Compact gigahertz frequency comb generation: how short do the pulses need to be?

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Abstract: We investigate the required pulse duration for coherent supercontinuum generation for CEO detection in the 1-µm and 1.5-µm spectral regime. We demonstrate the first self-referenceable frequency comb from a gigahertz diode-pumped solid state laser.

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1. Introduction

Stable frequency combs from femtosecond lasers have been a major breakthrough in optical science and metrology. Typical frequency combs are either based on complex green-pumped Ti:sapphire lasers or amplified fiber laser systems. Optically-pumped semiconductor lasers (OPSs) and diode-pumped solid-state lasers (DPSSLs) are promising technologies for more cost-efficient, reliable, and compact frequency combs. Similar to Ti:sapphire lasers, they operate with high-*Q* cavities and moderate intracavity nonlinearities, which results in a low fundamental quantum noise limit enabling a free-running carrier envelope offset (CEO) beating signal with a narrow linewidth. Furthermore, they can achieve watt-level average powers without any amplification and have proven to operate at tens of gigahertz repetition rate. Higher repetition rates provide increased power per mode and simpler access to individual optical lines, important for arbitrary waveform generation or calibration of spectrometers. However, to date no gigahertz octave-spanning frequency combs based on either semiconductor lasers or on DPSSLs have been realized. For comb self-referencing, the standard *f*-to-2*f* CEO detection requires a coherent octave-spanning supercontinuum (SC). 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. The soliton order has to be below ≈10 [1], which gives an easy accessible parameter for evaluating the requirements in pulse duration, pulse energy, fiber dispersion, and fiber nonlinearity. However, no comparative experimental studies have been performed so far.

Here we demonstrate the first experimental comparison of the influence of the pulse duration on the CEO beating signal, using two DPSSLs operating in the 1-µm and 1.5-µm spectral regions. In addition, we present the first CEO detection of a gigahertz DPSSL [2]. We further improved our previous 1-GHz SESAM-modelocked Yb:KGW laser [3] and generate 2.2-W average power in 290-fs pulses at the central wavelength of 1042 nm. Launching the pulses into a highly-nonlinear photonic crystal fiber, we generate an octave-spanning SC with 1-W average power. However, CEO detection is not possible in agreement with our simulations (the soliton order 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. The SC from 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) >27 dB. The soliton number is 5, which further confirms our theoretical prediction. The strong influence of the soliton order on the coherence is confirmed also in the 1.5-µm spectral range. Here we use a 75-MHz Er:Yb:glass DPSSL [4]. With input pulses with a duration of 170 fs, we achieve a SNR >49 dB and the soliton order is 8. In addition, we also generate an octave-spanning SC but without a detectable CEO beat signal using 170-fs pulses and a different fiber at a soliton number of >30. Furthermore, we discuss potential of increasing the repetition rate of the femtosecond Yb:KGW laser into the multi-GHz regime. We demonstrate a 2.4-GHz fundamentally modelocked Yb:KGW laser with a pulse duration of 290 fs and an average output power of 2.3 W. We also report on preliminary results in scaling up the repetition rate to 4.7 GHz with a pulse duration of 360 fs and an average power of 1.8 W.

2. 75-MHz frequency comb generation at 1.5 µm

The SESAM-soliton modelocked Er:Yb:glass oscillator generates 170-fs pulses with an average output power of 110 mW at a repetition rate of 75 MHz [4]. For spectral broadening the laser output is directly (without additional amplification or compression), launched into a dispersion-flattened, polarization-maintaining, highly nonlinear fiber (PM-HNLF). The fiber has a nonlinear coefficient of 10.5 $W^{-1}km^{-1}$ and exhibits anomalous dispersion at the wavelength of the input pulses (β_2≈-7 ps^2/km). After propagation of 1.3 m through this fiber, the spectrum covers an octave. For our parameters, the input soliton number N is approximately 8 which suggests that coherent supercontinuum broadening should be possible. Indeed this is the case, as indicated by the successful detection of the CEO beat frequency in an f-to-2f interferometer [5] shown in Figure 1. The CEO beat frequencies have a SNR >49 dB (resolution bandwidth (RBW): 100 kHz) and a linewidth of only 3.6 kHz FWHM. This is to our knowledge the narrowest CEO frequency linewidth of a free running laser in the 1.5 µm regime.

