Self-referenced CEO Frequency Detection of a Semiconductor Disk Laser using a Silicon Nitride Waveguide

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Abstract: We present the self-referenced detection of the carrier-envelope offset (CEO) frequency of a gigahertz SESAM-modelocked VECSEL with a coherent octave-spanning supercontinuum generated in a silicon nitride waveguide without the need of external pulse amplification.

OCIS codes: (140.5960) Semiconductor lasers; (140.7270) Vertical emitting lasers; (140.4050) Mode-locked lasers; (140.3480) Lasers, diode-pumped; (130.2755) Glass waveguide; (320.6629) Supercontinuum generation.

1. Introduction

Optical frequency combs (OFCs) are at the origin of important advancements in the fields of frequency metrology and spectroscopy. Commercially available OFCs are currently mostly based on Ti-sapphire or fiber lasers. However, diode-pumped ultrafast semiconductor disk lasers (SDLs) have reached comparable performance with several key advantages: Semiconductor bandgap engineering allows for the emission wavelength to be flexibly designed from the ultraviolet to the mid-infrared [1, 2]. In contrast to diode-pumped Yb-doped solid-state lasers, SDLs do not suffer from Q-switching instabilities and are ideally suited for pulse repetition rates in the gigahertz regime. High repetition rates result in a large comb line spacing which provides an increased power per comb line for the same average power, thus enhancing the signal-to-noise ratio (SNR). Furthermore, SDLs can be produced on a wafer scale and are pumped with multimode diode arrays which reduces complexity and cost.

An OFC can provide a reliable frequency ruler when both the pulse repetition rate and the carrier-envelope offset (CEO) frequency of the modelocked laser are stabilized. The repetition rate can be stabilized by controlling the cavity length and in this respect SDLs have shown excellent timing jittering noise performance [3, 4]. The stabilization of the CEO frequency is more challenging. A well-established self-referenced approach to detect the CEO frequency is the *f*-to-2*f* scheme [5] for which a coherent octave-spanning supercontinuum is required. This is typically generated in a photonic crystal fiber (PCF). Kilowatts of pulse peak power are usually needed to generate an octave-spanning spectrum and pulse durations shorter than 100 fs are necessary to maintain coherence [6]. Laser sources which do not directly deliver this laser performance, such as fiber lasers or SDLs, have relied on external pulse amplification and pulse compression so far. This external amplification approach has allowed for CEO frequency detection [7] and stabilization [8] of an ultrafast SDL.

Here, we present the first CEO frequency detection of an ultrafast SDL without any need of external pulse amplification and compression. The latest improvement of semiconductor saturable absorber mirror (SESAM) modelocked vertical external-cavity surface-emitting lasers (VECSELs) allowed us to obtain 100-fs pulses with an average output power as high as 100 mW [9]. In addition, a silicon nitride (Si_3N_4) waveguide instead of a PCF significantly lowers the peak power requirement and generates a supercontinuum with better noise performance [10]. Based on this progress, we are able to generate a coherent octave-spanning supercontinuum that enabled the detection of the CEO frequency by *f*-to-2*f* interferometry. We find the linewidth of the detected free-running CEO frequency to be reduced by an order of magnitude compared to previous results employing amplification and pulse compression [7].

2. Measurements and Results

The results presented here have been achieved with a diode-pumped SESAM-modelocked VECSEL. The laser cavity, the VECSEL gain chip, and the SESAM are analogous to those presented in [9]. The SDL produced 150-fs pulses at a pulse repetition rate of 1.6 GHz and an average power of 160 mW, resulting in a pulse energy of 100 pJ. The optical spectrum is centered at 1030 nm with a full width at half maximum (FWHM) of 9.5 nm (Fig. 1a). The waveguide is a spiraled 5-cm long SiO$_2$-clad Si$_3$N$_4$ waveguide with two zero-dispersion wavelengths and a sub-wavelength cross-section of 780 nm by 750 nm. Compared to previous demonstrations of this waveguide technology with diode-pumped Yb-doped solid-state lasers [10], the waveguide used here is about 7 times longer and was designed to generate dispersive waves spaced an octave apart. The seed laser is free-space coupled into the waveguide with a coupling efficiency up to 24%. Only 23 mW of coupled average power (i.e. 14 pJ of pulse energy and 84 W of pulse peak power) was sufficient to generate a coherent octave-spanning supercontinuum (Fig. 1a). The generated octave-spanning supercontinuum features two dispersive waves centered around 695 nm and 1495 nm (Fig. 1a). In order to detect the CEO frequency via f-to-2f interferometry, a spectral slice of the supercontinuum around 1434 nm was frequency-doubled in a 3-mm-long MgO-doped periodically poled lithium niobate (PPLN) crystal and beaten with the 717-nm part of the supercontinuum on a photodiode. The resulting microwave spectrum of the signal shows the two CEO beat frequencies between DC and the pulse repetition rate. The SNR of the CEO note is >30 dBc when measured with a resolution bandwidth (RBW) of 10 kHz (Fig. 1b). We measured the 3-dB linewidth of the free-running CEO frequency to be ≈1 MHz at a RBW of 3 kHz (Fig. 1d). This corresponds to a

