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Fully stabilized optical frequency comb with sub-radian CEO phase noise from a SESAM-modelocked 1.5-µm solid-state laser

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Abstract: We report the first full stabilization of an optical frequency comb generated from a femtosecond diode-pumped solid-state laser (DPSSL) operating in the 1.5-µm spectral region. The stability of the comb is characterized in free-running and in phase-locked operation by measuring the noise properties of the carrier-envelope offset (CEO) beat, of the repetition rate, and of a comb line at 1558 nm. The high *Q*-factor of the semiconductor saturable absorber mirror (SESAM)-modelocked 1.5-µm DPSSL results in a low-noise CEO-beat, for which a tight phase lock can be much more easily realized than for a fiber comb. Using a moderate feedback bandwidth of only 5.5 kHz, we achieved a residual integrated phase noise of 0.72 rad rms for the locked CEO, which is one of the smallest values reported for a frequency comb system operating in this spectral region. The fractional frequency stability of the CEO-beat is 20-fold better than measured in a standard self-referenced commercial fiber comb system and contributes only 10^{-15} to the optical carrier frequency instability at 1 s averaging time.

OCIS codes: (140.4050) Mode-locked lasers; (140.3580) Lasers, solid-state; (120.3930) Metrological instrumentation; (320.7090) Ultrafast lasers.

References and links

1. T. W. Hänsch, "Nobel lecture: passion for precision," Rev. Mod. Phys. **78**(4), 1297–1309 (2006).
2. J. Ye, H. Schnatz, and L. W. Hollberg, "Optical frequency combs: from frequency metrology to optical phase control," IEEE J. Sel. Top. Quantum Electron. **9**(4), 1041–1058 (2003).
3. M. C. Stowe, M. J. Thorpe, A. Pe'er, J. Ye, J. E. Stalnaker, V. Gerginov, and S. A. Diddams, "Direct frequency comb spectroscopy," Adv. At. Mol. Opt. Phys. **55**, 1–60 (2008).
4. M. J. Thorpe, K. D. Moll, R. J. Jones, B. Safdi, and J. Ye, "Broadband cavity ringdown spectroscopy for sensitive and rapid molecular detection," Science **311**(5767), 1595–1599 (2006).
5. B. Bernhardt, A. Ozawa, P. Jacquet, M. Jacquey, Y. Kobayashi, T. Udem, R. Holzwarth, G. Guelachvili, T. W. Hänsch, and N. Picqué, "Cavity-enhanced dual-comb spectroscopy," Nat. Photonics **4**(1), 55–57 (2010).
6. G. Steinmeyer, D. H. Sutter, L. Gallmann, N. Matuschek, and U. Keller, "Frontiers in ultrashort pulse generation: pushing the limits in linear and nonlinear optics," Science **286**(5444), 1507–1512 (1999).
7. U. Keller, "Ultrafast solid-state laser oscillators: a success story for the last 20 years with no end in sight," Appl. Phys. B **100**(1), 15–28 (2010).
8. U. Keller, "Recent developments in compact ultrafast lasers," Nature **424**(6950), 831–838 (2003).
9. 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**(4), 327–332 (1999).
10. R. Holzwarth, T. Udem, T. W. Hänsch, J. C. Knight, W. J. Wadsworth, and P. S. Russell, "Optical frequency synthesizer for precision spectroscopy," Phys. Rev. Lett. **85**(11), 2264–2267 (2000).
11. D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, "Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis," Science **288**(5466), 635–639 (2000).

