



# Reduced phase noise in an erbium frequency comb via intensity noise suppression

A. D. BRANDT,\* S. F. COOPER, Z. BURKLEY, AND D. C. YOST

Department of Physics, Colorado State University, 1875 Campus Delivery, Fort Collins CO 80523, USA

\*Adam.Brandt@colostate.edu

**Abstract:** We present a coherent erbium fiber frequency comb that achieves low phase noise operation through the active suppression of amplitude fluctuations within the laser oscillator. The amplitude noise servo has a bandwidth of 550 kHz and is achieved by current actuation of the laser pump diode. This servo reduces the integrated phase noise of the carrier envelope offset frequency of the comb,  $f_{ceo}$ , due to the strong coupling of amplitude and phase noise in the laser oscillator. Additionally, we use a composite error signal that utilizes information from both the amplitude noise and the  $f_{ceo}$  error signal to actuate the pump diode current, which further increases the coherence of the comb. With this locking scheme, the integrated phase noise on  $f_{ceo}$  is measured to be 270 mrad from 10 Hz to 1.5 MHz, indicating 93% of the optical carrier power is in the coherent signal. A simultaneous phase lock to a narrow-linewidth continuous-wave laser is achieved by actuating on the cavity length, and shows an integrated phase noise of 44 mrad.

© 2017 Optical Society of America

**OCIS codes:** (140.3500) Lasers, erbium; (140.4050) Mode-locked lasers; (190.4370) Nonlinear optics, fibers; (140.3425) Laser stabilization.

## References and links

1. T. Udem, R. Holzwarth, and T. W. Hänsch, "Optical Frequency Metrology," *Nature* **416**(6877), 233–237 (2002).
2. 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).
3. S. T. Cundiff and J. Ye, "Colloquium: Femtosecond optical frequency combs," *Rev. Mod. Phys.* **75**(1), 325–342 (2003).
4. N. R. Newbury, "Searching for applications with a fine-tooth comb," *Nat. Photonics* **5**(4), 186–188 (2011).
5. F. Krausz and M. Ivanov, "Attosecond physics," *Rev. Mod. Phys.* **81**(1), 163–234 (2009).
6. P. Gill, "Optical Frequency Standards," *Metrologia* **42**(3), S125–S137 (2005).
7. L. Hollberg, C. W. Oates, G. Wilpers, C. W. Hoyt, Z. W. Barber, S. A. Diddams, W. H. Oskay, and J. C. Bergquist, "Optical frequency/wavelength references," *J. Phys. At. Mol. Opt. Phys.* **38**(9), S469–S495 (2005).
8. S. A. Diddams, "The evolving optical frequency comb," *J. Opt. Soc. Am. B* **27**(11), B51–B62 (2010).
9. 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, "Ultralow noise microwave generation with fiber-based optical frequency comb and application to atomic fountain clock," *Appl. Phys. Lett.* **94**(14), 141105 (2009).
10. D. Fehrenbacher, P. Sulzer, A. Liehl, T. Kälberer, C. Riek, D. V. Seletskiy, and A. Leitenstorfer, "Free-running performance and full control of a passively phase-stable Er: fiber frequency comb," *Optica* **2**(10), 917–923 (2015).
11. L. E. Nelson, D. J. Jones, K. Tamura, H. A. Haus, and E. P. Ippen, "Ultrashort-pulse fiber ring lasers," *Appl. Phys. B* **65**(2), 277–294 (1997).
12. 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).
13. S. Koke, C. Grebing, H. Frei, A. Anderson, A. Assion, and G. Steinmeyer, "Direct frequency comb synthesis with arbitrary offset and shot-noise-limited phase noise," *Nat. Photonics* **4**(7), 462–465 (2010).
14. S. Kundermann, E. Portuondo-Campa, and S. Lecomte, "Ultra-low-noise 1  $\mu$ m optical frequency comb," *Electron. Lett.* **50**(17), 1231–1232 (2014).
15. T. R. Schibli, I. Hartl, D. C. Yost, M. J. Martin, A. Marcinkiewicz, M. E. Fermann, and J. Ye, "Optical frequency comb with submillihertz linewidth and more than 10 W average power," *Nat. Photonics* **2**(6), 355–359 (2008).
16. T.-H. Wu, K. Kieu, N. Peyghambarian, and R. J. Jones, "Low noise erbium fiber fs frequency comb based on a tapered-fiber carbon nanotube design," *Opt. Express* **19**(6), 5313–5318 (2011).

