High peak power gigahertz Yb:CALGO laser

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Abstract: We present a high-power gigahertz SESAM modelocked Yb:CALGO laser with sub-60-fs pulses. The laser delivers an average output power of 2.95 W at a pulse repetition rate of 1.8 GHz in fundamental modelocking without additional pulse compression or amplification. Stable modelocking with a single pulse per cavity round-trip is confirmed and results in an output peak power of 24.3 kW and a pulse energy of 1.64 nJ. The laser is pumped by a commercial multimode diode laser, which improves the reliability and robustness. This high-power gigahertz laser is expected to enable numerous applications in frequency metrology.

OCIS codes: (320.0320) Ultrafast optics; (140.0140) Lasers and laser optics; (140.3615) Lasers, ytterbium; (140.3480) Lasers, diode-pumped.

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1. Introduction

Progress in ultrafast solid-state laser technology has been pushing the knowledge frontier in optical science and enabled many industrial applications. The gigahertz pulse repetition rate regime is interesting for nonlinear bio-imaging and spectroscopy [1], ultra-high-speed optical communications [2, 3] and time and frequency metrology [4–6]. Solid-state lasers, fundamentally modelocked with semiconductor saturable absorber mirrors (SESAMs) [7–9] can generate very stable optical frequency combs [10], which define the standards for precision in science and technology in the megahertz regime.

Applications for optical frequency combs benefit from high pulse repetition rates. Gigahertz frequency combs are more compact and their optical spectrum is less dense, providing easier access to the individual comb lines. In addition, for a given average power, the power per comb line is increased, which improves the signal-to-noise ratio (SNR) and reduces acquisition time in comb-based experiments. Currently stabilized frequency combs in the gigahertz range are still pre-dominately based on Ti:sapphire lasers. Kerr-lens modelocked (KLM) Ti:sapphire lasers produce extremely short pulse durations at very low noise levels and support stable frequency combs with up to 10-GHz [11]. Several demanding applications, such as the Astrocomb [12] and ultrastable optical clocks [13] would benefit from even higher repetition rates, but KLM becomes increasingly more difficult because of its complicated coupling between absorber and cavity stability regime [14]. Furthermore green pumping with complex and expensive single-mode lasers increases the cost and therefore limits more widespread industrial applications. Fiber lasers are more attractive but very power-limited in the gigahertz regime [15, 16]. Typical gigahertz fiber lasers require external pulse amplification and compression to achieve ultrashort pulses and high-power operation [17]. This increases the overall complexity and leads to higher noise, deteriorating the desired performance even further.

SESAM modelocked diode-pumped solid-state lasers (DPSSLs) are ideal sources for extremely stable frequency combs [10, 18]. They combine the favorable properties of direct diode-pumping and the intrinsic low-noise operation of a high-Q cavity [19]. The laser geometry allows for very high repetition rates exceeding the 100-GHz benchmark [20, 21]. In contrast to KLM, SESAM modelocking enables reliable self-starting modelocking and operation without critical cavity alignment. Yb-based DPSSLs can achieve Watt-level average output powers without pulse amplification even at gigahertz repetition rates [9, 22], and they benefit from direct diode pumping with a low quantum defect. Being able to directly use inexpensive high-power pump diode arrays is a major advantage compared to Ti:sapphire lasers.

Recently gigahertz DPSSLs have shown remarkable progress. Kerr-lens modelocked DPSSLs have achieved pulse durations of ~150 fs and up to 6-GHz repetition rate, but their output powers are limited to the 10 mW range [23, 24]. Using SESAM modelocking, the shortest pulse duration of 55 fs was obtained from a 1-GHz Cr:LiSAF oscillator. The laser was pumped by six individual pump diodes and was limited to 110 mW of average output power [25]. Yb-based potassium tungstate lasers (Yb:KGW and Yb:KYW) have shown higher repetition rates [26] and high efficiency [27]. Long-term sustained operation at kW-

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level peak power have been demonstrated at 2.8 GHz [28]. High average output power enabled the first self-referenceable frequency comb from a gigahertz DPSSL using passive pulse compression [29]. More recently a 1.1-GHz Yb:KGW laser generated both high-power operation and ultrashort pulses with 125-fs duration [30]. This laser enabled a strong carrier envelope offset (CEO) beat signal without pulse amplification or compression in the gigahertz range [4].