12. R. Ell, U. Morgner, F. X. Kärtner, J. G. Fujimoto, E. P. Ippen, V. Scheuer, G. Angelow, T. Tschudi, M. J. Lederer, A. Boiko, and B. Luther-Davies, "Generation of 5-fs pulses and octave-spanning spectra directly from a Ti:sapphire laser," Opt. Lett. **26**(6), 373–375 (2001).
13. A. Bartels, D. C. Heinecke, and S. A. Diddams, "10-GHz self-referenced optical frequency comb," Science **326**(5953), 681 (2009).
14. B. R. Washburn, S. A. Diddams, N. R. Newbury, J. W. Nicholson, M. F. Yan, and C. G. Jørgensen, "Phase-locked, erbium-fiber-laser-based frequency comb in the near infrared," Opt. Lett. **29**(3), 250–252 (2004).
15. G. Marra, R. Slavík, H. S. Margolis, S. N. Lea, P. Petropoulos, D. J. Richardson, and P. Gill, "High-resolution microwave frequency transfer over an 86-km-long optical fiber network using a mode-locked laser," Opt. Lett. **36**(4), 511–513 (2011).
16. J. J. McFerran, W. C. Swann, B. R. Washburn, and N. R. Newbury, "Elimination of pump-induced frequency jitter on fiber-laser frequency combs," Opt. Lett. **31**(13), 1997–1999 (2006).
17. I. Hartl, G. Imeshev, M. E. Fermann, C. Langrock, and M. M. Fejer, "Integrated self-referenced frequency-comb laser based on a combination of fiber and waveguide technology," Opt. Express **13**(17), 6490–6496 (2005).
18. J. J. McFerran, W. C. Swann, B. R. Washburn, and N. R. Newbury, "Suppression of pump-induced frequency noise in fiber-laser frequency combs leading to sub-radian f_{ceo} phase excursions," Appl. Phys. B **86**(2), 219–227 (2007).
19. Y. Nakajima, H. Inaba, K. Hosaka, K. Minoshima, A. Onae, M. Yasuda, T. Kohno, S. Kawato, T. Kobayashi, T. Katsuyama, and F.-L. Hong, "A multi-branch, fiber-based frequency comb with millihertz-level relative linewidths using an intra-cavity electro-optic modulator," Opt. Express **18**(2), 1667–1676 (2010).
20. E. Baumann, F. R. Giorgetta, J. W. Nicholson, W. C. Swann, I. Coddington, and N. R. Newbury, "High-performance, vibration-immune, fiber-laser frequency comb," Opt. Lett. **34**(5), 638–640 (2009).
21. F. Quinlan, T. M. Fortier, M. S. Kirchner, J. A. Taylor, M. J. Thorpe, N. Lemke, A. D. Ludlow, Y. Jiang, and S. A. Diddams, "Ultralow phase noise microwave generation with an Er:fiber-based optical frequency divider," Opt. Lett. **36**(16), 3260–3262 (2011).
22. U. Keller, D. A. B. Miller, G. D. Boyd, T. H. Chiu, J. F. Ferguson, and M. T. Asom, "Solid-state low-loss intracavity saturable absorber for Nd:YLF lasers: an antiresonant semiconductor Fabry-Perot saturable absorber," Opt. Lett. **17**(7), 505–507 (1992).
23. U. Keller, K. J. Weingarten, F. X. Kärtner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. Aus der Au, "Semiconductor saturable absorber mirrors (SESAMs) for femtosecond to nanosecond pulse generation in solid-state lasers," IEEE J. Sel. Top. Quantum Electron. **2**(3), 435–453 (1996).
24. T. Südmeyer, S. V. Marchese, S. Hashimoto, C. R. E. Baer, G. Gingras, B. Witzel, and U. Keller, "Femtosecond laser oscillators for high-field science," Nat. Photonics **2**(10), 599–604 (2008).
25. A. E. H. Oehler, M. C. Stumpf, S. Pekarek, T. Südmeyer, K. J. Weingarten, and U. Keller, "Picosecond diode-pumped 1.5 µm Er:Yb:glass lasers operating at 10-100 GHz repetition rate," Appl. Phys. B **99**(1-2), 53–62 (2010).
26. L. Krainer, R. Paschotta, S. Lecomte, M. Moser, K. J. Weingarten, and U. Keller, "Compact Nd:YVO_4 lasers with pulse repetition rates up to 160 GHz," IEEE J. Quantum Electron. **38**(10), 1331–1338 (2002).
27. S. Pekarek, C. Fiebig, M. C. Stumpf, A. E. H. Oehler, K. Paschke, G. Erbert, T. Südmeyer, and U. Keller, "Diode-pumped gigahertz femtosecond Yb:KGW laser with a peak power of 3.9 kW," Opt. Express **18**(16), 16320–16326 (2010).
28. S. Yamazoe, M. Katou, T. Adachi, and T. Kasamatsu, "Palm-top-size, 1.5 kW peak-power, and femtosecond (160 fs) diode-pumped mode-locked Yb^{+3}:$KY(WO_4)_2$ solid-state laser with a semiconductor saturable absorber mirror," Opt. Lett. **35**(5), 748–750 (2010).
29. R. Holzwarth, M. Zimmermann, T. Udem, T. W. Hänsch, P. Russbüldt, K. Gäbel, R. Poprawe, J. C. Knight, W. J. Wadsworth, and P. S. J. Russell, "White-light frequency comb generation with a diode-pumped Cr:LiSAF laser," Opt. Lett. **26**(17), 1376–1378 (2001).
30. S. A. Meyer, J. A. Squier, and S. A. Diddams, "Diode-pumped Yb:KYW femtosecond laser frequency comb with stabilized carrier-envelope offset frequency," Eur. Phys. J. D **48**(1), 19–26 (2008).
31. M. C. Stumpf, S. Pekarek, A. E. H. Oehler, T. Südmeyer, J. M. Dudley, and U. Keller, "Self-referencable frequency comb from a 170-fs, 1.5-µm solid-state laser oscillator," Appl. Phys. B **99**(3), 401–408 (2010).
32. S. Pekarek, T. Südmeyer, S. Lecomte, S. Kundermann, J. M. Dudley, and U. Keller, "Self-referenceable frequency comb from a gigahertz diode-pumped solid-state laser," Opt. Express **19**(17), 16491–16497 (2011).
33. M. Hoffmann, O. D. Sieber, V. J. Wittwer, I. L. Krestnikov, D. A. Livshits, Y. Barbarin, T. Südmeyer, and U. Keller, "Femtosecond high-power quantum dot vertical external cavity surface emitting laser," Opt. Express **19**(9), 8108–8116 (2011).
34. 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," IEEE Photon. J. **3**(4), 658–664 (2011).
35. http://www.time-bandwidth.com/product/view/id/34
36. F. X. Kärtner, I. D. Jung, and U. Keller, "Soliton mode-locking with saturable absorbers," IEEE J. Sel. Top. Quantum Electron. **2**(3), 540–556 (1996).
37. A. Schlatter, B. Rudin, S. C. Zeller, R. Paschotta, G. J. Spühler, L. Krainer, N. Haverkamp, H. R. Telle, and U. Keller, "Nearly quantum-noise-limited timing jitter from miniature Er:Yb:glass lasers," Opt. Lett. **30**(12), 1536–1538 (2005).
38. B. R. Washburn, W. C. Swann, and N. R. Newbury, "Response dynamics of the frequency comb output from a femtosecond fiber laser," Opt. Express **13**(26), 10622–10633 (2005).