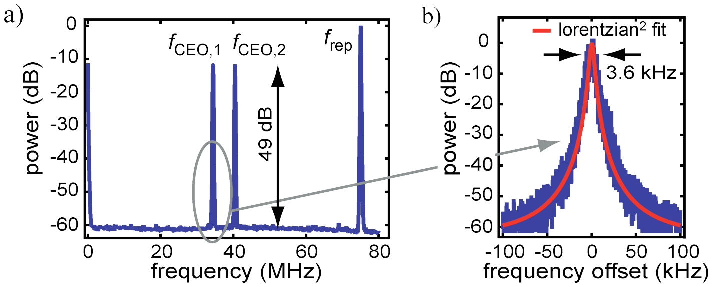

Fig. 1: 75-MHz frequency comb generation at 1.5 µm from an Er:Yb:glass laser: a) Microwave spectrum over a 80-MHz span with the two CEO beat frequencies and the repetition rate with a SNR >49 dB (RBW: 100 kHz) and b) zoom into the left CEO beat with a squared-Lorentzian fit with a linewidth of 3.6 kHz FWHM (RBW: 1 kHz).

In addition, we also generate an octave-spanning SC in a different fiber which is not polarization maintaining, has a higher nonlinear coefficient of 18 W^{-1}km^{-1} and also exhibits anomalous dispersion at the wavelength of the input pulses (β_2≈-0.82 ps^2/km). For this fiber, the 170-fs pulses correspond to a soliton order of >30 and therefore, we operate in a regime where we expect incoherent SC generation. Indeed the CEO beat frequency is not detectable in this setup.

3. 1-GHz frequency comb generation at 1 µm

The laser we use for high repetition rate frequency comb generation at 1 µm is an Yb:KGW oscillator. The SESAM-soliton-modelocked laser operates at the repetition rate of 1 GHz with an average output power of 2.2 W and a pulse duration of 290 fs. 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. For spectral broadening, the pulses are launched directly into a highly nonlinear photonic crystal fiber (PCF). The PCF is polarization maintaining, exhibits anomalous dispersion at the wavelength of the input pulses (β_2≈-15.4 ps^2/km) and has a nonlinear coefficient of 23 W^{-1}km^{-1}. After two meter propagation in this fiber the generated SC spans an octave as seen in Fig. 2a), *top*. We have performed realistic numerical simulations of our experiment [1]. As seen in Fig. 2a), *top*, we achieve good agreement between the simulated and the measured SC. The calculated coherence (Fig. 2a, *bottom*) is low, especially at the wavelengths used in the f-to-2f interferometer. This is consistent with the numerical guidelines as a soliton order of 13 is present. 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. 2b).

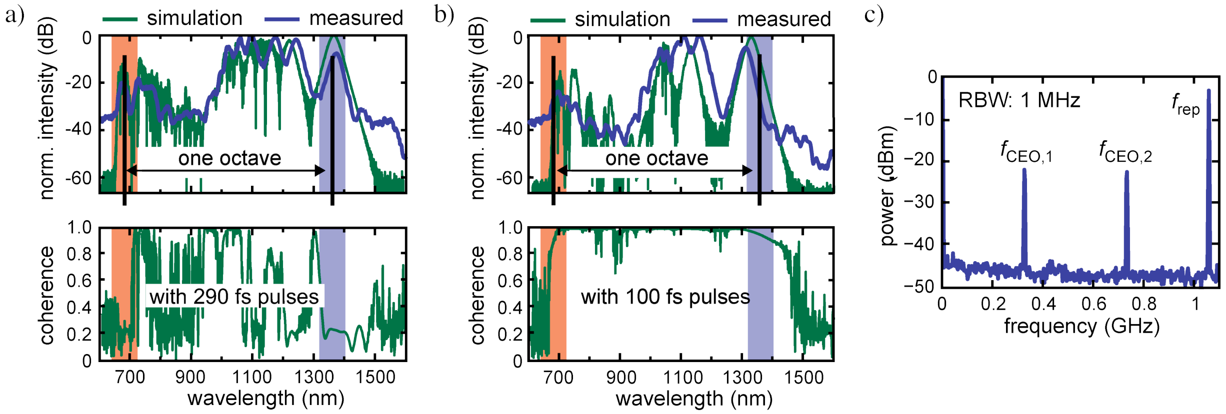

Fig. 2: 1-GHz frequency comb generation at 1 µm from an Yb:KGW laser: a) *top* measured and simulated SC and *bottom* calculated coherence generated with pulses of 290 fs and b) with 100 fs duration; the spectral ranges used in the f-to-2f interferometer are highlighted. c) Microwave spectrum with the two CEO beat frequencies with a SNR >27 dB (RBW: 1 MHz) and the repetition rate.