The generation of ultrashort pulses in the gigahertz range from DPSSLs is more challenging since the limited cavity length typically needs to accommodate two separate components for gain and absorber. In addition, the reduced pulse energies in the gigahertz regime increase the tendency for Q-switching instabilities [31]. The recent results with novel semiconductor lasers may offer even further simplifications in the future [32]. Meanwhile with regards to DPSSLs an excellent gain material for the generation of ultrashort pulses in the sub-100 fs range is Yb:CALGO [33]. Several state-of-the-art laser results are based on this material [34–36]. However only megahertz pulse repetition rates have been reported with this laser material so far.

Here we demonstrate the first gigahertz Yb:CALGO laser. At pulse repetition rate of 1.8 GHz we have demonstrated a record-short pulse duration of 59.4 fs without external pulse compression. These are the shortest pulses of any Yb-based laser in the gigahertz range to date. The combination of ultrashort pulses (i.e. sub-60 fs), high average output power (i.e. 2.95 W) and gigahertz pulse repetition rate (i.e. 1.8 GHz) makes this laser a unique source for high-power gigahertz frequency combs.

2. Experimental setup

The laser is based on an a-cut Yb(5% at.)-doped CALGO crystal (Yb:CaGdAlO$_4$) of 2-mm thickness with broadband anti-reflection coatings on both sides. Yb:CALGO provides an exceptional broad and smooth absorption and emission cross section [33], ideally suited for generating ultrashort pulses in the range of sub-100 fs. Additionally beneficial is the relatively low group delay dispersion (GDD; we measured + 108 fs^2/mm with a white light interferometer). The high thermal conductivity and low quantum defect of Yb:CALGO reduce undesired thermal lensing. In comparison to the more widely used Yb:KGW/KYW the tendency for Q-switched modelocking is slightly increased due to the higher gain saturation fluence.

Usually only high-brightness pump lasers are used for high repetition rate lasers [26, 37], since a tight focus is required in the gain to avoid Q-switching instabilities [31]. However, single-mode pump diodes are usually limited in power to a few hundred milliwatts. Instead of a cumbersome combination of multiple low-power pump diodes or using highly sensitive tapered amplifiers, we use a commercially available transversal-multimode fiber-coupled laser diode. This simple and robust pumping scheme offers high power and reduces the overall complexity and cost.

The fiber-coupled multimode pump diode (OCLARO, BMU25A-975-01-R03) delivers up to 25 W output power and provides a 4-nm broad spectrum centered around 974 nm at room temperature. For spectral overlap with the 979.5-nm absorption of Yb:CALGO we operated the pump diode at 45°C. The pump light is emitted by a multimode fiber with a 105-µm core diameter and a numerical aperture of 0.15. The comparable low brightness (measured $M^2 \approx 16$) necessitates achromatic pump optics and a careful cavity design to just enable a relatively small gain mode size. The integrated overlap of the low-brightness pump light with the fundamental mode of the cavity is calculated to be 77%, assuming a flat-top and a Gaussian beam profile with diameters of 107 µm and 115 µm, respectively. An insufficient overlap could either introduce reabsorption losses by the Yb-ions or degrade the beam quality. For our laser we confirmed undisturbed single-mode TEM$_{00}$ operation with a measured M^2 value of 1.03.

The laser setup is based on a Z-shape cavity (see Fig. 1). The limited number of cavity elements in gigahertz lasers reduces flexibility for dispersion management and makes the generation of ultrashort pulses experimentally more challenging. For this laser only a single Gires-Tournois interferometer (GTI) type mirror was used for dispersion compensation, leading to stable soliton modelocking, obtained by the balance between self-phase-modulation (SPM) and an overall negative group delay dispersion in the cavity [38].

