Self-referenceable frequency comb from a gigahertz diode-pumped solid-state laser

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Abstract: We present carrier envelope offset (CEO) frequency detection of a diode-pumped Yb:KGW (ytterbium-doped potassium gadolinium tungstate) laser with a repetition rate of 1 GHz. The SESAM-soliton-modelocked laser delivers 2.2-W average power in 290-fs pulses. This corresponds to a peak power of 6.7 kW and the optical-to-optical efficiency is 38%. With a passive pulse compression the duration is reduced to 100 fs at an average power of 1.1 W. Coherent supercontinuum (SC) generation in a highly nonlinear photonic crystal fiber (PCF) is achieved without additional amplification. Furthermore we have demonstrated that pulse compression towards lower soliton orders of approximately 10 was required for coherent SC generation and CEO detection. Additional numerical simulations further confirm these experimental results.

OCIS codes: (140.4050) Mode-locked lasers; (140.3615) Laser, ytterbium; (140.3480) Laser, diode-pumped; (140.3580) Lasers, solid-state; (320.7090) Ultrafast lasers; (120.3940) Metrology.

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1. Introduction

Stable frequency combs from femtosecond lasers have been a major breakthrough in optical science and metrology [1–3]. Although most widely employed frequency combs are either based on complex green-pumped Ti:sapphire lasers or amplified fiber laser systems, diode-pumped solid-state lasers (DPSSLs) are developing into highly promising alternatives for more reliable, low-noise and compact frequency combs. Similar to Ti:sapphire lasers, they operate with high-Q cavities and moderate intracavity nonlinearities, resulting in a low fundamental quantum noise limit and a free-running carrier envelope offset (CEO) beating signal with extremely narrow linewidth [4]. Furthermore, DPSSLs can achieve watt-level average powers without any amplification. An overview for the different laser materials and their modelocking results is given in [5].

In the picosecond regime DPSSLs have proven to operate at tens of gigahertz repetition rate [6–8]. More recently DPSSLs at gigahertz repetition rates also have been demonstrated with femtosecond pulse durations [9–11]. High repetition rate frequency combs are advantageous because higher repetition rates provide increased power per mode and simpler access to individual optical lines. This is for example important for arbitrary waveform generation or calibration of spectrometers. Currently, the highest repetition rate self-referenced frequency comb reported is from a 10-GHz Ti:sapphire laser generating 40-fs pulses with 1.2-W average output power [12]. Another important breakthrough in repetition rate was the realization of a 1-GHz frequency comb from an Yb-fiber laser [13]. Self-referenced frequency combs based on DPSSLs have been reported with repetition rates of a few hundreds of megahertz [4,14,15]. However, to date no gigahertz octave-spanning frequency combs from DPSSLs have been realized.

For frequency comb stabilization the two degrees of freedom of the comb, the repetition rate and the CEO frequency, have to be detected and stabilized. Whereas the detection of the repetition rate is straightforward, detecting the CEO frequency is more challenging, especially at high repetition rates. The standard f-to-$2f$ interferometer scheme [1] is based on a coherent octave-spanning supercontinuum (SC) which requires high peak powers and short pulses. Numerical simulations show that good coherence over the full octave sets an upper limit in the pulse duration for a given nonlinear fiber and pulse energy [16]. An easy accessible parameter for evaluating the requirements in pulse duration, pulse energy, fiber dispersion, and fiber nonlinearity is the soliton order. Numerical simulations have been used to develop a guideline for an upper limit of the soliton order of around 10 to generate a coherent SC under typical conditions using silica fibers [16]. This guideline has been consistent with many published results, but no comparative systematic experimental study using the same laser source has been performed so far.

