb³⁺ dopant ions. The drawback of SALLO is the
 55 lower segregation coefficient for Yb³⁺ ions, $K_{Yb} = 0.235$ [17].

56 The promising spectroscopic features, as well as the previous promising ML results
 57 motivated us to further explore the potential of Yb:SALLO. Implementing a SEMiconductor
 58 Saturable Absorber Mirror (SESAM) for starting and stabilizing the soliton pulse generation
 59 and dispersive mirrors (DMs) for intracavity group delay dispersion (GDD) management, we
 60 demonstrate sub-40 fs soliton pulse generation from a SESAM ML Yb:SALLO laser.

61 2. Experimental setup

62 The schematic of the Yb:SALLO laser is shown in Fig. 1. The high quality Yb:SALLO crystal
 63 with an Yb³⁺ doping of $1.36 \times 10^{20} \text{ cm}^{-3}$, corresponding to 1.175 at.% was employed. A cubic
 64 sample with an aperture of $3 \text{ mm} \times 3 \text{ mm}$ and a thickness of 3 mm was cut for light propagation
 65 along the *a*-axis (*a*-cut). This crystal orientation was selected to ensure access to the desirable
 66 π -polarization corresponding to stronger pump absorption. The two sides of the crystal were
 67 polished to laser quality and remained uncoated.



68
 69 **Fig. 1.** Schematic of the Yb:SALLO laser. FL: fiber laser; L: spherical focusing lens; M₁, M₂
 70 and M₄: concave mirrors (RoC = -100 mm); M₃: flat rear mirror used in the CW regime; DM₁ -
 71 DM₄: flat dispersive mirrors; OC: output coupler; SESAM: SEMiconductor Saturable Absorber
 72 Mirror.

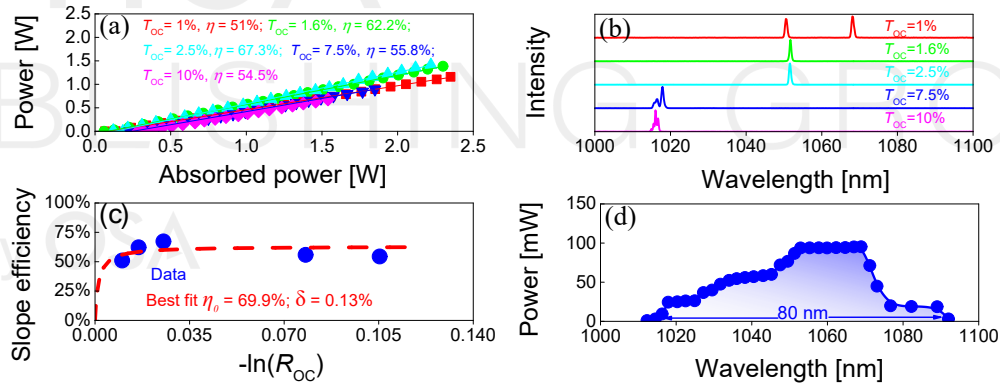
73 An X-folded astigmatically compensated linear cavity was constructed to evaluate the
 74 performance of the Yb:SALLO crystal both in the continuous-wave (CW) and ML regimes.
 75 The laser crystal was mounted in a water-cooled copper holder (coolant temperature: 20°C) and
 76 placed at the Brewster's angle between the two concave mirrors M₁ – M₂ (radius of curvature,
 77 RoC = -100 mm) to minimize the insertion loss. The pump source was a CW, narrow-linewidth
 78 (50 kHz) fiber laser at 976 nm. It emitted a nearly diffraction-limited beam with a propagation
 79 factor (M^2) of ~1.03. The pump beam was focused into the laser crystal through the dichroic
 80 mirror M₁ by a spherical focusing lens with a focal length of 75 mm, which resulted in a beam
 81 waist of $16.2 \mu\text{m} \times 29.5 \mu\text{m}$ in the sagittal and tangential planes, respectively.

82 In the CW regime, a four-mirror cavity was used: one cavity arm was terminated by a flat
 83 rear mirror M₃ and another arm – by a flat-wedged output coupler (OC) having a transmission
 84 at the laser wavelength T_{OC} in the range 1% - 10%, see Fig. 1. The cavity mode size in the
 85 crystal by the ABCD formalism yielded the radii of $24 \mu\text{m} \times 47 \mu\text{m}$ in the sagittal and the
 86 tangential planes, respectively.