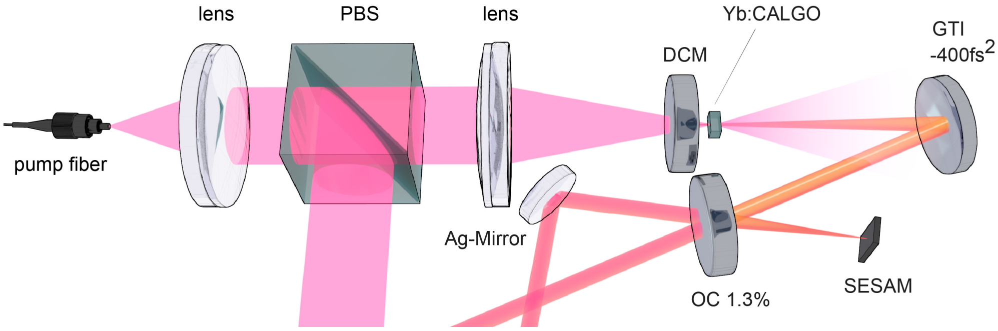

Fig. 1. Experimental setup of the 1.8-GHz SESAM modelocked diode-pumped Yb:CALGO laser oscillator: The gain crystal is end-pumped through a dichroic mirror (DCM). The Z-shaped cavity is formed by the DCM, a curved dichroic GTI mirror for dispersion compensation, a flat output coupler with 1.3% transmission and the SESAM placed as the second end-mirror. The intra- and extra-cavity beams are illustrated in red and the pump laser beam in purple. With this cavity design we have two output beams and the quoted output power is the added output power in each beam.

The GTI mirror provides a negative GDD of 400 fs^2 per bounce over a wavelength range of 60 nm centered at 1050 nm. We note that the GDD of all other cavity mirrors is negligible. In addition, the GTI mirror provides high transparency for the pump laser wavelength, which eliminates residual pump light and reduces the thermal load in the cavity. The Peltier-cooled Yb:CALGO crystal is pumped through a flat dichroic mirror placed closely to the crystal. The second folding mirror is used as a flat output coupler with 1.3% transmission per pass over a broad wavelength range. A SESAM placed as the second end-mirror is used to start and maintain soliton modelocking [38]. The SESAM is operated with an incident mode size diameter of 225 µm. The SESAM structure is based on an antiresonant design [39, 40] with a single InGaAs quantum well absorber generating a modulation depth of 1.36%, a saturation fluence of 11.3 µJ/cm^2 and nonsaturable losses below 0.3% (measured with 95-fs pulses at a center wavelength of 1051-nm as explained in more details in [41]). The SESAM is soldered onto a copper heat-spreader, which is cooled to 13.8°C using a Peltier element. The modelocking is self-starting and the laser was operated for at least 8 hours without decreasing performance.

3. Results

The SESAM modelocked gigahertz Yb:CALGO laser delivers an average output power of 2.95 W using 9.1 W of incident multimode pump power, giving an optical-to-optical efficiency of 32.3% and a slope efficiency of 37.7%. We measured pulses with record-short duration of 59.4 fs full-width half-maximum (FWHM) using a commercial autocorrelator (Femtochrome, FR-103MN). The second-harmonic autocorrelation trace as shown in Fig. 2(a) is pedestal-free and fits well to an ideal sech^2-pulse shape. The broad optical spectrum spans 25.7 nm FWHM and is centered at 1059.67 nm (Fig. 2(b)). We verified single pulse operation with the autocorrelation and a sampling oscilloscope measurement. Thus we obtained a very high peak power of 24.3 kW directly from this 1.8-GHz oscillator.

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Furthermore, the microwave frequency spectrum verifies cw modelocking without side peaks (Figs. 2(c) and 2(d)).

Figure 3 depicts a scan of the incident pump power and the resulting total average output power and pulse duration. The cw-lasing threshold is located at 949 mW incident pump power and the cw slope efficiency is 26.8%. Modelocking self-starts at a pump power of 4.24 W and is accompanied by a sharp increase in average output power from 876 mW to 1.07 W. The reduced cavity loss with the saturated absorber in the high-Q cavity results in a higher slope efficiency of 37.7%. No Q-switching instabilities are observed at any point of laser operation, despite the relatively large mode sizes in the crystal and on the SESAM.