In this paper, we demonstrate the first gigahertz frequency comb with DPSSLs and provide the first experimental comparison of the influence of pulse duration on the CEO beating signal. Based on a 1-GHz SESAM-modelocked Yb:KGW laser [11], we generate 2.2-W average power in 290-fs pulses at 1042 nm. These are to our knowledge the highest energy pulses generated from a GHz DPSSL. We use this laser with and without additional pulse compression to adjust the pulse duration and explore the regime for stable CEO detection and self-referencable gigahertz frequency comb generation. Note that these power levels were attained with no additional amplification, thus avoiding additional complexity and noise. With no additional pulse compression and with a highly-nonlinear photonic crystal fiber, we generate an octave-spanning SC with 1-W average power but without any CEO beat signal. This is in agreement with the numerical guidelines as the soliton order in this case is 13. When we reduce the pulse duration with a passive fiber-compressor to 100 fs at 1.1-W average power, we generate an octave-spanning SC with 0.7-W average power and a stable CEO beat signal. In this case the soliton order is 5. The SC generated with the shorter pulses has a similar optical spectrum, but substantially better coherence enabling a clear CEO beat signal with a signal-to-noise ratio (SNR) of 27 dB (with a 1-MHz resolution bandwidth).

2. Diode-pumped Yb:KGW solid state laser

The gigahertz modelocked laser (Fig. 1) is a further development of the one published in [11]. A distributed Bragg reflector (DBR) tapered diode laser delivers up to 6-W pump power at the wavelength of 980 nm with a nearly diffraction limited beam with an $M^2(1/e^2)$ of 1.1 where more than 70% of the power is in the central lobe [17]. The high brightness diode laser pumps a 2-mm-thick, anti-reflection coated Yb:KGW crystal with a doping concentration of 5 at.%. A Gires-Tournois interferometer (GTI)-mirror provides a group delay dispersion (GDD) of $-1200\ \text{fs}^2$. The SESAM [18] has a quantum-well based, antiresonant design with a modulation depth of 0.7%, nonsaturable losses less than 0.1% and a saturation fluence of 81 $\mu\text{J/cm}^2$ (measured with the setup presented in [19]). The output coupler of the cavity has a transmission of 3.3% for the lasing wavelength of 1042 nm and is highly transmissive for the pump radiation. We doubled the average output power compared to the previous results [11] with increased pump power, optimized optics and a different SESAM. Furthermore with the integration of the output coupler in the end-mirror M_1 (Fig. 1), the total average power is provided in a single output beam.

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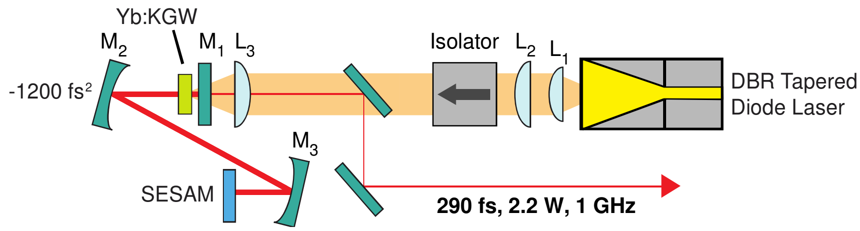

Fig. 1. Layout of the 1-GHz Yb:KGW laser. L_1, L_2, L_3: pump optics; SESAM: semiconductor saturable absorber mirror; M_1: flat mirror transparent for the pump wavelength and output coupler for the lasing wavelength, transmission 3.3%, M_2: curved highly reflective Gires-Tournois interferometer type mirror with a group delay dispersion of -1200 fs^2, radius of curvature (ROC): 50 mm; M_3: curved highly reflective mirror, ROC: 50 mm.

Stable and self-starting SESAM-soliton-modelocking [20] is achieved at the repetition rate f_{rep} of 1 GHz (Fig. 2c) with an average output power P_{av} of 2.2 W. The pulse duration τ_P is 290 fs (Fig. 2a) and the optical spectrum (Fig. 2b) is centered around 1042 nm and has a full width at half maximum (FWHM) of 4.8 nm corresponding to a time bandwidth product (TBP) of 1.2 times the theoretical value for sech^2-pulses. The corresponding peak power is 6.7 kW and the pulse energy is 2.2 nJ. These are to the best of our knowledge, the highest values ever reported for a gigahertz femtosecond DPSSL. The optical-to-optical efficiency is 38%, the slope efficiency is 44% and the electrical power consumption is less than 25 W.