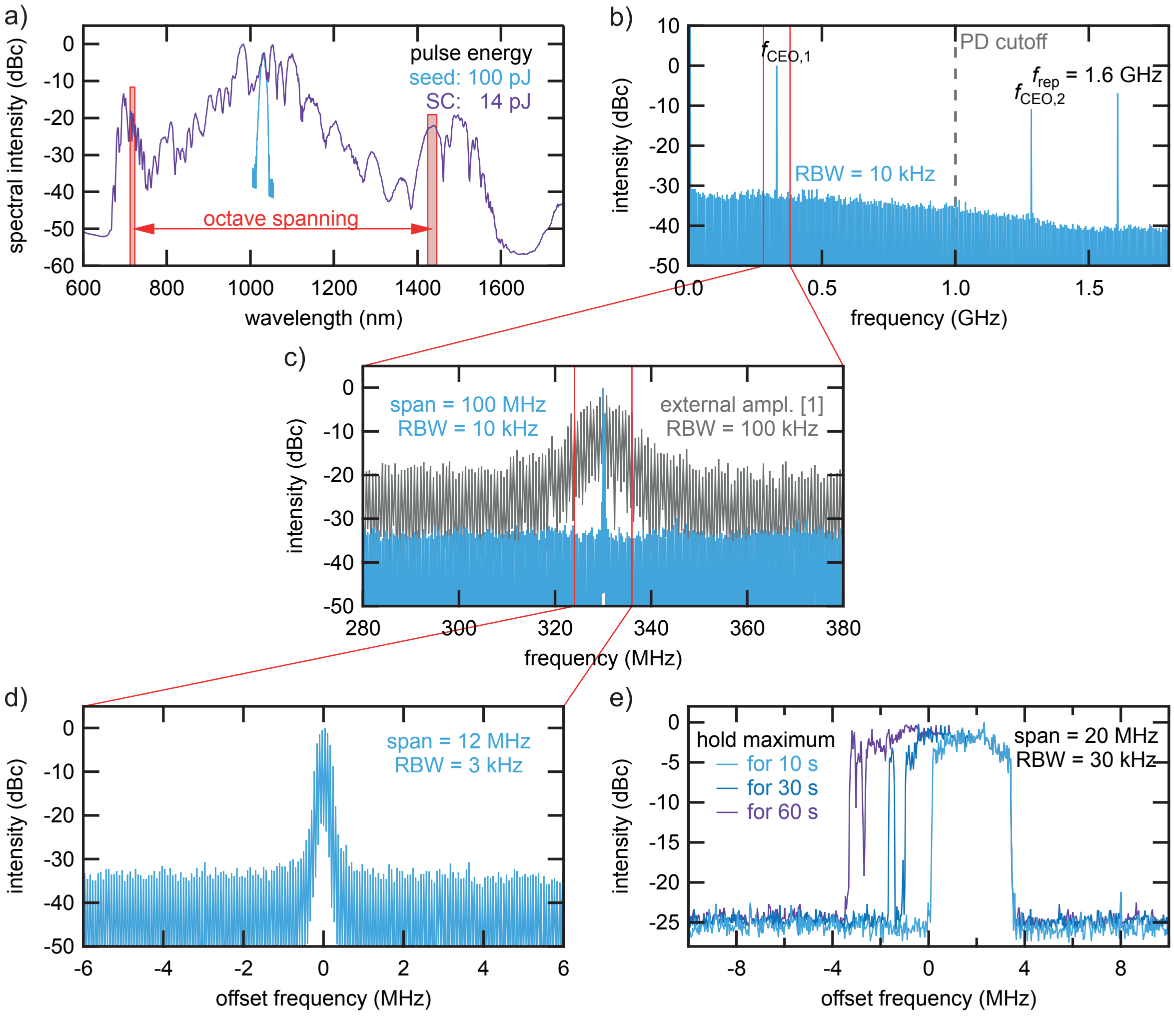

Fig. 1. a) Optical spectrum of the seed laser (blue) and of the generated octave-spanning supercontinuum (violet) with an average power of 160 mW and 23 mW respectively. The red areas indicate the frequencies used for the f-to-2f interferometry. b) Microwave spectrum of the f-to-2f interferometer photodiode (PD) signal showing the two CEO beat frequencies between DC and the pulse repetition rate. The signal-to-noise ratio of the CEO beat measured with a resolution bandwidth (RBW) of 10 kHz is >30 dBc. c) Comparison of the CEO frequency detection with the previous detection by Zaugg et al. [7], obtained with external pulse amplification and compression. d) The 3-dB linewidth of the CEO frequency is ≈1 MHz measured with a RBW of 3 kHz and a 12 MHz span. e) Microwave spectrum measurement holding the maximum value indicating the dirft of the CEO beat note over 8 MHz in 60 s.

