A gigahertz multimode-diode-pumped Yb:KGW enables a strong frequency comb offset beat signal

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Abstract: A high-power gigahertz SESAM modelocked Yb:KGW laser is pumped with a commercial multimode diode laser and enables a strong frequency comb offset beat signal without additional amplification or pulse compression. The ultrafast Yb:KGW solid-state laser oscillator generates 125-fs pulses at an average power of 3.4 W and a repetition rate of 1.06 GHz with a record-high peak power of 22.7 kW. An octave-spanning frequency comb was generated with a 1-m long highly nonlinear photonic crystal fiber (PCF) launching only 900 mW of the total average power with a PCF coupling efficiency of 70%. The frequency comb offset was successfully detected with a carrier-envelope offset (CEO) frequency beat signal of 30-dB signal-to-noise ratio for a resolution bandwidth of 100 kHz. The robust and simple pumping scheme based on a commercially available multimode diode laser makes this laser attractive for future frequency comb metrology applications.

OCIS codes: (320.0320) Ultrafast optics; (140.0140) Lasers and laser optics; (320.6629) Supercontinuum generation; (140.3615) Lasers, ytterbium; (140.3480) Lasers, diode-pumped; (120.3940) Metrology.

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1. Introduction

The recent advances of gigahertz femtosecond lasers has enabled many applications such as ultra-high-speed optical data transmission [1], nonlinear bio-imaging [2] and frequency metrology [3–5]. Semiconductor saturable absorber mirror (SESAM) modelocked solid-state lasers [6–8] are excellent sources for optical frequency combs, which have become some of the most precise instruments in fundamental science and technology to date. Frequency comb applications benefit from higher gigahertz pulse repetition rates, since the increased comb tooth spacing provides a simpler access to the individual optical comb lines [9]. In addition the increased power per comb line for a given average power improves the signal-to-noise ratio (S/N) for many comb applications, such as high-resolution spectroscopy [10] and the Astro-comb [11].

Different laser technologies, such as Kerr-lens modelocked (KLM) Ti:sapphire laser oscillators [12], fiber lasers, diode-pumped solid-state lasers (DPSSLs) and novel SESAM modelocked semiconductor lasers are being pushed into gigahertz pulse repetition rate regime with increased high peak power. Ti:sapphire lasers deliver very short pulses and exhibit low noise levels, but they rely on expensive multi-watt single-mode green pump lasers. Furthermore KLM requires critical laser cavity alignment, typically operated at the edge of a stability region, which increases the sensitivity to mechanical or thermal perturbations of the laser. More convenient and robust are diode-pumped fiber laser systems. However, fiber lasers operate with high gain and high nonlinearities, which can lead to higher phase noise [13]. To enter the GHz-regime short fibers of a few centimeters length become necessary, which limit the achievable output power [14]. SESAM modelocked diode-pumped solid-state lasers (DPSSLs) are excellent compact sources for frequency combs. They combine the favorable properties of cost-efficient diode-pumping and an intrinsic low quantum noise level [15]. Furthermore, DPSSLs can be modelocked robustly with SESAMs without any critical cavity alignments and achieve watt-level average powers without any amplification, even in combination with high repetition rates [8, 16].

Gigahertz SESAM modelocked DPSSLs have to overcome some challenges also because the decreased pulse energy may result in Q-switching instabilities [17] and the reduced pulse peak power makes nonlinear processes, such as supercontinuum generation, more difficult. To effectively address these challenges, shorter pulses and higher average powers are required. Short pulses with a duration of 55 fs were obtained from a 1-GHz Cr:LiSAF laser with an average output power of 110 mW [18]. Remarkable progress of GHz-DPSSLs was achieved using Yb-doped potassium tungstate lasers such as Yb:KGW and Yb:KYW: high efficiency [19], high repetition rate [20], with multimode pumping [21], KLM [22] and graphene modelocking [23] were reported in recent years. A stabilized frequency comb was generated from Yb:KYW in the MHz-regime [24], and the first self-referenceable frequency comb from a gigahertz DPSSL was demonstrated with an Yb:KGW laser, which delivered an average output power of 2.2 W in 290-fs pulses and a peak power of 6.7 kW [25]. In this case a more complex pump laser was used with the high-brightness DBR tapered diode laser [26], which was also more sensitive for optical feedback.