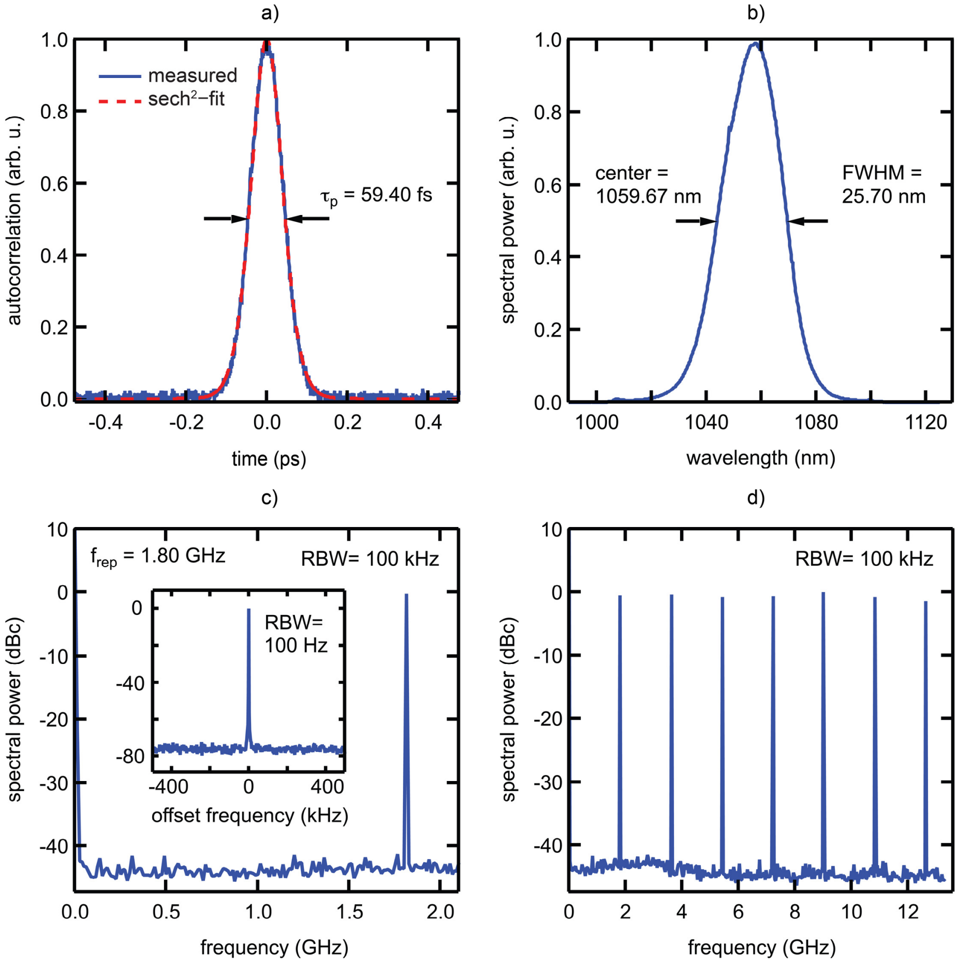

Fig. 2. SESAM modelocked and multimode-diode-pumped gigahertz Yb:CALGO laser: (a) pulse duration of 59.4-fs measured with a SHG-autocorrelation, (b) optical spectrum centered at 1059.67 nm and with a FWHM of 25.7 nm, The gigahertz pulse repetition rate is demonstrated with the microwave spectrum shown in (c) and (d) with different spans. RBW: resolution bandwidth of microwave spectrum analyzer.

The measured pulse duration and time-bandwidth limited duration, calculated from the optical spectrum, are in good agreement at lower powers. For higher powers additional SPM broadening explains the increased time-bandwidth product (TBP) (Fig. 3). At the maximum output power of 2.95 W we obtain a TBP of 0.41 (theoretical limit for sech^2-pulses is 0.315). Pump powers above 9.1 W introduce the generation of double pulses, clearly visible in the

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autocorrelation trace. This is a well-known issue for strongly saturated SESAMs [42] and needs to be checked when high peak power operation is reported. The reduced nonlinear phase shift causes an increase in pulse duration and a reduction in optical bandwidth, but reasonable stable double pulse operation opens the possibility for stable fundamental modelocking at 3.6 GHz, and shows the potential for higher repetition rate scaling with Yb:CALGO.

