Research Article | Vol. 30, No. 21 / 10 Oct 2022 / Optics Express 38684

Optics EXPRESS



# Collinear opto-optical loss modulation for carrier-envelope offset stabilization of a fiber frequency comb

DANIEL I. HERMAN,[1,2,*] JEAN-DANIEL DESCHÊNES,[2] HENRY TIMMERS,[3,4,5] IAN CODDINGTON,[1] AND NATHAN R. NEWBURY[1]

[1] NIST, Spectrum Technology and Research Division, Boulder, CO 80305, USA
[2] Octosig Consulting, Québec City, Québec G2K 1X6, Canada
[3] University of Colorado, Boulder, Department of Physics, Boulder, CO 80309, USA
[4] Currently with Vescent Photonics LLC, Golden, CO 80401, USA
[5] NIST, Time and Frequency Division, Boulder, CO 80305, USA
[*] daniel.isaac.herman@gmail.com

**Abstract:** Opto-optical loss modulation (OOM) for stabilization of the carrier-envelope offset (CEO) frequency of a femtosecond all-fiber laser is performed using a collinear geometry. Amplitude-modulated 1064 nm light is fiber coupled into an end-pumped semiconductor saturable absorber mirror (SESAM)-mode-locked all-polarization-maintaining erbium fiber femtosecond laser, where it optically modulates the loss of the SESAM resulting in modulation of the CEO frequency. A noise rejection bandwidth of 150 kHz is achieved when OOM and optical gain modulation are combined in a hybrid analog/digital loop. Collinear OOM provides a simple, all-fiber, high-bandwidth method for improving the CEO frequency stability of SESAM mode-locked fiber lasers.



## 1. Introduction

Optical frequency comb technology continues to enable fundamental and applied studies where frequency stability is required across wide bandwidths. The development of robust, low-cost, high-bandwidth comb stabilization techniques remains an important research area as combs become widely used for an array of applications. Specifically, recent research has made many advances in carrier-envelope offset (CEO) phase control of mode-locked fiber lasers. Traditionally, pump power feedback has been used to cancel CEO noise [1,2], but such techniques can have limited bandwidth in rare-earth doped fiber lasers which are commonly used for comb applications (*e.g.* optical timing and spectroscopy) [3,4]. Alternative techniques for fiber comb CEO stabilization include electro-optical intra-cavity loss modulation [5,6], opto-optical loss modulation [7], cross-gain modulation [8,9] and group velocity control using an integer-lambda interferometer [10]. Ideally, one or more of these techniques could be used to reduce the CEO frequency ($f_{\text{ceo}}$) noise of a semiconductor saturable absorber mirror SESAM-mode-locked erbium fiber laser, an attractive laser design for fieldable frequency combs [11], without significantly increasing the complexity and cost of this relatively simple frequency comb design. As we will show in this work, opto-optical loss modulation (OOM) has the potential for both high performance and simplicity.

In 2013, Hoffmann *et al*. [7], showed that OOM could be used for stabilization of the offset frequency of a SESAM mode-locked diode-pumped solid-state femtosecond laser. OOM works by modulating the number of available absorbers in the multiple quantum well (MQW) structure within the SESAM. Thus, a change to OOM light power incident on the SESAM modulates the nonlinear reflectivity of the SESAM and the round-trip cavity loss. As seen with other cavity loss modulation schemes [5], OOM can achieve CEO feedback bandwidths beyond the gain lifetime

#471877 https://doi.org/10.1364/OE.471877
Journal © 2022 Received 2 Aug 2022; revised 15 Sep 2022; accepted 15 Sep 2022; published 4 Oct 2022

Optics EXPRESS

limit [12]. OOM has also been used to stabilize other femtosecond lasers including a nonlinear polarization rotation (NPR) mode-locked Yb:fiber laser [12]. To date, all demonstrations of OOM have utilized a free space section to overlap the intra-cavity comb light and the OOM light on the SESAM used for loss modulation, adding complexity and possible sources of instability to the cavity designs.

In this work, we investigate a simple method for applying OOM to an all-polarization maintaining (PM) erbium fiber linear oscillator design using a new collinear pumping technique. For the first time, we achieve mode-locking and optical loss modulation using one monolithic device in a collinear geometry. The oscillator under study is mode-locked in the soliton regime using a SESAM. Our improved OOM technique requires only the addition of fiber components external to the laser cavity, utilizes the fiber laser cavity to ensure overlap of the comb light and OOM light on the SESAM and has no discernible effect on the stability of the cavity mode-locking. This geometry greatly simplifies the OOM technique, enabling the use of lower power OOM light sources and making it extremely insensitive to cavity perturbations.