39. S. Schilt, N. Bucalovic, L. Tombez, C. Schori, V. Dolgovskiy, G. Di Domenico, M. Zaffalon, and P. Thomann, “Frequency discriminators for the characterization of narrow-spectrum heterodyne beat signals: application to the measurement of a sub-hertz carrier-envelope-offset beat in an optical frequency comb,” Rev. Sci. Instrum. (submitted to).
40. G. Di Domenico, S. Schilt, and P. Thomann, “Simple approach to the relation between laser frequency noise and laser line shape,” Appl. Opt. **49**(25), 4801–4807 (2010).
41. T. M. Fortier, D. J. Jones, J. Ye, and S. T. Cundiff, “Highly phase stable mode-locked lasers,” IEEE J. Sel. Top. Quantum Electron. **9**(4), 1002–1010 (2003).
42. T. Fuji, J. Rauschenberger, C. Gohle, A. Apolonski, T. Udem, V. S. Yakovlev, G. Tempea, T. W. Hänsch, and F. Krausz, “Attosecond control of optical waveforms,” New J. Phys. **7**, 116 (2005).
43. H. M. Crespo, J. R. Birge, M. Y. Sander, E. L. Falcao-Filho, A. Benedick, and F. X. Kärtner, “Phase stabilization of sub-two-cycle pulses from prismless octave-spanning Ti:sapphire lasers,” J. Opt. Soc. Am. B **25**(7), B147–B154 (2008).
44. T. J. Yu, K.-H. Hong, H.-G. Choi, J. H. Sung, I. W. Choi, D.-K. Ko, J. Lee, J. Kim, D. E. Kim, and C. H. Nam, “Precise and long-term stabilization of the carrier-envelope phase of femtosecond laser pulses using an enhanced direct locking technique,” Opt. Express **15**(13), 8203–8211 (2007).
45. D. C. Heinecke, A. Bartels, and S. A. Diddams, “Offset frequency dynamics and phase noise properties of a self-referenced 10 GHz Ti:sapphire frequency comb,” Opt. Express **19**(19), 18440–18451 (2011).
46. A. Bartels, S. A. Diddams, C. W. Oates, G. Wilpers, J. C. Bergquist, W. H. Oskay, and L. Hollberg, “Femtosecond-laser-based synthesis of ultrastable microwave signals from optical frequency references,” Opt. Lett. **30**(6), 667–669 (2005).
47. T. M. Fortier, M. S. Kirchner, F. Quinlan, J. Taylor, J. C. Bergquist, T. Rosenband, N. Lemke, A. Ludlow, Y. Jiang, C. W. Oates, and S. A. Diddams, “Generation of ultrastable microwave via optical frequency division,” Nat. Photonics **5**(7), 425–429 (2011).
48. J. Millo, M. Abgrall, M. Lours, E. M. L. English, H. Jiang, J. Guéna, A. Clairon, M. E. Tobar, S. Bize, Y. Le Coq, and G. Santarelli, “Ultra-low noise microwave generation with fiber-based optical frequency comb and application to atomic fountain clock,” Appl. Phys. Lett. **94**(14), 141105 (2009).
49. A. Haboucha, W. Zhang, T. Li, M. Lours, A. N. Luiten, Y. Le Coq, and G. Santarelli, “Optical-fiber pulse rate multiplier for ultralow phase-noise signal generation,” Opt. Lett. **36**(18), 3654–3656 (2011).
50. V. Dolgovskiy, S. Schilt, G. Di Domenico, N. Bucalovic, C. Schori, and P. Thomann, “1.5-µm cavity-stabilized laser for ultra-stable microwave generation,” Proc. IFCS&EFTF Joint Conference, San Francisco, USA, May 2–5, 2011.
51. H. R. Telle, B. Lipphardt, and J. Stenger, “Kerr-lens, mode-locked lasers as transfer oscillators for optical frequency measurements,” Appl. Phys. B **74**(1), 1–6 (2002).

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1. Introduction

Self-referenced optical frequency combs from femtosecond lasers have enabled impressive progress in numerous research areas such as precision time and frequency metrology [1, 2] and high-resolution spectroscopy [3–5]. In the last decade, the interest in frequency combs has increased considerably, leading to further developments of the underlying femtosecond laser technology [6–8]. The first frequency combs [9–11] were based on solid-state Ti:sapphire lasers due to their high peak power. Ti:sapphire lasers are to date the only lasers capable of directly generating the octave-spanning spectrum required for comb self-referencing [12], they can operate at a high repetition rate of several gigahertz [13] and also benefit from low-noise properties owing to the high intracavity power that results from the high Q-factor of their optical resonator. Therefore, Ti:sapphire combs are still widely employed today, despite several disadvantages associated with their complexity, high cost and inefficient pumping. A first breakthrough in the search for simpler and more cost-efficient systems was the demonstration of a self-referenced Er-fiber comb [14]. Owing to several important advantages such as their compactness, robustness, efficient diode pumping and low cost, Er-fiber combs have emerged as a valuable alternative to Ti:sapphire laser combs in the past years and now constitute a commonly-used comb technology. They have the further advantage of covering the 1.5-µm transmission window of optical fibers, so that the broad laser spectrum can be distributed over large distances through proper noise-cancellation fiber links for simultaneous comparison of distant optical and microwave frequency standards [15].

In comparison to Ti:sapphire combs, fiber-laser combs generally exhibit significantly higher frequency noise and broader optical comb lines, due to their high gain, low Q-factor cavities and strong fiber nonlinearities. Significant improvements have recently been realized, in particular through the achievement of sub-Hz carrier-envelope-offset (CEO) linewidth [16–20]. However noise suppression in fiber lasers remains more challenging and generally requires a wide feedback bandwidth in the 100-kHz range [17]. Notable exceptions are the Er-fiber comb developed at NIST operating with a reduced bandwidth of ≈25 kHz [21] and the multi-branch Er-fiber comb of Nakajima et al. that achieved a CEO-beat linewidth of 10-30 kHz in free-running conditions [19].