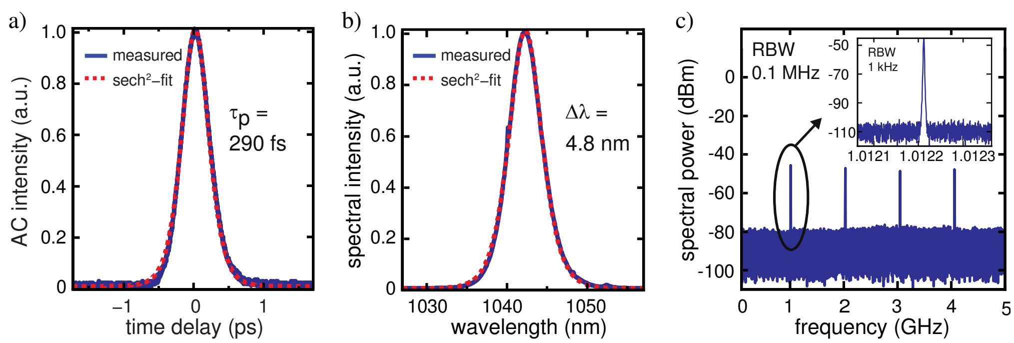

Fig. 2. SESAM soliton-modelocked 1-GHz Yb:KGW laser: a) Normalized autocorrelation (AC), and b) optical spectrum with fits for sech^2-pulses. The pulse duration is 290 fs and the spectral bandwidth is 4.8 nm centered around 1042 nm; c) microwave spectrum of the output power (monitored with a photodetector and a microwave spectrum analyzer) with a spectral span of 5 GHz and a resolution bandwidth (RBW) of 0.1 MHz. The pulse repetition rate is 1.01 GHz. The inset shows the spectrum on a small span of 300 kHz with a RBW of 1 kHz.

3. Pulse compression and supercontinuum generation

For spectral broadening, the pulses are launched directly into a highly nonlinear PCF. The PCF is polarization maintaining, has anomalous dispersion at 1042 nm ($\beta_2 \approx$-15.4 ps^2/km) and a nonlinear coefficient γ of 23 W^{-1}km^{-1}. After two meter propagation in this fiber, we see the characteristic spectral broadening features for SC generation (Fig. 3a, *top*) with the peak of the dispersive wave at short wavelengths and the Raman soliton at long wavelengths exactly spaced by one octave.

The stabilization of the frequency comb requires a highly coherent spectrum. We have performed realistic numerical simulations of our experiment using standard techniques to solve the generalized nonlinear Schrödinger equation [21]. As seen in Fig. 3a), *top*, we achieve good agreement between the simulated and the measured SC. The first-order coherence $|g_{12}^{(1)}|$ is calculated out of an ensemble of multiple spectra with different random noise as described in [16]. As can be seen in Fig. 3a, *bottom*, the spectra exhibit low coherence, especially at the wavelengths used in the *f*-to-2*f* interferometer (see below). The spectral incoherence seen in these simulations is consistent with the numerical guidelines based on the input pulse soliton order N which is given by:

$$N = \sqrt{\frac{L_D}{L_{NL}}} = \sqrt{\frac{\tau_P \cdot P_{av}}{f_{rep}} \cdot \frac{\gamma}{|\beta_2|} \cdot 0.283}, \tag{1.1}$$

where L_D is the dispersive length, L_{NL} is the nonlinear length [16], β_2 is the second order dispersion and the other parameters are described above. In particular, for our parameters we have the input pulse soliton order $N \approx 13$ so that we fall within the incoherent regime of $N > 10$ established in the numerical study performed in Ref [16]. This spectral incoherence was also seen in our experiments as we were unable to detect the CEO beat. Based on our numerical guidelines for a coherent SC we can reduce the soliton order with shorter pulse durations combined with less average power as shown in Fig. 3b). Of course this is to be expected from Eq. (1.1) but it is essential to optimize SC stability in more detail. In our case for example, we could also consider reduction in average power only, but simulations and experiments both indicate that this is unsatisfactory as the power reduction no longer yields the necessary octave spanning spectral width.