87 For ML operation, the mirror M_3 was replaced by a curved mirror M_4 (RoC = -100 mm) to
 88 create a second beam waist on the SESAM to ensure its deep bleaching. A commercial SESAM
 89 (BATOP, GmbH) with a modulation depth of 1.2%, a relaxation time of ~ 1 ps and a non-
 90 saturable loss of $\sim 0.8\%$ was implemented for starting and stabilizing the ML operation. The
 91 calculated radius of this second beam waist was ~ 77 μm . The intracavity GDD was optimized
 92 by inserting two or four different flat dispersive mirrors (DMs) in the other cavity arm having
 93 a negative GDD per bounce of: $\text{DM}_1 = -250$ fs^2 , $\text{DM}_2 = -250$ fs^2 , $\text{DM}_3 = -100$ fs^2 and $\text{DM}_4 = -$
 94 55 fs^2 . The group velocity dispersion (GVD) of the Yb:SALLO crystal was estimated from the
 95 dispersion curves [20] to be 220 ± 50 fs^2/mm at 1050 nm for π -polarization.

96 3. Continuous-wave laser operation

97 The Yb:SALLO laser generated a maximum CW output power of 1.42 W at 1051.6 nm with a
 98 high slope efficiency of 67.3% and a low laser threshold of 121 mW (for $T_{\text{OC}} = 2.5\%$ and an
 99 absorbed pump power of 2.22 W), see Fig. 2(a). The measured single-pass pump absorption
 100 under lasing conditions depended on the transmission of the OCs ranging from 25% to 49%,
 101 indicating a certain ground-state bleaching being suppressed by the recycling effect. The laser
 102 threshold gradually increased with the transmission of the OC, from 66 mW ($T_{\text{OC}} = 1\%$) to
 103 285 mW ($T_{\text{OC}} = 10\%$). The laser spectra varied with the output coupling: for low T_{OC} of 1%,
 104 the laser operated at two lines, 1050 and 1068 nm, for intermediate $T_{\text{OC}} = 1.6\% - 2.5\%$ - only
 105 at ~ 1051 nm and for high $T_{\text{OC}} = 7.5\% - 10\%$ - at yet shorter wavelength of ~ 1016 nm, see
 106 Fig. 2(b). Such a blue-shift of the laser wavelength with increasing the output coupling is
 107 typical for quasi-three-level Yb^{3+} lasers with inherent reabsorption at the laser wavelength and
 108 it agrees with the gain spectra of Yb:SALLO for π -polarization [17].



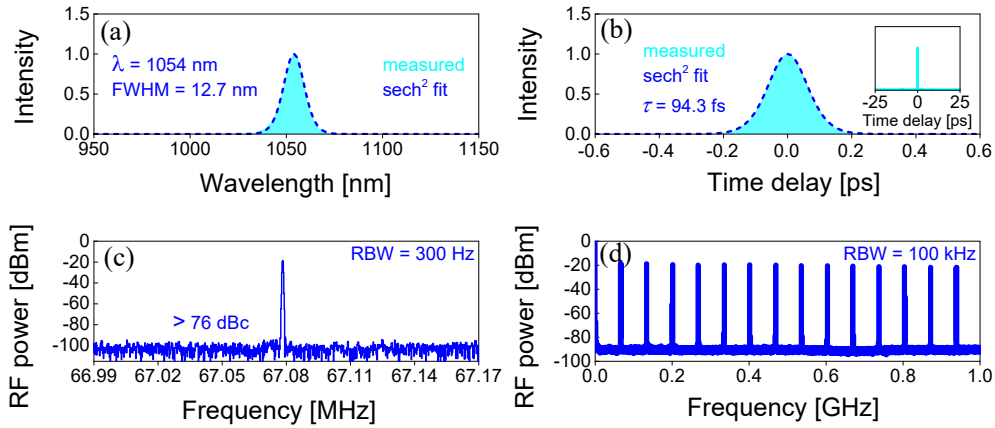
109
 110 **Fig. 2.** (a) CW performance of the Yb:SALLO laser with different OCs, η – slope efficiency;
 111 (b) laser spectra; (c) Caird analysis: slope efficiency plotted as a function of the OC reflectivity
 112 ($R_{\text{OC}} = 1 - T_{\text{OC}}$); (d) spectral tuning curve obtained with an intracavity SF10 prism and an OC
 113 with $T_{\text{OC}} = 0.6\%$.