A promising alternative to fiber-lasers are semiconductor saturable absorber mirror (SESAM)-modelocked diode-pumped solid state lasers (DPSSLs) [22, 23]. DPSSLs have low intrinsic noise owing to their high-Q cavities with low residual losses and can access substantially higher average power levels than unamplified femtosecond fiber oscillators [24]. Repetition rates larger than 100 GHz have already been achieved in fundamental modelocking in the picosecond pulse width regime [25, 26] and more recently larger than 1 GHz in the femtosecond regime [27, 28]. Despite the large number of femtosecond DPSSLs reported, CEO frequency detection has been demonstrated only occasionally to date, e.g. with a Kerr-lens modelocked 865-nm Cr:LiSAF laser oscillator [29], a fiber-amplified, temporally compressed 1030-nm Yb:KYW laser [30], a SESAM modelocked Er:Yb:glass laser oscillator at 1.5 μm [31], and most recently with a gigahertz diode-pumped Yb:KGW laser without any further amplification [32]. Emerging novel ultrafast semiconductor lasers look very promising when modelocked in the femtosecond domain [33] and exhibit excellent timing jitter very similar to diode-pumped solid-state lasers [34].

Here we present the first full stabilization of a compact frequency comb in the 1.5-μm regime based on an ultrafast DPSSL oscillator without further power amplification. With the "full stabilization" we refer to the simultaneous stabilization of both the CEO frequency and the repetition rate to the same 10-MHz local reference, using pump power and laser cavity length as frequency actuators. The ultrafast laser oscillator is based on a SESAM-modelocked diode-pumped Er:Yb:glass laser that we refer to as the ERGO [35]. With this laser, a clean CEO beat signal suitable for self-referencing [9] was previously obtained [31] and we demonstrate and characterize here the full stabilization of this comb. The impact of the CEO and repetition rate on the frequency noise and stability of an optical line is assessed from the heterodyne beat measurement with an ultra-narrow linewidth laser, while the comb is referenced to an H-maser. The results are reported for the free-running as well as for the fully stabilized comb. The locked CEO-beat has an integrated phase noise of 0.72 rad, achieved with a feedback bandwidth of only 5.5 kHz. Furthermore, a 20-fold improvement in the CEO fractional frequency stability is shown compared to a commercial self-referenced fiber comb emitting in the same 1.5-μm spectral region.

2. ERGO optical frequency comb

The ERGO comb (Fig. 1) is based on a passively modelocked femtosecond Er:Yb:glass laser oscillator emitting a ≈15-nm wide spectrum (FWHM) centered at 1558 nm. The spectrum is subsequently broadened to one octave for CEO generation in a 1.5-m long, dispersion-flattened, polarization-maintaining, highly nonlinear fiber (PM-HNLF) without any prior amplification or pulse compression. The laser is an improved version of the system described in [31], generating 170-fs transform-limited laser pulses with 110 mW average output power at a repetition rate of f_{rep} = 75 MHz. A significant advantage is the direct pumping by a 600-mW fiber-coupled telecom-grade laser diode at 976 nm for reliable and efficient laser operation, and the SESAM for stable and self-starting soliton modelocking [36]. The SESAM is mounted on a piezo transducer (PZT) and on a stepper-motor for fine and coarse adjustment of the cavity length, respectively. The total round-trip losses of the cavity are well below 3%, which leads to a substantially higher Q-factor and a significantly lower quantum noise limit as compared to typical fiber lasers [37].

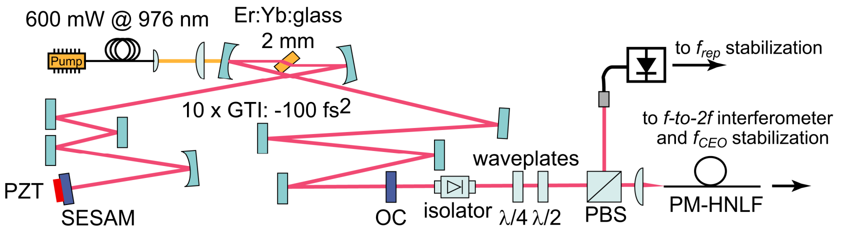

Fig. 1. Schematic of the diode-pumped Er:Yb:glass laser oscillator (ERGO). SESAM: semiconductor saturable absorber mirror; GTI: highly reflective Gires-Tournois interferometer type mirror, dispersion –100 fs^2; OC: output coupler; PBS: polarization beamsplitter cube; PM-HNLF: polarization-maintaining highly non-linear fiber. The laser output passes through an isolator for protection against optical feedbacks and waveplates for polarization control.

The new laser is built on a 10-cm thick optical breadboard to make it transportable and is protected by an enclosure for better thermal and mechanical stability. It occupies an area of 30 x 60 cm^2. A small fraction of the laser output power is used for f_{rep} stabilization, the remaining power being used for supercontinuum generation in the PM-HNLF. Details on the fiber properties, the mechanisms of spectral broadening, and the optimization of the pump parameters for efficient CEO beat frequency generation in a standard *f*-to-2*f* interferometer [9] were given in [31]. As a main result, we just recall here that a very clean CEO-beat signal is obtained at 1025 nm. The previously reported squared-Lorentzian fit of 3.6 kHz FWHM still represents the narrowest CEO-beat linewidth of a free-running laser in the 1.5-µm region to our knowledge, which reflects the intrinsic stability of the laser oscillator.