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. A shorter pulse duration of 100 fs 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 and an SF10 glass prism pair. The average power after the compressor is 1.1 W. The SC generated in the same PCF as used in case of the 290-fs pulses is again octave-spanning. The simulations are in excellent agreement with the experiment as shown in Fig. 2b, *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. 2b, *bottom*). This is confirmed by the CEO beat detection in an *f*-to-2*f* interferometer [1] (Fig. 2c). The SNR of the CEO beats is >27 dB with a 1-MHz resolution bandwidth. 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.

4. Towards even higher repetition rates

Up to date, the highest repetition rate femtosecond DPSSL operates at 2.8 GHz with an average power of 680 mW and a peak power of 1.5 kW [6]. With the setup shown in Fig. 3 and a high brightness distributed Bragg reflector (DBR) tapered diode laser which delivers up to 6-W pump power [7], we realized a 2.4-GHz fundamentally SESAM-soliton-modelocked femtosecond Yb:KGW laser. The pulse duration is 290 fs, the average output power is 2.3 W and the corresponding peak power is 2.9 kW. The TBP is 1.4 times the ideal value for sech^2-pulses. The obtained peak power of 2.9 kW and the pulse energy of 1.0 nJ are record high values for a multi-GHz femtosecond DPSSL. Furthermore, we report on scaling the repetition rate even further. We recently realized a 4.7-GHz fundamentally modelocked Yb:KGW laser with a pulse duration of 360 fs and an average power of 1.8 W. However, in these initial experiments some higher order spatial modes are present.

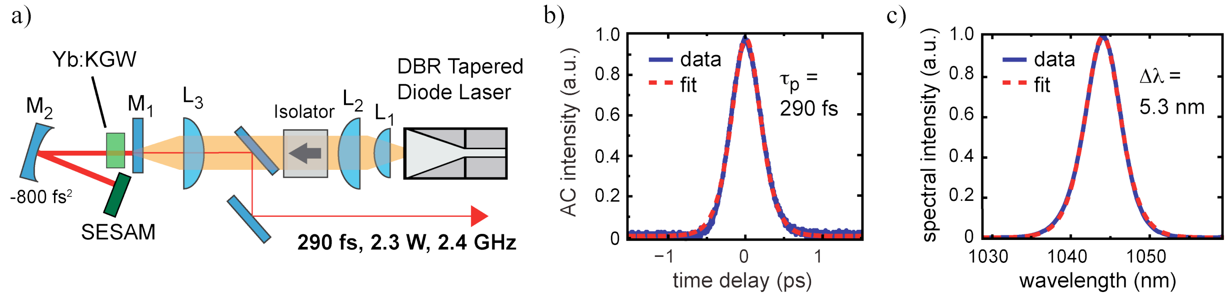

Fig. 3: 2.4-GHz femtosecond Yb:KGW laser: a) Layout of the cavity with: L_1, L_2, L_3: pump optics; M_1: flat mirror transparent for the pump wavelength and OC for the lasing wavelength, transmission 2.8%, M_2: curved GTI mirror with a GDD of -800 fs^2, ROC: 30 mm and a SESAM with a saturation fluence of 40 µJ/cm^2, a modulation depth of 0.5% and nonsaturable losses <0.1%. b) Normalized autocorrelation (AC) and c) optical spectrum plotted with the fit curves assuming sech^2-pulses. The pulse duration is 290 fs and the spectral bandwidth is 5.4 nm, centered around 1044 nm.

5. Conclusion and outlook

In conclusion, we presented first experimental evidence that the soliton order is the critical parameter for coherent supercontinuum generation in agreement with the theoretical prediction that the soliton order should be smaller than ≈10. This sets an upper limit in pulse duration for a given combination of laser and fiber parameters. Moreover, we demonstrated the first CEO beat frequency detection of a gigahertz DPSSL and we presented results on scaling up the repetition rate of femtosecond DPSSLs into the multi-GHz regime. Our result gives important guidelines for future compact gigahertz frequency comb generation.

6. References

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