17. K. Iwakuni, H. Inaba, Y. Nakajima, T. Kobayashi, K. Hosaka, A. Onae, and F.-L. Hong, "Narrow linewidth comb realized with a mode-locked fiber laser using an intra-cavity waveguide electro-optic modulator for high-speed control," *Opt. Express* **20**(13), 13769–13776 (2012).
18. C.-C. Lee, C. Mohr, J. Bethge, S. Suzuki, M. E. Fermann, I. Hartl, and T. R. Schibli, "Frequency comb stabilization with bandwidth beyond the limit of gain lifetime by an intracavity graphene electro-optic modulator," *Opt. Lett.* **37**(15), 3084–3086 (2012).
19. N. Kuse, C.-C. Lee, J. Jiang, C. Mohr, T. R. Schibli, and M. E. Fermann, "Ultra-low noise all polarization-maintaining Er fiber-based optical frequency combs facilitated with a graphene modulator," *Opt. Express* **23**(19), 24342–24350 (2015).
20. N. Kuse, J. Jiang, C.-C. Lee, T. R. Schibli, and M. E. Fermann, "All polarization-maintaining Er fiber-based optical frequency combs with nonlinear amplifying loop mirror," *Opt. Express* **24**(3), 3095–3102 (2016).
21. W. Hänsel, H. Hoogland, M. Giunta, S. Schmid, T. Steinmetz, R. Doubek, P. Mayer, S. Dobner, C. Cleff, M. Fischer, and R. Holzwarth, "All polarization-maintaining fiber laser architecture for robust femtosecond pulse generation," *Appl. Phys. B* **123**(1), 41–47 (2016).
22. 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).
23. 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).
24. N. R. Newbury and W. C. Swann, "Low-noise fiber-laser frequency combs (Invited)," *J. Opt. Soc. Am. B* **24**(8), 1756–1770 (2007).
25. A. Cingöz, D. C. Yost, T. K. Allison, A. Ruehl, M. E. Fermann, I. Hartl, and J. Ye, "Broadband phase noise suppression in a Yb-fiber frequency comb," *Opt. Lett.* **36**(5), 743–745 (2011).
26. C. Benko, A. Ruehl, M. J. Martin, K. S. E. Eikema, M. E. Fermann, I. Hartl, and J. Ye, "Full phase stabilization of a Yb:fiber femtosecond frequency comb via high-bandwidth transducers," *Opt. Lett.* **37**(12), 2196–2198 (2012).
27. R. Paschotta, "Timing jitter and phase noise of mode-locked fiber lasers," *Opt. Express* **18**(5), 5041–5054 (2010).
28. C. C. Harb, T. C. Ralph, E. H. Huntington, D. E. McClelland, H.-A. Bachor, and I. Freitag, "Intensity-noise dependence of Nd:YAG lasers on their diode-laser pump source," *J. Opt. Soc. Am. B* **14**(11), 2936–2945 (1997).
29. F. X. Kartner, I. D. Jung, and U. Keller, "Soliton mode-locking with saturable absorbers," *IEEE J. Sel. Top. Quantum Electron.* **2**(3), 540–556 (1996).
30. L. C. Sinclair, I. Coddington, W. C. Swann, G. B. Rieker, A. Hati, K. Iwakuni, and N. R. Newbury, "Operation of an optically coherent frequency comb outside the metrology lab," *Opt. Express* **22**(6), 6996–7006 (2014).
31. S. Namiki and H. A. Haus, "Noise of the stretched pulse fiber laser: part I—theory," *IEEE J. Quantum Electron.* **33**(5), 649–659 (1997).
32. R. Paschotta, "Noise of mode-locked lasers (Part II): timing jitter and other fluctuations," *Appl. Phys. B* **79**(2), 163–173 (2004).
33. R. Paschotta and U. Keller, "Passive mode locking with slow saturable absorbers," *Appl. Phys. B* **73**(7), 653–662 (2001).