3. Full comb stabilization

Phase-stabilization of the repetition rate is performed using customized commercial stabilization electronics (Menlosystems RRE100). A small fraction of the femtosecond laser output power (<300 µW) is coupled into a singlemode optical fiber and detected with a fast photodiode (Thorlabs DET01CFC, 2 GHz bandwidth). The 28th harmonic of f_{rep} at 2.1GHz is bandpass-filtered, amplified and compared in a double-balanced mixer to the reference signal of a 2.1-GHz dielectric resonator oscillator (DRO, model Miteq DLCRO-010-02100) referenced to an H-maser. The comparison at the 28th harmonic enhances the detection sensitivity of the phase fluctuations, but a side effect of this choice is that the implemented DRO has excess phase noise in the range 2-400 Hz compared to the H-maser. The error signal at the output of the mixer is low-pass filtered and forwarded to a PI servo-controller to generate the correction signal, which drives the PZT controlling the laser cavity length.

The CEO-beat is phase-stabilized to a 20-MHz external reference from the same H-maser, using commercial locking electronics (Menlosystems XPS800-E) that includes a digital phase detector with a large, linear detection range of $\pm 32 \cdot 2\pi$ phase difference and a PI servo-controller. Feedback is applied to the pump laser current. The gain of the PI servo is adjusted to minimize residual phase fluctuations of the CEO-beat and to maximize the feedback bandwidth while keeping the loop stable. The overall loop transfer function (amplitude and phase), obtained from the experimentally measured transfer functions for each loop component (phase detector, PI servo, and CEO-beat), is shown in Fig. 2. From this transfer function, one observes that the feedback bandwidth is only 5.5 kHz, mainly limited by the dynamics of the Er gain medium in the femtosecond laser [38]. At the 5.5-kHz unity gain, the phase margin is ≈15 deg.

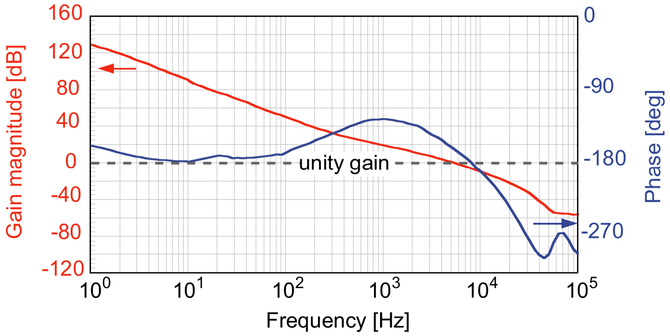

Fig. 2. Overall transfer function (gain on the left scale and phase on the right scale) of the CEO stabilization loop.

4. Stabilized comb properties

4.1 CEO noise and stability

Despite the limited bandwidth of the CEO stabilization loop (obtained without any differentiating component or other type of phase-lead filter that can be used to extend the bandwidth while keeping a stable loop), a tight phase lock of the CEO-beat can be achieved. This is made possible with the low-noise properties of the free-running CEO-beat. In complement to the previously reported CEO linewidth [31], which is a single parameter that gives only a partial picture of the CEO noise, we report here the frequency noise power spectral density (PSD) of the CEO-beat, measured using a home-made frequency discriminator [39]. At any Fourier frequency f, the CEO frequency noise PSD $S_{CEO}(f)$ only contributes to the CEO-beat linewidth if its value lies above the β-separation line [40], i.e. if $S_{CEO}(f) > (8\ln(2)/\pi^2)\cdot f$. From the measured spectrum shown in Fig. 3, this corresponds only to Fourier frequencies smaller than 3 kHz, which demonstrates that the CEO linewidth can be significantly narrowed using a feedback bandwidth of a few kilohertz only. Alternatively, one notices that the CEO linewidth calculated from the frequency noise spectrum [40] and shown on the right scale of Fig. 3 is in good agreement with the previously reported value extracted from the RF spectrum (e.g. a ≈5 kHz linewidth is calculated at 1 ms observation time).

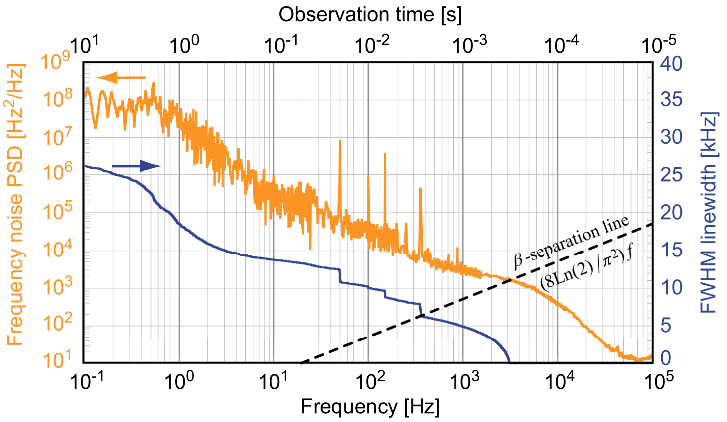

Fig. 3. ERGO comb frequency noise properties. Left scale: frequency noise power spectral density (PSD) of the free-running CEO-beat, measured using a frequency discriminator to demodulate the 20-MHz beat. The β-separation line which is relevant for the determination of the beat linewidth [40] is also shown. Right scale: linewidth (FWHM) of the free-running CEO calculated from the frequency noise spectrum [40] as a function of the observation time (upper axis, increasing to left).

