Diode-pumped gigahertz femtosecond Yb:KGW laser with a peak power of 3.9 kW

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Abstract: We present a diode-pumped Yb:KGW laser with a repetition rate of 1 GHz and a pulse duration of 281 fs at a wavelength of 1041 nm. A high brightness distributed Bragg reflector tapered diode laser is used as a pump source. Stable soliton modelocking is achieved with a semiconductor saturable absorber mirror (SESAM). The obtained average output power is 1.1 W and corresponds to a peak power of 3.9 kW and a pulse energy of 1.1 nJ. With harmonic modelocking we could increase the pulse repetition rate up to 4 GHz with an average power of 900 mW and a pulse duration of 290 fs. This Yb:KGW laser has a high potential for stable frequency comb generation.

OCIS codes: (140.4050) Mode-locked lasers; (140.3615) Laser, ytterbium; (140.3480) Laser, diode-pumped; (140.3580) Lasers, solid-state

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1. Introduction

Self-referenced frequency combs from femtosecond lasers offer a phase stable link between optical and microwave frequencies [1–3]. They enabled a huge progress in a wide range of areas such as precision metrology [4] and spectroscopy [5], calibration of astronomical spectrometers [6,7], waveform synthesis [3], stable microwave generation [2] and optical clocks [8]. The separation distance of the frequency lines is exactly given by the pulse repetition rate of the modelocked laser. For many applications, frequency combs from modelocked lasers with gigahertz repetition rates [9] have advantages compared to megahertz repetition rates. The spacing of the lines in frequency space is less dense, which leads to a higher power per mode, if the overall optical bandwidth and the total power are the same. This allows for higher signal-to-noise ratio in many measurements. Furthermore, it is substantially easier to resolve the individual frequency lines of the comb. This led to novel high-resolution spectroscopic techniques [10]. Also for the calibration of astronomical spectrographs, the favored frequency is in the gigahertz domain [11]. Another benefit of high repetition rate frequency combs is the compactness of the laser systems.

The detection of the carrier envelope offset (CEO) frequency is essential for the stabilization of the frequency combs. The standard technique to measure the CEO frequency is the implementation of an f-to-2f interferometer [1], which needs a coherent octave spanning spectrum. Typically, the spectrum of the laser is broadened in a highly nonlinear fiber. This requires pulses with sufficiently high peak power, which is challenging at GHz repetition rates. The highest repetition rate from a self-referenced optical frequency comb is currently 10 GHz, which was achieved by a Ti:sapphire laser generating 40 fs pulses with 1.2 W average power [12]. Ti:sapphire systems are advantageous because of the extremely short pulse durations and the possibility for very low noise levels. However, typical Ti:sapphire lasers have also several drawbacks such as the demand of an expensive multi-Watt green pump laser or the Kerr-lens modelocking (KLM) mechanism which usually requires alignment at the limits of the stability zones and is not self-starting. For applications outside of laser laboratory environments, passive modelocking with a semiconductor saturable absorber mirror (SESAM [13,14]), appears better suited than KLM, as it is more reliable and self-starting. An important break-through was the demonstration of a stabilized frequency comb from a fundamentally modelocked femtosecond fiber laser with a repetition rate of 1 GHz [15]. However, fiber oscillators suffer from a higher quantum noise limit and it seems to be challenging to substantially scale up the repetition rate. On the other hand, diode-pumped solid state lasers (DPSSLs) combine the favorable properties of cost-efficient diode pumping and an intrinsic low quantum noise limit. Picosecond SESAM-modelocked DPSSLs with repetition rates up to 100 GHz at 1.5 μm [16] and 160 GHz at 1 μm [17] have already been demonstrated. The main challenge to obtain continuous-wave (cw) modelocking at high repetition rates is to overcome the Q-switched modelocking (QML) regime [18]. This can be achieved by an optimized SESAM design [19], soliton modelocking [20], and small mode areas both in the gain and on the absorber. A pump source with high brightness is required to efficiently operate at small mode sizes. Therefore, single-frequency distributed Bragg reflector (DBR) tapered diode lasers [21] with their high brightness and high output power are very attractive for gigahertz femtosecond DPSSLs.