In this paper, we report a gigahertz femtosecond DPSSL with the highest average power and a record-high peak power based on a SESAM modelocked diode-pumped Yb:KGW. This laser delivers a pulse repetition rate of 1.06 GHz, a pulse duration of 125 fs and an average output power of 3.43 W. These parameters correspond to a pulse energy of 3.2 nJ and a peak power of 22.7 kW. Without any additional amplification and pulse compression a self-

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referenceable frequency comb was generated, launching the output of this laser into a highly nonlinear photonic crystal fiber (PCF).

2. Experimental setup

The laser is based on a 5% Yb-doped KGW (potassium gadolinium tungstate, $Yb{:}KGd(WO_4)_2$) crystal of 2 mm thickness with broadband anti-reflection coatings on both sides. Yb:KGW provides favorable large absorption and emission cross sections [27, 28] supporting low lasing threshold, high efficiency and a reduced tendency for Q-switched modelocking (QML). Furthermore, the gain material has proven to be capable to deliver pulse durations down to 100 fs [29] and average output powers up to 10 W [30]. A strong absorption line located around 981 nm is used to pump the crystal.

So far only high-brightness close to Gaussian beam pumps have been used for high-repetition-rate lasers [20, 31], since small mode sizes are required to avoid QML [17]. However, the output power of such high-brightness laser diodes is usually limited to a few hundred milliwatts. More powerful tapered amplifier laser diodes [26] are highly sensitive to back-reflections from the system, potentially leading to a catastrophic damage of their facets [32]. For the current laser a commercially available transversal-multimode fiber-coupled laser diode is used. We consider this approach simpler, cheaper and more robust because it is based on a standard diode-pumping scheme typically used for commercial DPSSLs.

The multimode pump diode (LUMICS, LU0975T250) delivers up to 24 W output power and provides a 4.2-nm broad spectrum centered around 978 nm. Its multimode character (M^2 ≈25) results in a comparably low brightness. A careful choice of pump optics and an appropriate cavity design still enables a relatively small gain mode size of approximately 115 µm in diameter (calculated with ABCD-matrix formalism).

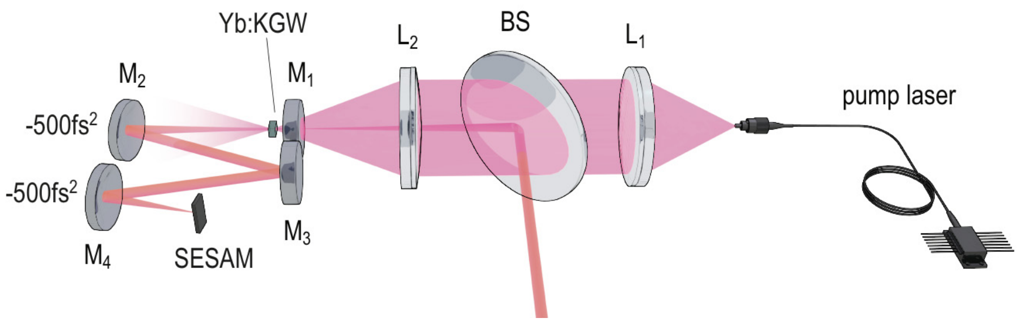

Fig. 1. Experimental setup of the 1-GHz SESAM modelocked diode-pumped KGW laser oscillator: L_1 and L_2 denote the pump optics, BS is a dichroic beam splitter; M_1 is the input-output coupler; M_2, M_4 are curved GTI mirrors; M_3 is a flat dichroic folding mirror and the SESAM is placed as the second end-mirror. A 3.2% output coupling was used with the M_1 mirror.

We followed the approach of building a Σ-shaped cavity instead of a simpler Z-shape (Fig. 1). The additional folding mirror provides more flexibility especially for cavity dispersion management. One cavity end-mirror (M_1) and a flat folded mirror (M_3) are highly transparent for the pump wavelength. Therefore M_1 transmits the pump power for the gain medium, while M_3 eliminates the remaining pump light protecting the SESAM.