114 The total round-trip resonator losses δ (reabsorption losses excluded) as well as the intrinsic
 115 slope efficiency η_0 (accounting for the mode-matching efficiency and the quantum efficiency)
 116 were estimated using the Caird analysis by fitting the laser slope efficiency as a function of the
 117 OC reflectivity ($R_{\text{OC}} = 1 - T_{\text{OC}}$) [21]. The best fitting curve gave $\eta_0 = 69.9\%$ and $\delta = 0.13\%$, as
 118 shown in Fig. 2(c). Such low value of δ is an evidence for the excellent optical quality of the
 119 Yb:SALLO crystal. The spectral tuning curve in the CW regime was studied at an absorbed
 120 pump power of 0.77 W using a SF10 prism and a 0.6% OC. The wavelength was continuously
 121 tunable between 1012 - 1092 nm corresponding to a range as broad as 80 nm, Fig. 2(d).

122 4. Mode-locked laser operation

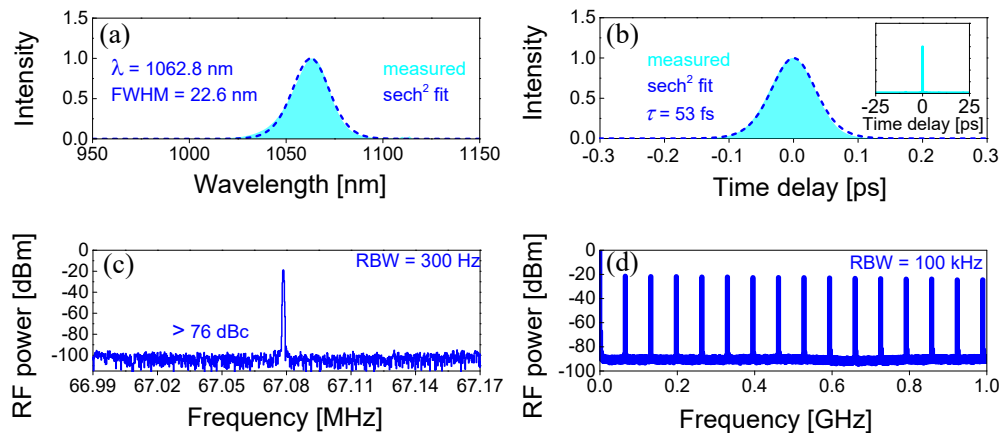
123 Stable and self-starting SESAM ML operation was readily achieved by implementing two flat
 124 DMs ($\text{DM}_1 - \text{DM}_2$) into the cavity arm terminated by the OC, Fig. 1, which provided a total

125 round-trip negative GDD of -2000 fs^2 to balance the material dispersion, as well as the induced
 126 self-phase modulation (SPM).



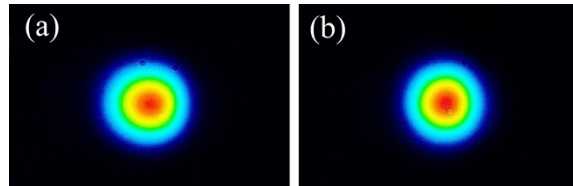
127
 128 **Fig. 3.** SESAM ML Yb:SALLO laser with $T_{OC} = 2.5\%$. (a) Optical spectrum and (b) SHG-based
 129 intensity autocorrelation trace. *Inset* in (b): autocorrelation trace in a time span of 50 ps. RF
 130 spectra: (c) fundamental beat note at ~ 67 MHz recorded with a resolution bandwidth (RBW) of
 131 300 Hz, and (d) harmonics on a 1-GHz frequency span, RBW = 100 kHz.