So far, there were only a few DPSSLs demonstrated, which combine repetition rates in the GHz range and fs pulse durations. A KLM modelocked laser based on Yb:KY$(WO_4)_2$ (Yb:KYW) at 1 GHz was demonstrated [22]. Its pulse duration was estimated from the optical spectrum to be 200 fs, but no autocorrelation was provided. The average output power was 115 mW. Recently, a SESAM modelocked Yb:KYW laser was operated at 2.8 GHz repetition rate delivering 162 fs long pulses with 680 mW average output power [23]. 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 [24].

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Here, we present a SESAM modelocked diode-pumped Yb:KGd(WO$_4$)$_2$ (Yb:KGW) laser oscillator delivering femtosecond pulses at the repetition rate of 1 GHz with sufficient peak power for octave spanning continuum generation. The average output power of 1.1 W corresponds to a pulse energy of 1.1 nJ and a peak power of 3.9 kW. To our knowledge these are the highest values ever demonstrated for a DPSSL at gigahertz repetition rates and pulse durations in the femtosecond domain. Using a smaller focus on the SESAM, we observed harmonic modelocking with up to 4 GHz at an average output power of 0.9 W and with 290 fs pulse duration. This shows the potential for multi-GHz operation at fundamental modelocking using different cavity mirror curvatures to maintain the current cavity mode sizes. Fundamental modelocking is preferred because we obtain better noise performance and no active stabilization is required to prevent a pulse drop-out. Without any further pulse compression and amplifier stage this laser is very attractive for stable frequency comb generation based on our recent results with a femtosecond Er:Yb:glass laser [25].

2. Experimental setup

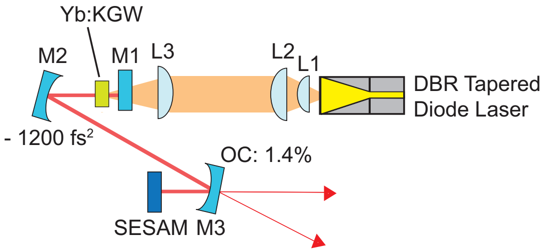

Fig. 1. Layout of the 1-GHz Yb:KGW laser. L1, L2, L3: pump optics; SESAM: semiconductor saturable absorber mirror; M1: pump mirror, M2: high reflective Gires-Tournois interferometer type mirror with a dispersion of −1200 fs^2; M3: output coupler with a transmission of 1.4%.

Figure 1 shows a schematic set-up of the gigahertz Yb:KGW laser. The pump source is a distributed Bragg reflector tapered diode-laser (DBR TDL) [21,26]. Such a device exhibits a high optical output power with a longitudinal single mode emission and a good beam quality. The pump diode is divided into a 4-mm-long gain-guided tapered section and a 2-mm-long, 4-µm-wide index-guided straight ridge-waveguide section containing a 1-mm-long surface Bragg-grating. The DBR TDL emits at 980 nm with a spectral linewidth of less than 13 pm (FWHM). Moreover, the device shows a nearly diffraction limited output beam with a lateral beam propagation factor of $M^2_{1/e^2} = 1.1$, containing more than 70% of the power in the central lobe. The output power is 5.5 W and the light is collimated by an aspheric lens with a focal length f of 3.1 mm (L1 in Fig. 2) and a cylindrical lens with $f = 30$ mm (L2). Together with an achromatic focusing lens with $f = 35$ mm (L3) we achieved a small and circular pump spot with a radius of ≈38 µm on the gain material. No damage is observed despite the high pump intensity of 120 kW/cm^2 in the gain material. The gain material is a 2-mm-thick, anti-reflection coated Yb:KGW crystal with a doping concentration of 5 at.%.

Yb:KGW is a promising candidate for femtosecond gigahertz lasers due to the following characteristics. Among Ytterbium doped hosts, Yb:KGW exhibits comparably large emission and absorption cross-sections, a broad emission bandwidth and good thermal properties [27,28]. To date, at low pulse repetition rates pulse durations as short as 100 fs [29] and an average output power of up to 10 W [30] have been demonstrated. No active cooling of the crystal is needed at the applied pump power level.