The dichroic cavity mirror M_1 offers 3.2% transmission at the lasing wavelength of 1046.6 nm. Therefore it is used as an output coupler for the oscillator. Subsequently a dichroic beam splitter (BS) separates the pulsed laser light from the pump light.

Two Gires-Tournois interferometer (GTI) type mirrors (M_2, M_4) provide a negative group delay dispersion (GDD) of −500 fs^2 each. Thus stable soliton modelocking [33] is obtained by the balance between self-phase-modulation (SPM) and an overall negative GDD in the cavity. To start and maintain the fundamental continuous-wave (cw) modelocking we inserted a single InGaAs quantum-well based SESAM with an incident mode size diameter of 215 µm.

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The SESAM structure is based on an antiresonant design [34, 35] and was modified by deposition of a 60 nm thick fused silica layer, leading to a modulation depth of 2% and a saturation fluence of ≈20 μJ/cm^2 (measured at 1030 nm with the setup presented in [36]). The nonsaturable losses are below 1%. The SESAM is soldered onto a copper heat-spreader, which is kept at room temperature via a Peltier element. Note, that the laser is a self-starting “turn-key” system, which can operate at least 12 hours without decreasing performance.

3. Results

The SESAM modelocked diode-pumped Yb:KGW laser described in the previous section delivers an average output power of 3.43 W using 13 W of multimode pump power, giving an optical-to-optical efficiency of 26% and a slope efficiency of 34%. Optical pulses as short as 125 fs are obtained at a center wavelength of 1046.6 nm (Fig. 2). Thus a record-high peak power of 22.7 kW is obtained directly from the gigahertz DPSSL.

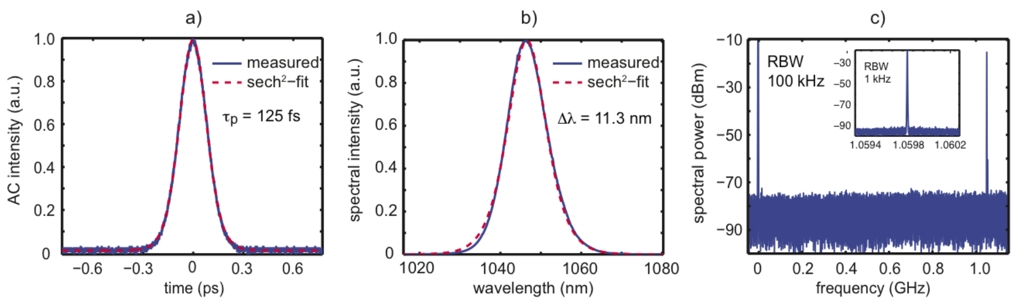

Fig. 2. SESAM modelocked multimode-diode-pumped Yb:KGW laser at a 1-GHz pulse repetition rate generates the measured autocorrelation (a), optical spectrum (b) and microwave spectrum (c). RBW: resolution bandwidth of microwave spectrum analyzer.

The second-harmonic autocorrelation trace and the optical spectrum are shown in Fig. 2(a) and 2(b) respectively. Both are fitted assuming ideal sech^2-shape pulses. The integrated overlap of the low-brightness pump light with the fundamental mode of the cavity is calculated to be 78%, assuming a tophat and a Gaussian beam profile respectively. An insufficient overlap could lead to gain for higher-order spatial modes of the cavity. However undisturbed single-mode TEM_{00} operation is confirmed by the measured M^2 of the laser of 1.04. Furthermore, the microwave frequency spectrum verifies cw modelocking without side peaks (Fig. 2(c)). Thus brightness conversion via the gain crystal works effectively.