## 1. Introduction

Optical frequency combs have become indispensable tools for precision frequency metrology [1–4]. Additionally, frequency combs have been applied to a number of other disciplines, such as attosecond physics, optical atomic clocks, and high fidelity microwave generation [4–10]. While frequency combs were initially developed using solid-state, mode-locked lasers, fiber-based frequency combs quickly became an attractive alternative due to their low cost, alignment free operation, and insensitivity to environmental perturbations [8,11]. Unfortunately, fiber-based frequency combs have historically suffered from worse phase noise performance as compared to their solid-state counterparts (see for example [12–14]). While sophisticated laser designs and electronic feedback systems have now greatly increased the achievable coherence of fiber-based frequency combs [15–21], a continued decrease in phase noise is beneficial for many applications. As an example, we require a frequency comb for coherence transfer and as an optical frequency reference for high precision studies of atomic hydrogen – applications that will benefit tremendously from increased coherence and stability.

A common way to improve the coherence of frequency combs is through increasingly fast frequency feedback loops [17–21]. However, many available frequency actuators often operate on a linear combination of the two degrees of freedom of the frequency comb –  $f_{ceo}$  and  $f_{rep}$  [22]. As a result, a fast  $f_{ceo}$  feedback loop can interfere with the  $f_{rep}$  loop, or vice-versa. Therefore, it is also attractive to investigate the origin of the noise and to suppress it at its source. It has been shown for erbium fiber frequency combs, the pump diode's relative

intensity noise (RIN) can be a major contributor to the laser's phase noise, and reducing the pump diode RIN may result in improved phase noise performance [23,24]. Later, it was shown in two Ytterbium-based fiber frequency combs that there are other significant contributions to amplitude noise [25,26], which in turn couple to phase and frequency fluctuations [27]. Some of these other contributions include amplified spontaneous emission (ASE), fluctuations in cavity loss, vacuum field fluctuations entering through the output coupler, and gain medium dipole fluctuations [28]. For these Yb-systems, suppression of the comb RIN was shown to directly reduce the phase noise of an individual comb tooth [25] and of the  $f_{ceo}$  frequency itself [26]. Since the quantum noise sources in these systems were non-negligible, it was more effective to suppress on the amplitude noise of the frequency comb itself as, even in the limit of a perfectly quiet pump laser, the quantum noise sources would remain.

In this work, we apply an amplitude noise servo to a mode-locked, erbium-fiber frequency comb. Erbium-based frequency combs are of particular interest due to the wide availability and low cost of the telecom components necessary for their construction. While it may be expected that the long upper state lifetime of erbium, as compared to ytterbium, would greatly limit the bandwidth of the RIN servo, we demonstrate a 550 kHz bandwidth with a carefully designed feedback loop. Additionally, our results indicate that quantum noise sources contribute significantly to the amplitude noise of the comb. Due to the strong correlation of amplitude and phase noise in our frequency comb, we find that reducing the amplitude noise of the frequency comb simultaneously reduces the residual phase noise on the  $f_{ceo}$  frequency lock and a comb tooth near the center frequency of 1555 nm. These results show that a simple frequency comb design, with an amplitude noise (RIN) servo, can achieve near state-of-the-art phase noise performance for an erbium fiber frequency comb.

In contrast to previous applications of RIN servos for Yb: fiber frequency combs [23,24], the  $f_{ceo}$  phase lock and the RIN servo both actuate on the pump current simultaneously using a simple summation circuit. Our analysis of this composite lock shows that this scheme is advantageous as it effectively stabilizes the  $f_{ceo}$  lock and enables an increase in the feedback gain. This can be understood because, while RIN and the  $f_{ceo}$  are highly correlated, the RIN can generally be detected with much smaller line delays as compared with  $f_{ceo}$  since the latter usually requires amplification, spectral broadening, and extra signal conditioning. Therefore, by utilizing the RIN information for the highest feedback frequencies, the locking bandwidth can be extended. Employing this composite feedback technique results in 270 mrad and 44 mrad integrated phase noise on  $f_{ceo}$  and  $f_{beat}$  respectively. This result is competitive with other state of the art erbium fiber frequency combs. For example, the frequency comb in [20], which is based on a nonlinear amplifying loop mirror, has demonstrated integrated phase noise of 160 mrad and 130 mrad on  $f_{ceo}$  and  $f_{beat}$  respectively. Additionally, we believe this composite feedback technique could be used in conjunction with fast frequency actuators, such the loss modulation in [19,20], for even greater feedback gain and bandwidths than shown here. Therefore, we believe this demonstrates a generally useful strategy for improving  $f_{ceo}$  lock performance in fiber frequency combs.