The frequency noise spectrum of the phase-stabilized CEO-beat is measured from the in-loop error signal of the digital phase detector, taking into account the measured phase discrimination sensitivity [39]. The achieved frequency noise leads to a drastic reduction of the CEO linewidth and a tight phase-lock is thus realized, as proved by the coherent peak observed in the CEO spectrum with 30 dB signal-to-noise ratio (at 30 Hz resolution bandwidth) with respect to the servo bumps (inset of Fig. 4). In contrast to some former observations, e.g. in a Ti:sapphire laser [41], we did not observe any discernable increase of the intensity noise of our laser resulting from the stabilization of the CEO through the pump power, apart from a tiny rise at the servo bump. We believe that this results from the fact that the CEO frequency noise is essentially due to pump power fluctuations in the ERGO comb, as also previously shown in the case of Er-fiber lasers [16]. Therefore, feedback to the pump current must reduce pump power fluctuations to get a stable CEO phase-locked operation and the relative intensity noise of the femtosecond laser should be slightly reduced accordingly.

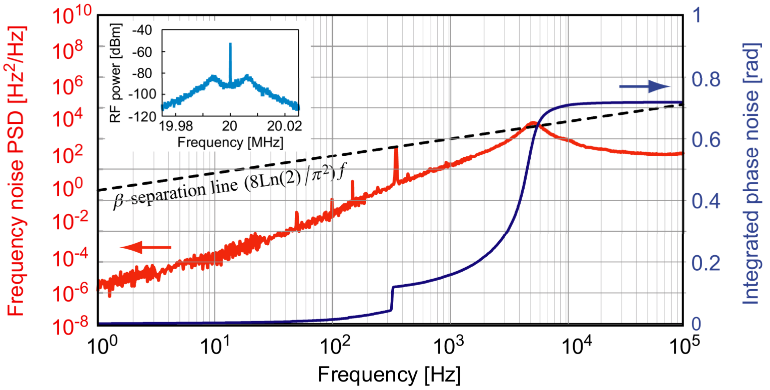

Fig. 4. ERGO comb frequency noise properties. Left scale: frequency noise PSD of the phase-locked CEO-beat, measured from the in-loop phase detector. Right scale: integrated phase noise (integration from 0.1 Hz up to the cut-off frequency). Inset: coherent peak with 30 dB signal-to-noise ratio (at 30 Hz resolution bandwidth) observed in the CEO-beat RF spectrum.

The residual noise in the pedestal underneath the coherent peak corresponds to an integrated phase noise $\Delta\phi_{rms} = \left[\int df\ S_{CEO}(f)/f^2\right]^{1/2}$ of 0.72 rad rms (integrated from 0.1 Hz to 100 kHz, but the phase noise at higher frequency has an insignificant contribution), which is the lowest CEO phase noise obtained to date for an optical frequency comb in the 1.5-µm range achieved with such a low feedback bandwidth of only ≈5.5 kHz.

In comparison with fiber lasers, the best reported values for the integrated phase noise in Er-fiber combs in the same spectral range are generally around 1 rad [15, 17], achieved with a much larger feedback bandwidth of hundred kilohertz. Improved performances have been demonstrated very recently for an Er-fiber comb developed at NIST, which achieved 0.8 rad integrated phase noise with ≈25 kHz feedback bandwidth [21], while Nakajima et al. showed a relative comb line stability of $3.7\cdot10^{-16}$ (at 1 s averaging time) in the comparison of two multi-branch Er-fiber combs stabilized to a common optical frequency standard [19]. But the best performance for an Er-fiber comb results from the figure-eight laser reported by Baumann et al. [20], where a CEO phase-lock bandwidth of 59 kHz combined with a stabilization of the comb to an optical reference (cavity-stabilized laser) with a large bandwidth of 1.6 MHz achieved with an intra-cavity EOM leads to an integrated in-loop phase noise of the heterodyne beat between the comb and the reference laser of 32 mrad from 1 Hz to 1 MHz, limited by the residual noise of the CEO.

In comparison with Ti:sapphire lasers, the best performances in terms of CEO phase noise have been achieved with Ti:sapphire combs at the <100 mrad level [42–44] which however comes at the expense of complexity and cost as discussed in section 1.

The major contribution to the integrated phase noise in the ERGO comb originates from the 5.5-kHz servo bump as shown in Fig. 4, but a small technical contribution of $\approx$10% results from a peak at 360 Hz which is also visible in the frequency noise spectrum. This noise peak is due to a mechanical resonance in a translational stage holding the pump laser focusing lens in the laser resonator, which is excited by ambient acoustic noise. The residual phase noise in the ERGO comb could certainly be further reduced by improving the mechanical stability of the resonator and by adding a proper phase lead filter in the feedback loop in order to extend the loop bandwidth to higher frequencies [18].