Figure 3(a) depicts the average laser output power versus pump power. The cw-lasing threshold is located at 2.1 W pump power and the cw slope efficiency is 20%. Modelocking starts at a pump power of 7.2 W, accompanied by a jump in average output power from 1.07 W to 1.38 W and an increase of the slope efficiency to 34.6% due to reduced cavity losses for a saturated absorber in a high-Q cavity. The observed Q-switched modelocking (QML) range is remarkably narrow: it occurs only within a 100 mW pump power range at 7.2 W and is then suppressed quickly. One may have expected a stronger tendency for QML considering the relatively large mode sizes in the gain and absorber and the moderate modulation depth of the SESAM. However, both soliton modelocking and SESAM roll-over provide better stabilizing mechanisms against QML [17, 37].

The measured pulse duration and the time-bandwidth product (TBP) limited pulse duration calculated from the measured optical spectrum are in good agreement with each other at lower power and additional SPM broadening explains the lower TBP limit at higher power (Fig. 3(a)). At the maximum output power of 3.43 W we obtain a TBP of 0.386 (theoretical limit would be 0.315 for sech^2-pulses).

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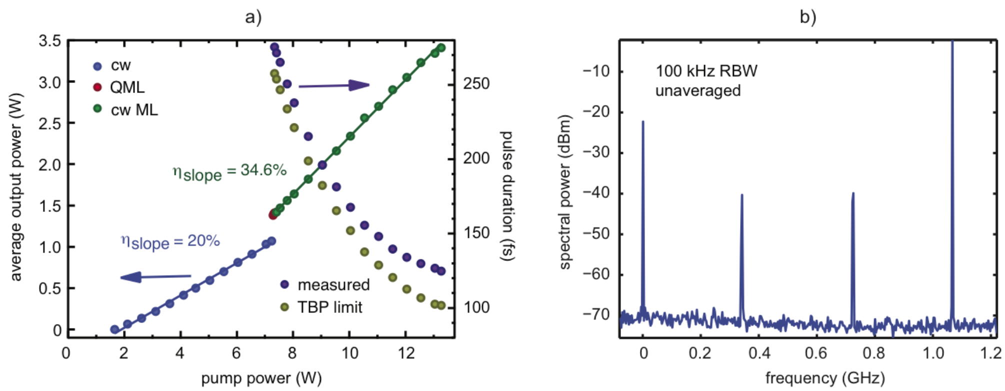

Fig. 3. SESAM modelocked multimode-diode-pumped Yb:KGW laser at a 1-GHz pulse repetition rate: (a) Average output power vs. pump power: continuous-wave (cw) lasing (blue), Q-switched modelocking (QML) (red) and cw modelocking (green); pulse duration vs. pump power: measured pulse duration (purple) and calculated pulse duration from measured optical spectrum (yellow) (b) f_{CEO} beats measured with 30 dB S/N at 100 kHz RBW (unaveraged) including f_{rep}.

We used this laser without additional pulse compression and explored the regime for stable CEO frequency detection and self-referenceable gigahertz frequency comb generation. Launching only 900 mW of the total average power with a coupling efficiency of 70% directly into a 1-m long highly nonlinear photonic crystal fiber (PCF) we generated an octave-spanning spectrum. The PCF has a zero-dispersion wavelength at 945 nm and a 3.2-µm core diameter. The stabilization of the frequency comb requires a highly coherent spectrum [38] which should be obtained for short pulses with high peak power. In this regime the spectral broadening should be dominated by higher order dispersion and stimulated Raman scattering without modulation instabilities and noise amplification. A proposed simplified metric for the supercontinuum coherence is a soliton order N below 10 [39]. For our specific laser pulses and fiber parameters we calculated $N = 5.6$, indicating a coherent supercontinuum generation according to this simple guideline.

A standard f-to-$2f$ interferometer scheme [3] was utilized to measure the CEO frequency. We used a dichroic mirror for wavelength separation in the quasi-common path interferometer (Fig. 4). We obtained a strong beat signal with 30 dB signal-to-noise ratio at 100 kHz resolution bandwidth (RBW) (Fig. 3(b)), which will be used to stabilize this self-referenceable gigahertz frequency comb. However, CEO stabilization using a electronic feedback to the pump laser is not straightforward. We note that it has been recently shown that a high signal-to-noise ratio and a low-noise CEO beat signal alone is not sufficient for stable frequency comb generation [40]. Therefore, additional work beyond the scope of this paper will be necessary in order to finally demonstrate a stabilized frequency comb.