## 2. Laser configuration

Our frequency comb begins with a mode-locked, erbium fiber laser in a linear cavity arrangement, as shown in Fig. 1. Mode-locked operation is achieved via a commercial 2 ps lifetime, semiconductor saturable absorber (SA). The SA has a 15% modulation depth and 10% non-saturable loss. All optical fiber in the oscillator is anomalously dispersive with a round trip dispersion of  $\sim 7000$  fs<sup>2</sup>, which promotes stable soliton mode-locking [29]. The oscillator is pumped with a 976 nm laser diode through an optically coated FC/PC connector coupled to an uncoated FC/PC connector. The coated connector has a reflectivity of 80% at 1550 nm but has high transmission at 976 nm. This cavity design was implemented for its

simplicity. Such designs are compatible with all polarization maintaining fiber, and have demonstrated robust performance outside the laboratory [30].

Since the noise performance of mode-locked lasers is also correlated with the pulse duration [31,32], the cavity design favors broader spectral operation [33]. The fiber section of the cavity is 31 cm to minimize dispersion and reduce nonlinear phase shifts to prevent destabilization. The rest of the oscillator is free space to ensure appropriate SA saturation, resulting in a repetition rate of  $\approx 115$  MHz. The output of the laser is 10 mW with a spectral bandwidth of  $\approx 16$  nm, indicating a bandwidth-limited pulse duration of  $\sim 170$  fs for a  $\text{sech}^2$  distribution. We believe that the spectral output of this laser is currently limited by the lifetime of the SA [33].

The output of the oscillator is sent to an amplification stage for  $f_{ceo}$  detection. The amplifier is composed of erbium-doped fiber, which is pumped by a pair of 700 mW, 976 nm diodes in the forward and backward directions. After amplification, the average power is  $\approx 270$  mW, and the spectrum is broadened to 60 nm of bandwidth. The pulse train then enters a length of SMF-28 to recompress the pulse before 22 cm of highly nonlinear fiber (HNLf). An octave of bandwidth is achieved after the HNLf, spanning 960–2100 nm. The light is then guided to an  $f$ -to- $2f$  interferometer, as shown in Fig. 1, for  $f_{ceo}$  detection. For  $f_{ceo}$  stabilization, the pump current is actuated.

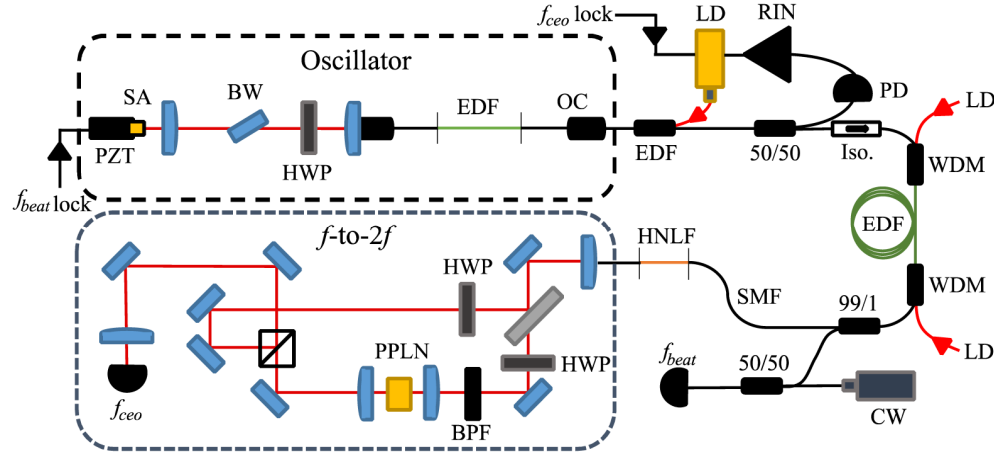


Fig. 1. Schematic layout of laser system. SA, Semiconductor saturable absorber mirror; PZT, piezoelectric transducer; BW, Brewster Window; HWP, half wave plate; EDF, erbium doped fiber; OC, output coupler; WDM, wavelength division multiplexer; LD, 976 nm laser diode; PD, photodiode; RIN, relative intensity noise servo; Iso, optical isolator; HNLf, highly nonlinear fiber; CW, continuous wave, single mode laser; BPF, optical bandpass filter; PPLN, periodically-poled lithium niobate.