One end mirror of the cavity is a flat mirror which is highly reflective for the laser wavelength (1041 nm) and highly transmissive for the pump wavelength of 980 nm (M1). Soliton modelocking is obtained by a balance of both negative dispersion and self-phase modulation. A single dispersive mirror (M2) with a radius of curvature (ROC) of 50 mm provides a negative group delay dispersion (GDD) of −1200 fs^2. Self-phase modulation is provided by the Kerr nonlinearity of the Yb:KGW crystal ($n_2 = 15x10^{-16}$ cm^2/W at the lasing wavelength [31]). For this first demonstration, the folding mirror M3 is used as an output coupler, resulting in two output beams. As has been demonstrated many times before, the output coupler functionality can be integrated into the pump mirror M1 or the SESAM [32]. Mirror M3 has an ROC of 38 mm and a transmission of 1.4% at the lasing wavelength resulting in a total output coupling of 2.8% (i.e. into both beams). The total length of the resonator is 145 mm corresponding to a repetition rate of 1 GHz (see Fig. 2). Self-starting passive mode-locking is achieved using a SESAM with a saturation fluence of 40 µJ/cm^2, a modulation depth of 0.5%, and low non-saturable losses (<0.1%). It is a standard quantum well (QW) based, antiresonant SESAM with a dielectric top coating. Modelocked lasers operating at GHz repetition rates often use SESAMs with low saturation fluence to overcome the QML threshold [19]. However, this is not the main motivation in our case because the high brightness pump source allows for small laser spot sizes and high intracavity power. The main motivation here is the reduction of intracavity losses, as the employed SESAM has less than 0.1% nonsaturable losses.

3. Results

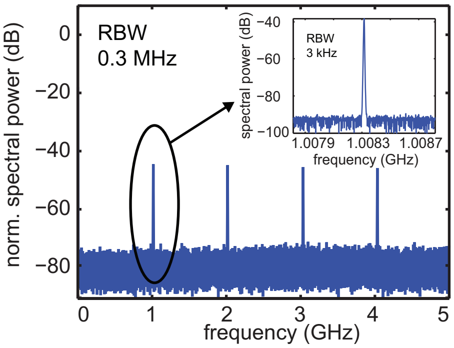

Fig. 2. The microwave spectrum of the output power (monitored with a photodetector and a microwave spectrum analyzer) with a spectral span of 5 GHz and a resolution bandwidth (RBW) of 0.3 MHz shows a repetition rate of 1.01 GHz. The inset shows the spectrum on a small span of 0.8 MHz with a RBW of 3 kHz.

With the setup described above, self-starting and stable modelocking was achieved at 1.01 GHz repetition rate. The microwave frequency spectrum shown in Fig. 2 confirms clean continuous-wave (cw) modelocking without side peaks or disturbances. The pulse duration is 281 fs with a spectral bandwidth of 4.9 nm at a center wavelength of 1041 nm (see Figs. 3a and 3b). Both the autocorrelation and the optical spectrum are well fitted with an ideal sech^2-pulse shape.

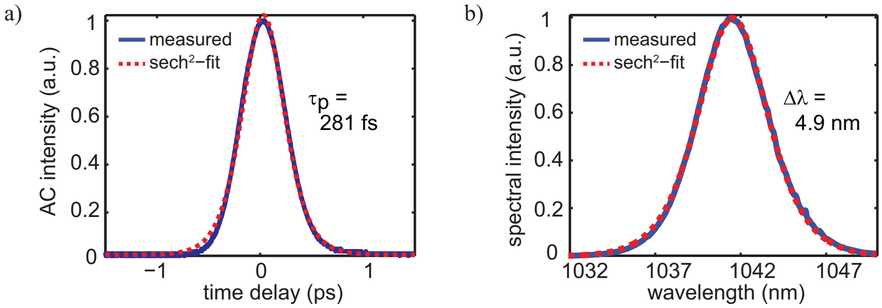

Fig. 3. a) Normalized autocorrelation (AC), and b) optical spectrum plotted with the fits for sech^2-pulses. The pulse duration is 281 fs and the spectral bandwidth is 4.9 nm centered around 1041 nm.

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The time-bandwidth product (TBP) of 0.381 is 1.2 times the theoretical value of 0.315 for sech^2-pulses. This might be due to the limited dispersion optimization with the given dispersive mirror M2 in Fig. 1 or strong SESAM saturation in combination with two-photon absorption. Furthermore, an optimization of the dispersion was not performed yet. The beam quality is measured to be $M_x^2 = 1.2$ and $M_y^2 = 1.1$. At a pump power of 5.5 W the obtained average output power is 1.1 W. This corresponds to a peak power of 3.9 kW and a pulse energy of 1.1 nJ. In Fig. 4 the average output power as a function of the input power is shown. At lower pump power, the laser operates in cw operation, whereas for pump power above 3.5 W stable cw modelocking is obtained. The optical-to-optical efficiency is 20% and the slope efficiency is 28% with respect to the pump power.