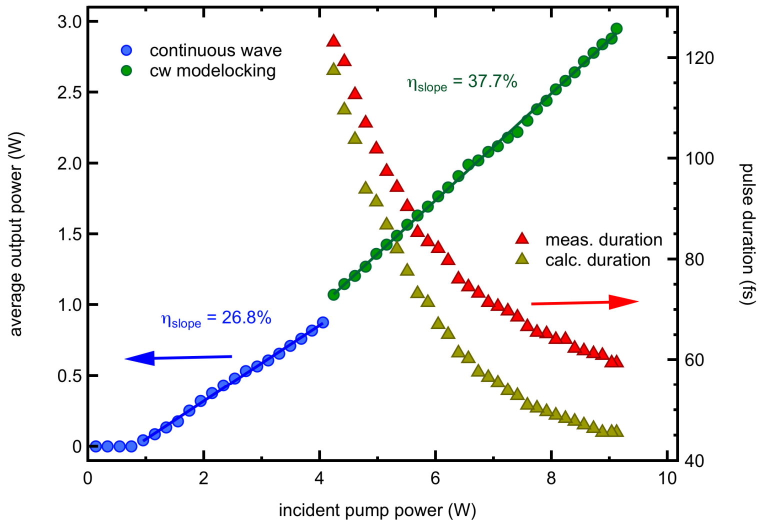

Fig. 3. SESAM modelocked multimode-diode-pumped Yb:CALGO laser at 1.80-GHz pulse repetition rate: Average output power vs. incident pump power with continuous-wave (cw) lasing (blue) and cw modelocking (green) and pulse duration vs. pump power with measured pulse duration (red) and calculated from measured optical spectrum assuming a transform-limited soliton pulses duration (yellow).

4. Conclusion and outlook

We reported the first ultrafast gigahertz Yb:CALGO laser with a repetition rate of 1.8-GHz, delivering pulses with 59.4 fs and an average output power of 2.95 W. Therefore the laser generates the shortest pulses from any Yb-based gigahertz DPSSL to date. Reliable and self-starting soliton modelocking is achieved using a SESAM. Robust and efficient pumping is enabled by an inexpensive commercial multimode laser diode. The high-power direct diode-pumping is advantageous compared to the expensive and power-limited green pumping used for Ti:sapphire lasers and is attractive for industrial applications. Combining sub-60-fs pulses at gigahertz repetition rate with 24.3 kW peak power makes this laser a promising ultrafast light source for high repetition rate frequency combs and nonlinear experiments in the gigahertz range.

To achieve even shorter pulses the intracavity dispersion requires further optimization. Adapting ultra broadband double-chirped mirror pairs, typically used for Ti:sapphire lasers, to the 1060-nm wavelength range is one possible option. However, the amount of dispersion is usually limited to several tens of fs^2 rather than the required few hundreds of fs^2. A promising alternative is soliton modelocking in the positive dispersion regime using cascaded χ^2-nonlinearities. This concept has recently proven to be capable of generating ≈100-fs pulses from a MHz-Yb:CALGO [43]. Another potential improvement is to reduce the recovery time of the SESAM. The newest generation already reaches the 1-ps range for the slow component of the recovery time. Precise design and excellent semiconductor growth will allow even faster SESAMs in the near future.

The absence of Q-switching instabilities and the observation of reasonable stable operation with double pulses at average output powers exceeding 2.95 W will allow further repetition rate scaling. The interplay of soliton effects and gain filtering as well as SESAM roll-over are possible stabilizing mechanisms against Q-switching instabilities [44]. Since the Z-shaped cavity comprises only one curved mirror we can explore higher pulse repetition rates when the flat output coupler is integrated into the dichroic pump-mirror. Such multi-integrated mirror coatings with broadband and flat reflection and dispersion are required to improve femtosecond gigahertz DPSSLs in terms of pulse duration and to obtain higher repetition rates. The 10-GHz milestone with several kilowatt peak power becomes feasible and could allow for stable supercontinuum generation and high-power frequency comb generation based on robust SESAM modelocked Yb-based gigahertz DPSSLs.

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