### 3. RIN servo

In order to effectively suppress the comb's relative intensity noise,  $RIN_{comb}$ , it is critical to first determine its origin. If  $RIN_{comb}$  is found to originate exclusively from pump diode intensity noise,  $RIN_{pump}$ , then reducing the pump noise would clearly be the most effective strategy. However, if other noise sources, such as ASE, also contribute significantly, then direct detection and suppression  $RIN_{comb}$  is more effective.

To determine the contribution of  $RIN_{pump}$  to  $RIN_{comb}$ , we first measured the amplitude response of the comb to pump diode fluctuations,  $H(\omega)$ . The comb's amplitude noise which is due to the pump diode fluctuations only,  $RIN'$ , can then be determined through.

$$RIN'(\omega) = H(\omega) RIN_{pump}(\omega) \quad (1)$$

For frequencies where  $RIN_{comb}(\omega) = RIN'(\omega)$ , the amplitude noise on the comb is determined exclusively by the pump diode. For frequencies where  $RIN_{comb}(\omega) > RIN'(\omega)$ , noise sources other than the pump diode limit the amplitude noise performance of the oscillator.

While determining the amplitude noise of the pump diode, it was found that our particular pump diode operates in two distinct noise regimes, one much noisier than the other. We attribute the regime shift to the laser diode switching between multiple and single longitudinal mode operation. The regime shifts appears to occur randomly, and the pump diode is generally in the noisy regime. While the pump diode is only infrequently in the quiet regime, it is useful for determining what level the amplitude noise of the comb is due to quantum noise sources, as the pump diode noise contribution is less prominent. In the noisy regime,  $RIN_{pump}$  determines the noise up to  $\approx 200$  kHz, and in the quiet regime,  $\approx 80$  kHz. This performance is shown in Fig. 2(a) and Fig. 2(b).

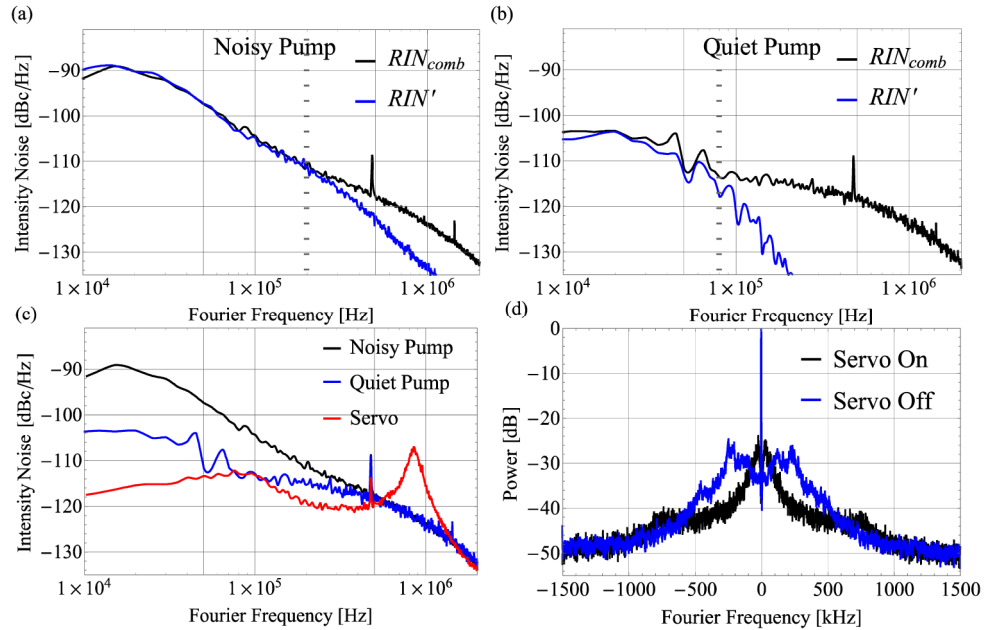


Fig. 2. (a)  $RIN_{comb}$  vs  $RIN'$ , noisy regime. The dotted line (200 kHz) indicates end of pump limited intensity noise. (b)  $RIN_{comb}$  vs  $RIN'$ , quiet regime. The dotted line (80 kHz) indicates end of pump limited intensity noise. (c) Measured intensity noise for both quiet and noisy regimes, as well as with the RIN servo active. (d)  $f_{ceo}$  with the RIN servo on and off (421 and 811 mrad r.m.s. phase noise respectively).