132 For 2.5% OC, the measured optical spectrum and the second harmonic generation (SHG)
 133 based intensity autocorrelation trace are shown in Fig. 3(a) and Fig. 3(b), respectively. The
 134 observed excellent sech²-shaped spectral and temporal profiles (although in theory in both cases
 135 this is an approximation) are an evidence for soliton-like pulse generation. The pulse duration
 136 of 94.3 fs at a central wavelength of 1054 nm and the emission bandwidth (FWHM) of 12.7 nm
 137 correspond to a time-bandwidth product (TBP) of 0.323 indicating nearly bandwidth-limited
 138 pulses. The inset of Fig. 3(b) shows an intensity autocorrelation trace on a longer time scale
 139 (50 ps) indicating single-pulse mode-locking without multiple pulse instabilities. The average
 140 output power of the ML laser amounted to 1.05 W for an absorbed pump power of 2.72 W.
 141 This corresponds to an optical efficiency of 38.6%. The recorded radio frequency (RF)
 142 spectrum of the laser output is shown in Fig. 3(c) and (d). A sharp peak at the fundamental beat
 143 note of 67.08 MHz exhibited a high extinction ratio of 76 dBc above the noise level. The
 144 uniform harmonics on a 1-GHz frequency span reveal high stability of the ML operation.



145
 146 **Fig. 4.** KLM assisted SESAM ML Yb:SALLO laser with $T_{OC} = 2.5\%$. (a) Optical spectrum and
 147 (b) SHG-based intensity autocorrelation trace. *Inset*: autocorrelation trace on a time span of
 148 50 ps. RF spectra: (c) fundamental beat note at ~ 67 MHz recorded with a resolution bandwidth
 149 (RBW) of 300 Hz, and (d) harmonics on a 1-GHz frequency span, RBW = 100 kHz.

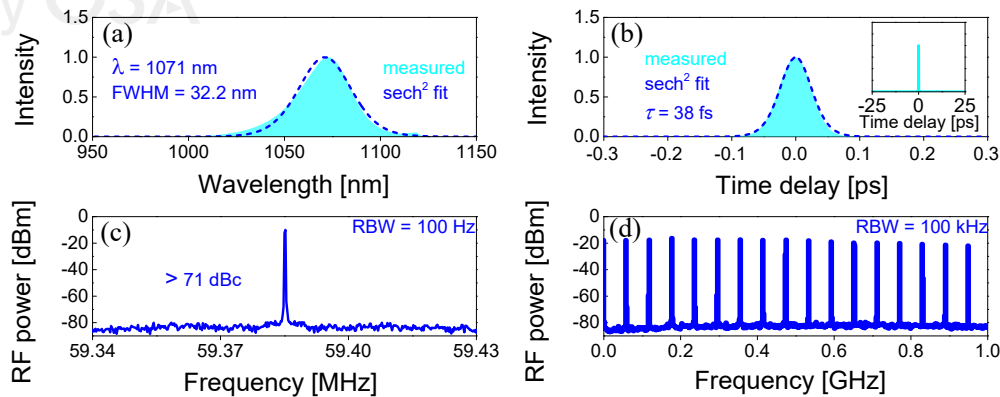
150 A rapid spectral broadening was observed by translating the folding mirror M_2 by few
 151 hundred of micrometers away from the laser crystal. After carefully aligning the cavity, the
 152 bandwidth (FWHM) of the laser spectrum increased from 12.7 to 22.6 nm, the average output
 153 power dropped to 404 mW and the central laser wavelength experienced a red-shift to
 154 1062.8 nm, see Fig. 4(a). The recorded autocorrelation trace gave a pulse duration of 53 fs
 155 (FWHM), as shown in Fig. 4(b). The corresponding TBP of 0.318 was even closer to the
 156 Fourier-transform limit. The long-time autocorrelation trace (Fig. 4(b), inset) and the RF
 157 spectra, Fig. 4(c-d), confirmed similarly stable and single pulse mode-locking performance.



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Fig. 5. Measured far-field beam profiles of the ML Yb:SALLO laser: transition of (a) SESAM ML to (b) Kerr-lens assisted SESAM ML regimes.