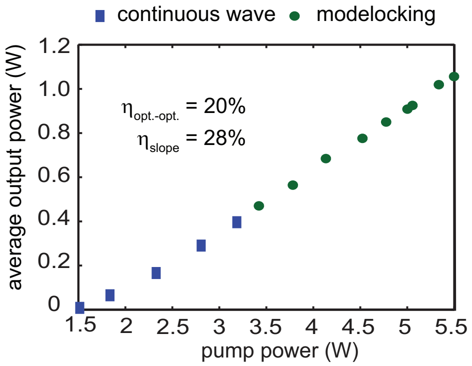

Fig. 4. The average output power as a function of the pump power.

By decreasing the mode size on the SESAM and therefore increasing the saturation of the SESAM with the same setup also harmonic modelocking [33–35] can be achieved (see Fig. 5).

At low pump power levels again fundamental modelocking is obtained. If the pump power is increased, first evenly spaced double pulsing corresponding to harmonic modelocking at 2 GHz is observed. By further increasing the pump power, first 3 GHz and finally 4 GHz harmonic modelocking is achieved. We therefore believe that 4-GHz fundamental modelocking with femtosecond pulse duration should be feasible with a shorter cavity length maintaining the intracavity power and the mode sizes of the present setup. This requires a new set of cavity optics and was therefore not done at this point.

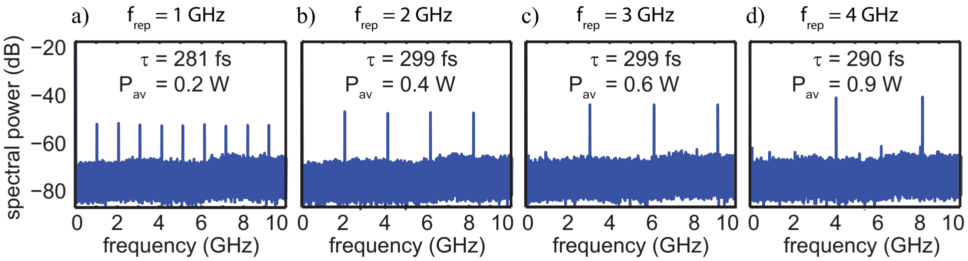

Fig. 5. The microwave spectrum in case of a) fundamental modelocking at 1 GHz repetition rate (f_{rep}) at 1.8 W pump power, b) harmonic modelocking at 2 GHz at 2.6 W pump power, c) harmonic modelocking at 3 GHz at 3.4 W pump power, and d) harmonic modelocking at 4 GHz at 4.9 W pump power; τ: pulse duration; P_{av}: average output power.

4. Conclusion and outlook

We demonstrated a SESAM-modelocked DPSSL with a repetition rate of 1 GHz and a pulse duration of 281 fs delivering 1.1 W average output power. The peak power of 3.9 kW and the pulse energy of 1.1 nJ have been to the best of our knowledge the highest values obtained

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from a gigahertz femtosecond DPSSL so far. The successful demonstration of harmonic modelocking at 4 GHz shows the feasibility of a fundamental modelocked multi-GHz femtosecond DPSSL. Furthermore, a standard anti-resonant QW-SESAM with relatively high saturation fluence was used. Similar to previous picosecond modelocked lasers, switching to SESAMs with lower saturation fluence should enable repetition rates in the tens of GHz regime [19], [36-38].

Even higher average output power should be possible with more pump power. Similar DBR tapered diodes delivering more than 10 W pump power were demonstrated [21]. Furthermore, because the time-bandwidth product is 1.2 times the ideal value, also shorter pulse durations should be obtainable with either optimized dispersion and/or smaller SESAM saturation. For shorter pulse durations and/or further power scaling, other crystal matrix hosts should be investigated. Borates for example are promising due to their very broad emission bandwidth [39] and sesquioxides due to the high thermal conductivity [40], respectively.

The CEO beat frequency detection appears feasible with the current pulse duration, pulse energy and peak power. Stumpf et al. succeeded to detect the CEO beat frequency from a 75 MHz laser at the wavelength of 1550 nm with pulses as long as 278 fs, a peak power of 3.5 kW and a pulse energy of 1 nJ using an f-to-2f interferometer without any external amplification or pulse compression [25]. Therefore the presented 1-GHz Yb:KGW DPSSL is a promising candidate for a stabilized frequency comb with a multi-GHz comb line spacing.

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