Since our results show that noise sources other than  $RIN_{pump}$  also significantly contribute to  $RIN_{comb}$ , our servo detects and reduces  $RIN_{comb}$  directly. As shown in Fig. 2(c), the servo actively suppresses the noise beyond the limit set by  $RIN_{pump}$  alone. The effect of the amplitude noise servo on  $f_{ceo}$  is shown in Fig. 2(d). Integrating from 10 Hz to 1.5 MHz, we measure 811 mrad integrated phase noise with the RIN servo off, and only 421 mrad with the servo active. This is an improvement of 51% to 84% power in the coherent spike in the  $f_{ceo}$  lock, indicating that amplitude noise and phase noise are highly correlated within the oscillator.

#### 4. Composite error signal phase locking

The results shown in Fig. 2(d) were obtained by optimizing the  $f_{ceo}$  frequency lock, and then engaging the RIN servo. As shown in the figure, the RIN servo clearly increases the coherence of the  $f_{ceo}$  lock. However, at Fourier frequencies between 10 kHz and 100 kHz,



there is an increase of noise with the RIN servo engaged. This is an artifact of the feedback scheme since the RIN servo and the frequency lock both modulate the same degree of freedom (the pump current). Therefore, the two may interfere when the gain of both feedback loops are comparable. This suggests that improved performance can be obtained by adjusting the gain and corners of these two loops in concert.

To optimize the performance, we consider the RIN servo and the  $f_{ceo}$  frequency lock together as a single composite feedback loop. This feedback loop has an error signal in which both the detected RIN and the  $f_{ceo}$  error contribute. We analyze a simple model of this composite lock, pictorially depicted in Fig. 3(a). The detected RIN is conditioned with an ideal proportional amplifier and the frequency error is conditioned by a proportional-integral amplifier. Then, the signals are summed, and fed to the pump diode. The laser oscillator responds as a low pass filter, so an additional low pass term is applied to both the RIN servo and frequency lock. In Fig. 3(b) and Fig. 3(c), the gain and phase response of the modeled feedback loops are plotted, including the composite transfer function. The total transfer function is dominated by the RIN signal at frequencies above 40 kHz, so the phase margin at unity gain is determined entirely by the RIN information. This is advantageous due to the smaller phase delays of the RIN servo. Therefore, when compared with a feedback loop based only on the  $f_{ceo}$  signal, the gain of the composite loop can be increased. Optimizing the composite lock as shown in Fig. 3 results in the stabilized  $f_{ceo}$  as shown in Fig. 4(a).

Integrating from 10 Hz to 1.5 MHz, the total integrated phase noise is 270 mrad with 93% of the power in the coherent peak, which is a significant improvement over the performance shown in Fig. 2(d).