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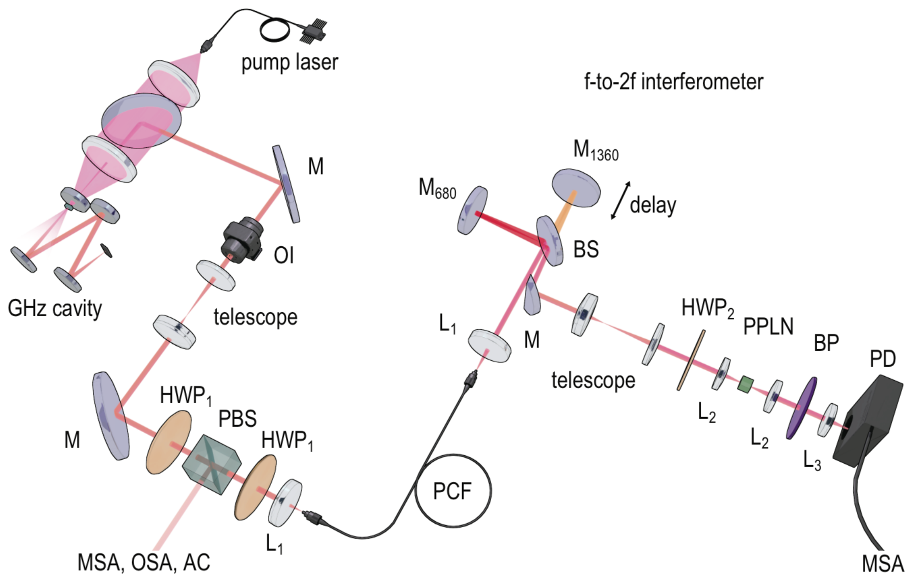

Fig. 4. Full experimental setup including 1-GHz SESAM modelocked Yb:KGW oscillator, PCF and f-to-2f interferometer. M: silver mirror; M_{680}, M_{1360}: Notch-type mirror for 680 nm, 1360 nm; BS: dichroic beam splitter; OI: optical isolator; HWP_1, HWP_2: half-wave-plate for 1050 nm and 1310 nm; L_1, L_2, L_3: lenses (focal lengths: 3.1 mm, 40 mm and 50 mm); PBS: polarizing beam splitter; PCF: photonic crystal fiber (see text for specs.); PPLN: periodically poled lithium niobate for SHG of 1360 nm; BP: bandpass filter 680-10, PD: amplified photodiode with 0.5 ns response time; MSA: microwave spectrum analyzer; OSA: optical spectrum analyzer; AC: second harmonic autocorrelator.

4. Conclusion

We presented a 1-GHz DPSSL with record-high peak power of 22.7 kW enabling stable frequency comb generation without additional pulse compression or amplification. Strong f_{CEO} beats of 30 dB S/N (100 kHz RBW) are detected, which will be explored for stable frequency comb generation in the future. The presented laser combines a gigahertz pulse repetition rate with femtosecond pulses and a high average output power level with record-high peak power.

The 1-GHz laser is pumped by a robust and low-cost pump source. This approach is advantageous compared to Ti:sapphire laser oscillators, which require expensive single-mode pumps in the green (e.g., generated by the second-harmonic of a solid-state laser, which itself is pumped by a diode laser). The high performance and simplicity of the present system is very interesting for numerous applications and commercializing of such compact and reliable laser sources.

Further increasing the repetition rate of the presented laser appears feasible, since the observed QML-range is negligibly small. The given power and pulse duration should allow scaling of the system to a 10-GHz repetition rate with a peak power remaining in kW-range.

For improved f_{CEO} beat detection even shorter pulse durations can be beneficial. Optimizing the cavity dispersion and utilizing a faster SESAM could lead to sub-100 fs pulses. Moreover, our observation on suppressed QML enables the possibility to substitute Yb:KGW by a gain material with broader emission-bandwidth, such as Yb:CALGO [41, 42], which could provide even shorter pulses.

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