Although SESAM mode-locked lasers operating in the soliton regime are noisier than other types of femtosecond lasers such as stretched pulse and NALM lasers [13], their mode-locking properties are very repeatable and robust to environmental perturbations, making them well suited for field applications [14,15]. The exact laser oscillator studied in this work was previously used to demonstrate frequency comb locking in a moving van [16] and similar lasers have enabled a variety of field applications including optical time and frequency transfer [17,18] and open-path dual frequency comb spectroscopy [14,15,19,20]. The highest servo bandwidth for $f_{\text{ceo}}$ control using traditional gain modulation reported in erbium femtosecond lasers was ~900 kHz where NPR was the mode-locking mechanism [21]. However, for SESAM mode-locked all-PM erbium fiber lasers, the highest reported gain modulation CEO servo bandwidths are between 100 kHz to 260 kHz [6,11,16,22]. The current record for CEO servo bandwidth of a SESAM mode-locked all-PM erbium fiber laser is ~1.4 MHz, achieved using intra-cavity loss modulation of a graphene modulator [6]. We note that the bandwidths quoted in these papers refer to servo bump location not the noise rejection bandwidth, which is generally much lower [23].

Our novel collinear OOM technique allows us to increase the servo bandwidth for $f_{\text{ceo}}$ control (as inferred from servo bump location) of a simple SESAM mode-locked erbium fiber laser from 150 kHz to 1.15 MHz. This corresponds to a 3 dB noise rejection bandwidth increasing from 70 kHz to 150 kHz. The integrated CEO phase noise of the soliton laser is decreased by 66% from 2.75 radians to 0.92 radians (in-loop values integrated from 3 Hz to 5 MHz; fluctuations on these values are ~20 milliradians). At this sub-radian integrated phase noise, the radio frequency (RF) spectrum of the $f_{\text{ceo}}$ signal shows the expected coherent carrier. Compared to previous designs, the collinear fiber geometry reduces the continuous-wave (CW) laser power requirements for opto-optical modulation locking and increases the sensitivity of the CEO beat to power modulation. Implementation of this technique requires no redesign of the laser cavity, merely the addition of extra-cavity components. We also demonstrate that the OOM does not degrade the ability to lock the comb to a narrow linewidth CW laser which could occur if there existed undesired crosstalk between the locks [22]. This work represents a proof-of-principle in that neither the laser cavity nor the SESAM used for this experiment were optimized for opto-optical loss modulation. In the future, the application of collinear OOM techniques to SESAM mode-locked erbium laser cavities with optimized free-running noise properties will enable ultra-low noise fieldable comb metrology in an extremely simple package.

## 2. Experimental design

### 2.1. Optical design

The laser oscillator is described in detail in Ref. [16], so we provide only a brief review here. The femtosecond laser oscillator design, shown in Fig. 1, utilizes an end-pumped, PM fiber, linear

Optics EXPRESS

geometry, based around a SESAM micro-optic package with integrated fast-axis blocking and a spot size on the SESAM of ~20 µm. The SESAM itself is 91% reflective at low powers with a modulation depth of 3% and a non-saturable loss of 6%. The cavity has a longitudinal mode spacing of ~213 MHz and supports soliton mode-locking with a round-trip cavity dispersion of approximately -0.02 $ps^2$. The other cavity end is bounded by a dielectric output coupler with a reflectivity at 1560 nm of approximately 90%. Using the standard gain modulation approach for CEO stabilization, the integrated CEO phase noise (1 Hz to 5 MHz) is ~2.9 radians with a servo bump appearing near 150 kHz [16]. Here, we seek to improve these values through the collinear addition of OOM.