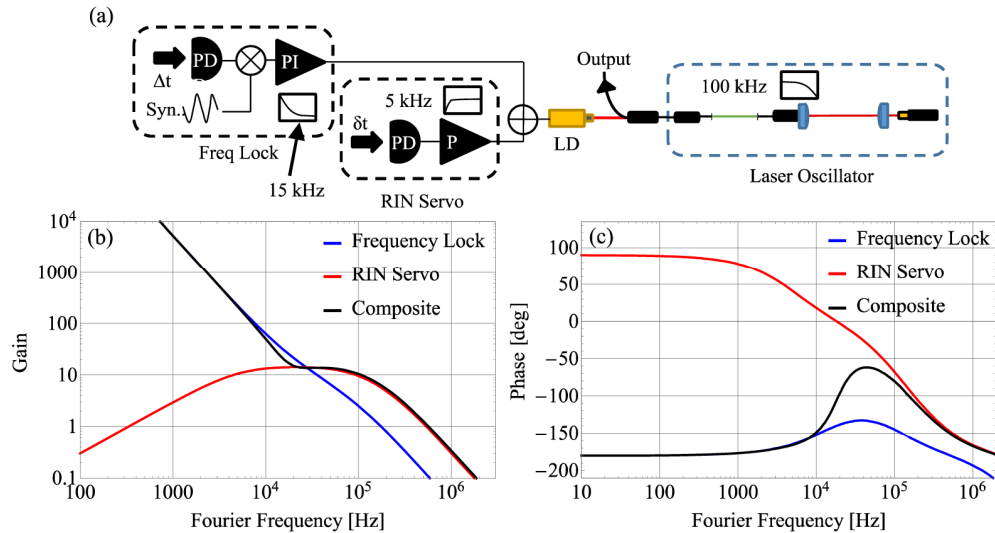


Fig. 3. (a) Schematic of RIN servo and  $f_{ceo}$  Frequency lock model.  $\Delta t$ , 50 ns line delay; PD, Photodetector; Syn., digital frequency synthesizer; PI, Proportional-Integral Amplifier;  $\delta t$ , 10 ns line delay; P, Proportional amplifier; LD, pump laser diode; Oscillator, laser oscillator. Dashed lines delineate subsystems of the system (feedback loops and the laser oscillator). (b) Model amplitude response of the frequency lock, RIN servo, and composite signal (c) Model phase response of the frequency lock, RIN servo, and composite signal showing the increased phase margin obtained by utilizing the RIN information.

While utilization of this composite locking technique ultimately produces a more robust  $f_{ceo}$  frequency lock, it should not be forgotten that it also has the net effect of reducing  $RIN_{comb}$ , which is anticipated to also reduce the phase noise across the comb structure. We tested this by simultaneously phase locking a single comb mode to a homebuilt, cw-laser at 1550 nm. The homebuilt cw-laser is estimated to have a linewidth less than 20 kHz, and has a

power output of 2 mW. The phase lock is achieved via actuation of two intracavity PZT's; one for fast feedback with a smaller modulation depth, and another with a large modulation depth for slow drifts. The effect of the composite lock on the beat frequency,  $f_{beat}$ , between the single comb mode and the cw laser is shown in Fig. 4(b). The integrated phase noise on  $f_{beat}$  drops from 166 mrad to 44 mrad by activating the composite lock. Since the phase noise of both the degrees of freedom of the comb,  $f_{ceo}$  and  $f_{beat}$ , are reduced, this result indicates that the coherence of the entire comb structure is increased by utilizing the composite feedback loop.

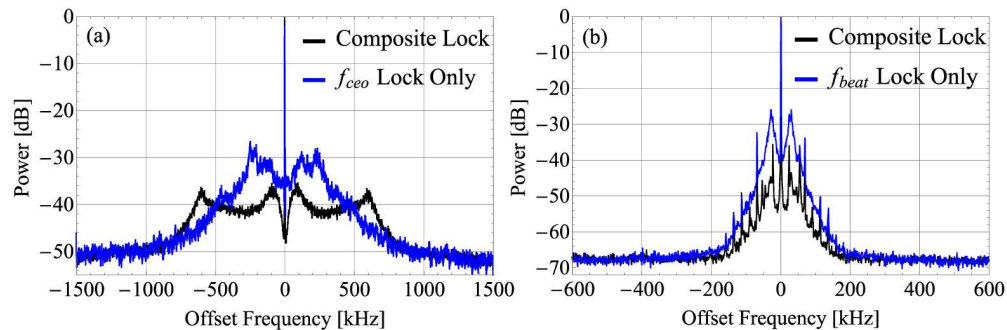


Fig. 4. (a) Final measured in-loop RF spectrum of  $f_{ceo}$  (1 kHz RBW) (b) Measured Inloop RF spectra of  $f_{beat}$  with composite lock on and off (1 kHz RBW).

## 5. Conclusion

To summarize, we have achieved highly coherent phase locks on both of the frequency comb's degrees of freedom. Amplitude noise suppression in the comb results in substantially improved coherence of the comb, indicating that there is a strong correlation between amplitude and phase fluctuations. Also, we have shown that reduction of pump diode fluctuations alone is ultimately less effective than directly suppressing the comb RIN. Because phase noise and amplitude noise are highly correlated, a composite feedback scheme allows for a large locking bandwidth of 550 kHz on  $f_{ceo}$  without fast frequency actuators, leveraging the minimal line delay in RIN detection. This simple feedback scheme should be compatible with other mode-locking mechanisms, e.g. non-linear polarization rotation or Sagnac loop initiated mode-locking [17,18], indicating that this technique could further improve the coherence of many other optical frequency combs.

## Funding

The NSF CAREER Development award (Award # 1654425); NIST Precision Measurement Grant (Award # 60NANB16D270).

## Acknowledgments

We would like to thank Jacob Roberts, Wei-Ting Chen and Stefan Droste for helpful discussions.