linewidth reduction by a factor of 10 in comparison to the CEO beat note detected by Zaugg et al. [7], which used external pulse amplification and compression for the supercontinuum generation in a PCF (Fig. 1c). A microwave spectrum measurement recording the maximum peak value shows the fluctuation of the free-running CEO peak over 8 MHz in 60 s (Fig. 1e). These low-frequency drifts can be attributed to air fluctuation and mechanical vibrations of our free-standing and open system and should be drastically reduced when placing the laser cavity in a proper housing. This is also required for CEO stabilization in the near future.

3. Conclusion

We have presented the first CEO frequency detection of a SESAM-modelocked VECSEL without any external pulse amplification. The coherent octave-spanning supercontinuum used for the *f*-to-2*f* interferometry was generated in a Si_3N_4 waveguide using only 14 pJ of coupled pulse energy. The linewidth of the CEO frequency is ≈1 MHz, which is comparable to the CEO frequency of diode-pumped Yb-doped solid-state laser at similar repetition rate [11] and an order of magnitude less than reported for an externally amplified VECSEL [7].

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5. References

1. B. W. Tilma, M. Mangold, C. A. Zaugg, S. M. Link, D. Waldburger, A. Klenner, A. S. Mayer, E. Gini, M. Golling, and U. Keller, "Recent advances in ultrafast semiconductor disk lasers," Light Sci. Appl. **4**, e310 (2015).
2. M. Guina, A. Rantamäki, and A. Härkönen, "Optically pumped VECSELs: review of technology and progress," Journal of Physics D: Applied Physics **50**, 383001 (2017).
3. V. J. Wittwer, C. A. Zaugg, W. P. Pallmann, A. E. H. Oehler, B. Rudin, M. Hoffmann, M. Golling, Y. Barbarin, T. Südmeyer, and U. Keller, "Timing Jitter Characterization of a Free-Running SESAM Mode-locked VECSEL," Photonics Journal, IEEE **3**, 658-664 (2011).
4. M. Mangold, S. M. Link, A. Klenner, C. A. Zaugg, M. Golling, B. W. Tilma, and U. Keller, "Amplitude Noise and Timing Jitter Characterization of a High-Power Mode-Locked Integrated External-Cavity Surface Emitting Laser," IEEE Photonics Journal **6**(2014).
5. H. R. Telle, G. Steinmeyer, A. E. Dunlop, J. Stenger, D. H. Sutter, and U. Keller, "Carrier-envelope offset phase control: A novel concept for absolute optical frequency measurement and ultrashort pulse generation," Appl. Phys. B **69**, 327-332 (1999).
6. J. M. Dudley, G. Genty, and S. Coen, "Supercontinuum generation in photonic crystal fiber," Reviews of Modern Physics **78**, 1135-1184 (2006).
7. C. A. Zaugg, A. Klenner, M. Mangold, A. S. Mayer, S. M. Link, F. Emaury, M. Golling, E. Gini, C. J. Saraceno, B. W. Tilma, and U. Keller, "Gigahertz self-referenceable frequency comb from a semiconductor disk laser," Opt. Express **22**, 16445-16455 (2014).
8. N. Jornod, K. Gürel, V. J. Wittwer, P. Brochard, S. Hakobyan, S. Schilt, D. Waldburger, U. Keller, and T. Südmeyer, "Carrier-envelope offset frequency stabilization of a mode-locked semiconductor laser," ASSL (OSA Laser Congress) **AW1A.6** (2017).
9. D. Waldburger, S. M. Link, M. Mangold, C. G. E. Alfieri, E. Gini, M. Golling, B. W. Tilma, and U. Keller, "High-power 100 fs semiconductor disk lasers," Optica **3**, 844-852 (2016).
10. A. Klenner, A. S. Mayer, A. R. Johnson, K. Luke, M. R. E. Lamont, Y. Okawachi, M. Lipson, A. L. Gaeta, and U. Keller, "Gigahertz frequency comb offset stabilization based on supercontinuum generation in silicon nitride waveguides," Opt. Express **24**, 11043-11053 (2016).
11. A. Klenner, S. Schilt, T. Südmeyer, and U. Keller, "Gigahertz frequency comb from a diode-pumped solid-state laser," Opt. Express **22**, 31008-31019 (2014).