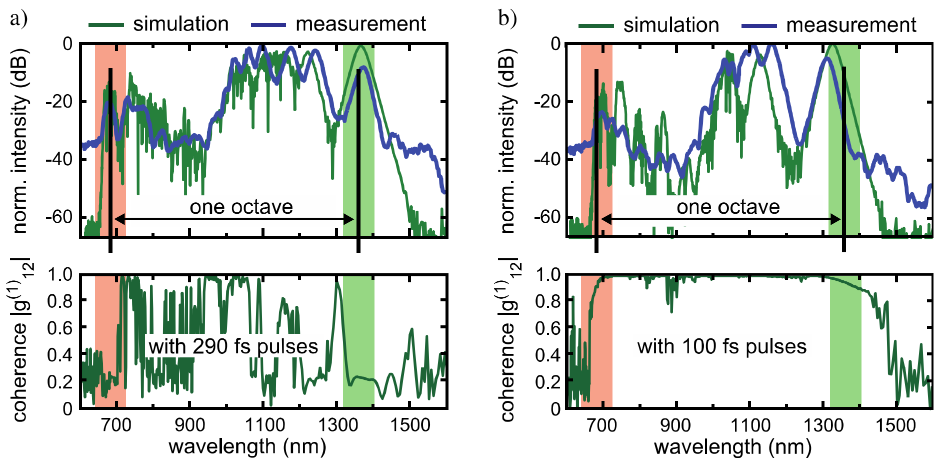

Fig. 3. GHz supercontinuum (SC) generation: a) *top* measured and simulated SC and *bottom* calculated coherence generated with pulses of 290 fs and b) with 100 fs duration; the spectral ranges used in the *f*-to-2*f* interferometer are highlighted.

A shorter pulse duration of 100 fs (Fig. 4) is achieved with a fiber pulse compression using self-phase modulation (SPM) for spectral broadening in a 1-m long, polarization maintaining PCF with a mode field diameter of 12.7 µm. After the fiber the spectrum has a FWHM of 17 nm (Fig. 4b). With a SF10 glass prism pair with an apex-to-apex distance of 1.2 m, the imposed group delay dispersion is ≈-10’000 fs^2, and the pulses are compressed to 100 fs (Fig. 4a). The TBP is 1.5 times the theoretical value for sech^2-pulses and the average power after the compressor is 1.1 W. For SC generation, these compressed pulses are launched into the same highly nonlinear PCF as described above. Again the generated spectrum is octave-spanning.

Using unchirped sech^2-shaped compressed pulses of 100-fs duration as the input pulses in simulations yielded results in excellent agreement with experiment as shown in Fig. 3b, *top*. In particular, the pulse compression reduces the soliton order to ≈5 and in case of the compressed pulses our stochastic simulations now predict that the calculated spectra are coherent (Fig. 3b, *bottom*). The improved coherence with lower soliton number arises from the decreased sensitivity to noise of the initial soliton fission process that occurs at the onset of the supercontinuum generation. In this case, the soliton ejection from soliton fission occurs

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in a deterministic manner, such that the effects of spontaneous noise processes such as modulation instability have negligible effect on the subsequent dynamics. Experimentally, the coherence of the SC in this parameter regime is confirmed, because with the SC generated from the compressed pulses, the CEO beat was detected as described in the following section.

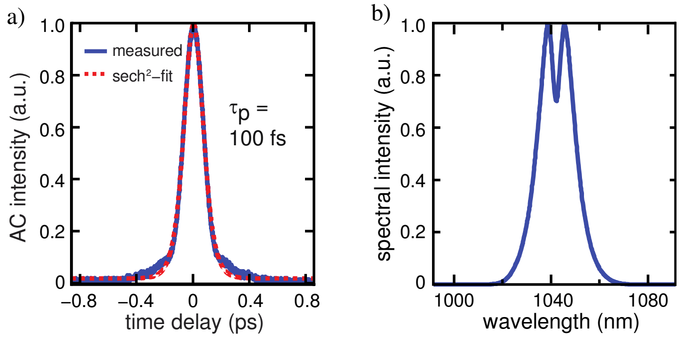

Fig. 4. Fiber pulse compression: a) normalized autocorrelation (AC) with the fit for sech^2-pulses and b) optical spectrum. The pulse duration is 100 fs and the FWHM of the optical spectrum is 17 nm centered around 1042 nm.