161 Far-field beam profiles were measured to reveal the dominating ML mechanism for such a
 162 transition. An IR camera was placed ~ 1.1 m away from the OC. In the SESAM ML regime (cf.
 163 Fig. 3), the laser beam diameters were $2.10 \text{ mm} \times 1.96 \text{ mm}$, see Fig. 5(a). After spectral
 164 broadening (cf. Fig. 4), a significant change appeared in the measured far-field beam profile
 165 with a beam diameter of $1.89 \text{ mm} \times 1.89 \text{ mm}$, see Fig. 5(b). The shrinking of the far-field beam
 166 profile validated the underlying spectral broadening mechanism dominated by Kerr-lens mode-
 167 locking (KLM) stabilized by the SESAM, which is supported by the high-brightness of the
 168 pump laser. Such soft-aperture Kerr-lens effect occurred due to the gradually increasing laser
 169 mode size inside the Yb:SALLO crystal when varying the separation between the pump mirror
 170 M_1 and the folding mirror M_2 . Nevertheless, pulse shaping by the SESAM cannot be ruled out
 171 in view of the much wider stability zone and the self-starting mode-locking operation compared
 172 to our previous work [18]. Such hybrid pulse shaping mechanism introduced an enhanced self-
 173 amplitude modulation (SAM) by the Kerr-lens effect, which assisted the SESAM ML operation
 174 for shorter pulse duration, i.e., Kerr-lens assisted SESAM ML operation.



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Fig. 6. Characterization of the shortest pulses from the ML Yb:SALLO laser. (a) Optical spectrum and (b) SHG-based intensity autocorrelation trace with a sech^2 -fit. *Inset:* simultaneously measured long-scale background free intensity autocorrelation trace for the time span of 50 ps. Radio-frequency (RF) spectra of the ML Yb:SALLO laser: (a) fundamental beat note at ~ 59.4 MHz recorded with a resolution bandwidth (RBW) of 100 Hz, and (b) harmonics on a 1-GHz frequency span, measured with a RBW of 100 kHz.

182 The pulse duration could be further shortened by reducing the total intracavity negative
 183 GDD in the Kerr-lens assisted SESAM ML regime. By implementing two extra bounces on flat

184 DMs (DM₃ and DM₄, see Fig. 1) with a total negative intracavity GDD of -1620 fs², the
185 Yb:SALLO laser delivered soliton pulses as short as 38 fs at 1071 nm for the same 2.5% OC,
186 see Fig. 6(a) and (b). The optical spectrum of the ML laser had a bandwidth (FWHM) of
187 32.2 nm assuming a sech²-shape spectral profile (due to the very strong SPM, the measured
188 spectrum exhibited a slight deviation from such an ideal sech²-shaped spectral profile). The
189 average output power amounted to 86 mW at an absorbed pump power of 0.78 W. The resulting
190 TBP was 0.32, very close to the Fourier transform limit value (0.315). The steady-state ML
191 pulse train corresponding to the shortest pulse duration was characterized by long scale
192 autocorrelation, inset Fig. 6(b), and RF spectra, as shown in Fig. 6(c) and (d). The sharp first
193 beat note at ~59.4 MHz with a signal-noise-ratio above 71 dBc, and the uniform harmonics
194 again proved stable CW mode-locking without any Q-switched instability.

195 5. Conclusion

196 In conclusion, we demonstrate for the first time, to the best of our knowledge, SESAM ML
197 operation of an Yb:SALLO laser. Assisted by enhanced self-amplitude modulation (SAM)
198 originating from the Kerr-lens effect, the laser produced soliton pulses as short as 38 fs at
199 1071 nm with an average output power of 86 mW. Watt-level sub-100 fs pulse generation was
200 obtained in the SESAM ML regime at the expense of longer pulse duration of 94.3 fs at
201 1054 nm: the average output power reached 1.05 W at an absorbed power of 2.72 W, which
202 corresponded to a peak power of 146 kW and an optical efficiency of 38.6%. The excellent
203 spectroscopic and thermo-mechanical properties of the Yb:SALLO crystal reveals a great
204 potential for power scalable operation in the sub-50 fs time domain via Kerr-lens assisted
205 SESAM ML technique in combination with commercially available high-power InGaAs pump
206 diode lasers.

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212 **Disclosures.** The authors declare no conflicts of interest.

213 **Data availability.** Data underlying the results presented in this paper are not publicly available at this time but may
214 be obtained from the authors upon reasonable request.

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