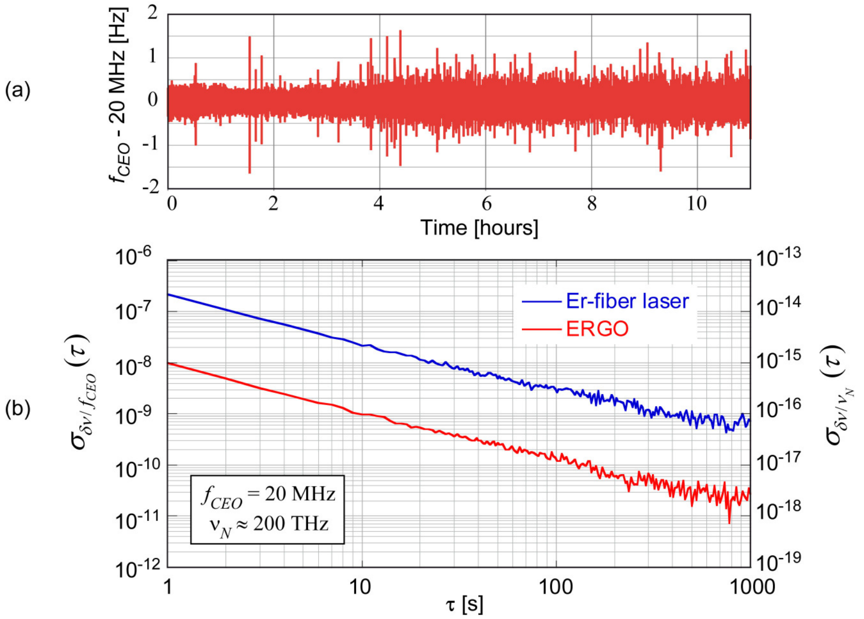

Fig. 5. (a) ERGO frequency comb: recorded time series of more than 10 hours of continuous stabilized operation of f_{CEO} acquired on a 1-s gate time counter. (b) Allan deviation of the CEO frequency in the ERGO comb and in a commercial self-referenced Er-fiber comb for comparison. The fractional stability is shown with respect to the CEO frequency f_{CEO} = 20 MHz on the left scale and with respect to the optical frequency ν_N = 200 THz on the right scale.

The CEO long-term stability was assessed by recording the stabilized CEO frequency with a 1-s gate time counter. Figure 5a shows a time series of more than 10 hours of continuous stable operation of the ERGO comb. The Allan deviation (Fig. 5b) shows a fractional frequency instability of $10^{-8}\cdot\tau^{-1}$ for the 20-MHz CEO frequency, which thus contributes only 10^{-15} to the optical carrier frequency instability ($\nu_N \approx$200 THz) at 1 s integration time. For comparison, Fig. 5b also displays the same measurement performed with a commercial self-referenced Er-fiber comb (FC1500-250 from Menlosystems, Germany, with 250 MHz repetition rate). The 20-fold improvement in the CEO fractional frequency stability observed in the ERGO comb compared to a standard Er-fiber comb demonstrates the excellent CEO noise properties of the solid-state frequency comb. This partially results from the three times higher repetition rate of the fiber comb [45], but more significantly from the larger *Q*-factor of the ERGO laser resonator. These noise properties are attractive for the future use of this comb as an optical-to-microwave frequency divider for all-optical ultra-low noise microwave generation [21,46–49], as a CEO contribution to the instability of the microwave at the 10^{-15} level can be considered without CEO subtraction as often required with Er-fiber combs [48].

4.2 Frequency noise and linewidth of an optical comb line

A first evaluation of the properties of an optical comb line was obtained with the ERGO comb stabilized to our RF reference. The characterization was performed by beating one line of the comb at 1.56 µm with a cavity-stabilized ultra-narrow linewidth laser [50]. The beat signal was measured with a fiber-coupled photodiode by combining ≈800 µW from the 1557.5-nm ultra-stable laser with ≈200 nW from the ERGO laser output beam, spectrally filtered to a 0.3-nm width using a diffraction grating. A beat note with a signal-to-noise ratio higher than 30 dB (at 100 kHz resolution bandwidth) was detected at ≈29 MHz. After filtering, amplification and frequency up-conversion, the beat signal was demodulated by our home-made frequency discriminator and measured on a FFT spectrum analyzer. The frequency noise PSD of the beat signal (Fig. 6) corresponds to the noise of the optical comb line $S_\nu(f)$ as the contribution of the ultra-stable laser is negligible. For comparison, the frequency noise of the repetition rate $S_{rep}(f)$, characterized using a phase noise measurement system (from SpectraDynamics Inc, USA) for the free-running and stabilized ERGO comb, is also shown in Fig. 6.

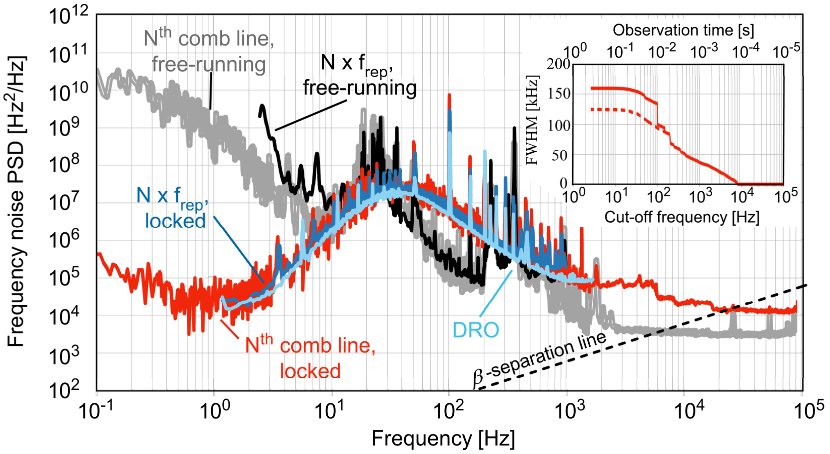

Fig. 6. Stability limitations of ERGO frequency comb locked to an RF reference: frequency noise PSD of a comb line at 1557.5 nm (N ≈2’570’000) obtained from the heterodyne beat with a cavity-stabilized laser, for the free-running and fully stabilized comb. The contribution of the repetition rate to the optical comb line ($N\cdot f_{rep}$) is also shown for comparison, obtained by scaling the repetition rate frequency noise PSD by N^2. The β-separation line that is relevant for the determination of the comb linewidth [39] is also displayed. Inset: linewidth (FWHM) of a comb optical line at 1558 nm calculated from the measured frequency noise spectrum [39] as a function of the cut-off frequency (inverse of the observation time). The straight line is obtained by considering the entire frequency noise spectrum, while the dashed line is obtained by removing the contribution of some parasitic noise peaks present in the frequency noise spectra of the reference (mainly 50 Hz and harmonics).