4. CEO frequency detection in a f-to-2f interferometer

The SC generated with the compressed pulses (Fig. 5a) is launched into a *f*-to-2*f* interferometer for CEO beat detection [1] (Fig. 5b). A dichroic mirror separates the Raman soliton at 1360 nm and the dispersive wave at 680 nm. In one arm of the interferometer a delay line is included to ensure the temporal overlap for the beating. Afterwards the two spectral parts are combined again and, after polarization adjustment, the beam is focused in a 1-mm long, periodically poled lithium niobate (PPLN) crystal with a poling period of 13.8 µm for frequency-doubling of the Raman soliton. After a bandpass filter centered at 680 nm, the CEO beat is detected with a free-space photodiode and a microwave spectrum analyzer. Figure 5c) shows the detected CEO beats and the peak of the repetition rate. The SNR of the CEO beat is 27 dB in a 1-MHz resolution. The current setup is not yet optimized for stability. A higher SNR can be expected with improved mechanical stability of the mounts, a more compact setup and an additional cover. The CEO beat frequency can be tuned by changing the pump current. This mechanism will be used for the electronic stabilization of the CEO frequency.

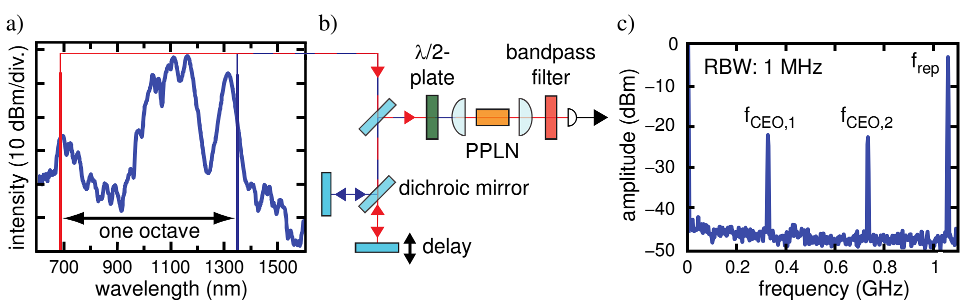

Fig. 5. Stable 1-GHz frequency comb with a compact DPSSL setup using a pulse compression stage but no additional external amplifiers: a) Supercontinuum (SC) after the highly nonlinear PCF generated with the 100 fs pulses. b) Layout of the *f*-to-2*f* interferometer for the CEO frequency detection. c) Microwave spectrum with the two CEO beat frequencies ($f_{CEO,1}$ = 0.33 GHz and $f_{CEO,2}$ = 0.73 GHz) and the repetition rate (f_{rep} = 1.06 GHz), resolution bandwidth (RBW): 1 MHz.

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5. Conclusion and Outlook

We have demonstrated a gigahertz frequency comb based on Yb-doped DPSSLs. This further confirms that diode-pumped SESAM-modelocked solid-state lasers are excellent sources for compact, high repetition rate, low noise frequency combs. Previously we have already demonstrated excellent performance in the MHz regime [15]. We have demonstrated the first CEO beat detection, and therefore a self-referencable frequency comb using a gigahertz DPSSL. Full electronic stabilization of the comb can be achieved with phase-locked loops to stabilize the two degrees of freedom, the repetition rate and the CEO frequency, to an external reference with feedback to the cavity length and the pump current, respectively. This full comb stabilization will be one of our next targets.

Furthermore, we have shown that pulse compression to a soliton order below 10 was necessary for coherent SC generation and therefore CEO beat detection. Future work is required to explore in more experimental detail the exact transition point for stable SC generation. Our results give more concrete guidelines for future ultrafast laser developments such as multi-10-Watt average power thin disk lasers [22,23], multi-gigahertz DPSSLs or SESAM-modelocked optically pumped semiconductor disk lasers (or vertical external cavity surface emitting lasers, VECSELs) [24] or even integrated external-cavity surface emitting lasers (MIXSELs) [25,26]. Especially the recent developments towards high average power femtosecond VECSELs [27] together with their excellent noise properties [28] make these sources very attractive for more compact gigahertz frequency comb generation.

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