While the low-frequency noise is strongly reduced by the feedback loop, excess noise is observed for both the repetition rate and the comb line in the range 2-400 Hz compared to the H-maser. This technical noise originates from the reference DRO, as the noise spectrum of the stabilized repetition rate coincides precisely with the noise of the DRO, which was separately measured. This shows that the repetition rate stabilization loop works properly and that the noise properties of the RF reference are transferred to the repetition rate (within the loop bandwidth). Thus the stability of the comb line is currently limited by the RF reference and not by the laser or the phase lock loop. For the fully stabilized comb, a good overlap is also observed between $S_\nu(f)$ and $N^2\cdot S_{rep}(f)$, i.e. the contribution of the repetition rate noise $S_{rep}(f)$ scaled to the optical frequency by N^2 (with the comb mode number N ≈2’570’000 in the present case). This indicates that the noise of the optical comb lines is dominated by the noise of the repetition rate and the CEO contribution is negligible. This even holds for the kilohertz range where the CEO servo bump is not visible, which is generally the case in Er-fiber combs [21].

The linewidth of the optical comb line in the fully stabilized ERGO comb (comb locked to an RF reference) was calculated from the measured frequency noise spectrum [39] and is displayed in the inset of Fig. 6 as a function of the observation time. A linewidth of ≈160 kHz is obtained for observation times larger than 100 ms, but the excess noise of the 2.1-GHz DRO used for the stabilization of the comb repetition rate mainly contributes to this linewidth. A small contribution also results from parasitic 50 Hz and harmonics noise peaks (mainly at 100 Hz). The optical linewidth is slightly reduced to ≈130 kHz when these contributions are removed from the frequency noise spectrum. A narrower optical linewidth and a better fractional frequency stability of a comb line can be achieved using a lower noise frequency reference for the stabilization of the comb repetition rate.

5. Conclusion and outlook

We have demonstrated the first fully stabilized optical frequency comb from a DPSSL in the 1.5-µm spectral region, and we have carefully characterized its noise properties. The DPSSL is a SESAM-modelocked Er:Yb:glass laser oscillator, referred to as the ERGO laser [35]. The high *Q*-factor of the ERGO laser resonator results in a low-noise CEO-beat and leads to the narrowest free-running CEO linewidth observed in this spectral region, with less than 4 kHz FWHM. The excellent noise properties allow for a tight phase-lock of the CEO frequency to a 20-MHz external reference using pump-power control with a feedback bandwidth of less than 5.5 kHz. The CEO integrated phase noise of 0.72 rad rms is one of the smallest values obtained to date in the 1.5-µm region, especially for such a low servo-loop bandwidth. This result could be further improved with the use of a phase lead filter, in order to compensate for the slow dynamics of the ERGO laser and to consequently extend the feedback bandwidth while maintaining a stable loop operation. However, even with such an improvement, the ERGO comb will probably not compete with the record low CEO phase noise from Ti:sapphire laser combs (<100 mrad rms), which benefit from the very short upper state lifetime of the Ti:sapphire gain medium to achieve a high stabilization bandwidth. Novel ultrafast vertical emitting semiconductor lasers (such as VECSELs and MIXSELs) [33] may become very attractive from this point of view.

In terms of long-term fractional frequency stability, an Allan deviation of $10^{-8}\cdot\tau^{-1}$ has been achieved for the 20-MHz CEO-beat. This is 20-times better than what we measured in a commercial self-referenced Er-fiber comb for comparison. The CEO contribution to the fractional frequency stability of the optical carrier thus amounts to only 10^{-15} at 1 s averaging time, which is totally negligible in comparison to the contribution of the repetition rate. The low-noise and high-stability properties of the CEO-beat make the ERGO comb attractive for ultra-low noise microwave generation, despite its low repetition rate that decreases the available power at a given harmonic of the repetition rate and might thus reduce the noise performances of the generated microwave far from the carrier due to photodetection shot-noise [49]. The transfer of the relative frequency stability of a cavity-stabilized laser to the microwave domain using the ERGO comb can be envisaged using the simplest possible scheme, i.e. by simply phase-locking one line of the self-referenced comb to the laser, without the need for CEO subtraction [48] or to use the comb as a transfer oscillator [51], as the CEO is not expected to have an observable contribution to the phase noise and stability of the generated microwave.

The frequency noise of a comb line at 1558 nm, characterized from the heterodyne beat signal between the comb line and an ultra-narrow linewidth laser, showed to be limited by the DRO used as an RF reference in the stabilization of the comb repetition rate. Using feedback to the cavity length applied through a PZT, the frequency noise characteristics of the DRO are properly transferred to the comb line. A comb linewidth of ≈130 kHz is calculated from the frequency noise spectrum when the contribution of some spurious noise peaks is removed.

The frequency noise and linewidth of the ERGO comb could be slightly improved by the use of a better (lower noise) DRO for the stabilization of the repetition rate. However, much better results may be obtained by referencing the comb directly to an optical reference (ultra-stable laser), which we are going to implement in the near future. Based on this scheme, we will generate ultra-low noise microwave with the ERGO comb locked to our ultra-stable laser.

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