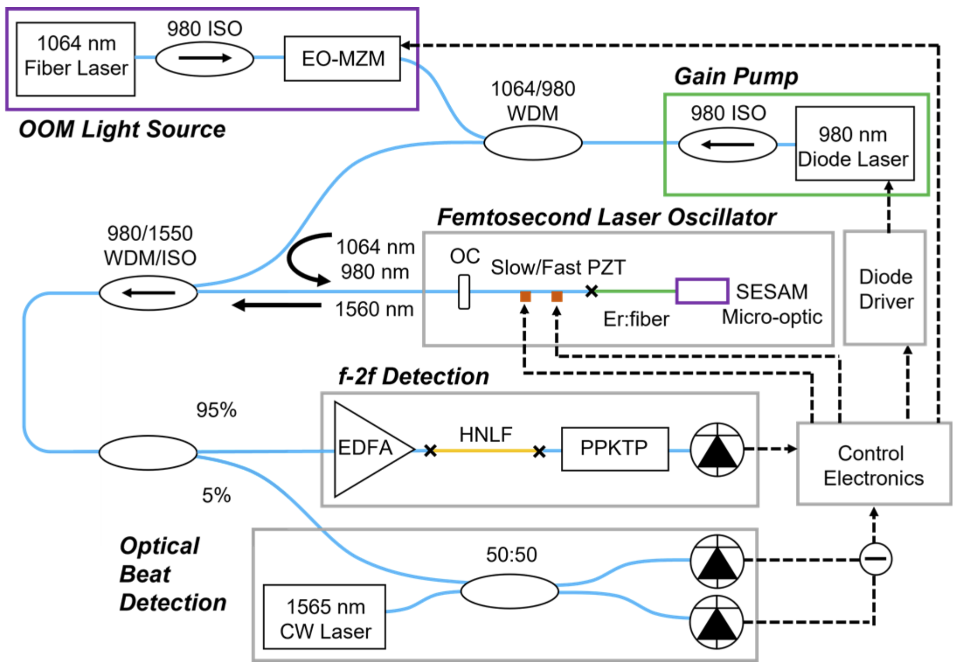


**Fig. 1.** Experimental design for the collinear opto-optical modulation experiment. Note all fiber sections (blue lines) are either PM 1550 or PM 980 except for a small section of SMF-28 near the electro-optical Mach-Zehnder modulator (EO-MZM). Black dotted lines are electrical connections. OC: dielectric-coated output coupler; Er:fiber (green line in oscillator box): anomalous group velocity dispersion erbium doped PM fiber; HNLF (yellow): highly nonlinear fiber; WDM: wavelength division multiplexer; ISO: isolator; EDFA: erbium doped fiber amplifier. Note: output of PPKTP is filtered at 980 nm before CEO beat detection; 5% oscillator tap is filtered at 1565 nm using a DWDM device before combining with the CW reference laser.

We must consider several factors in order to choose a suitable wavelength for our collinear OOM light source. Firstly, the InGaAs MQW structure inside of the SESAM must absorb the OOM light and the erbium fiber gain section must not. Secondly, the OOM light wavelength should optimally be guided in a single transverse mode of the optical fiber cavity and be transmitted through the dichroic output coupler of the laser along with the 980-nm pump laser. Lastly, there should exist easily available light sources and fiber components at the chosen OOM wavelength.

In previous non-collinear demonstrations, the OOM light source wavelength was mostly chosen in the 800 nm region [12]. While 800 nm light experiences relatively low absorption in the erbium fiber gain section, it is not single mode in PM 980 or PM 1550 fiber. The next available region occurs to the long wavelength side of the erbium absorption band centered at 975 nm,

Optics EXPRESS

beginning around 1025 nm and extending to 1425 nm [24]. The InGaAs MQW should absorb some amount of light throughout this entire band [25]. The output coupler was designed to be transmissive near the pump wavelength of 980 nm, which sets the general wavelength range for the OOM light source. Taking into consideration availability of lasers and fiber components, we selected a 1064 nm laser as the collinear OOM light source. This wavelength is slightly below the single-mode cutoff of PM 1550 but will be guided in fewer modes than 800 nm light. Here, we use a relatively quiet single-mode fiber laser source chosen for its wavelength and availability, but based on previous OOM work [7] we do not expect the coherence of the 1064 nm laser nor its low intensity noise to be important requirements.

A schematic of the fiber optical setup is shown in Fig. 1. Our OOM light source consists of a 1064-nm PM fiber laser with an external isolator and an electro-optical Mach-Zehnder modulator (EO-MZM) for amplitude modulation. The output of the EO-MZM is about 12 mW and is combined with 980-nm pump light using a 1064/980 PM wavelength-division multiplexer (WDM). The output of the first WDM is sent to a 1550/980 PM WDM which reflects the short wavelengths into the end-pumped femtosecond laser cavity. The femtosecond laser output centered at 1567 nm is amplified in a doubly pumped erbium-doped fiber amplifier (EDFA) and sent through a section of anomalous group velocity dispersion highly nonlinear fiber (HNLF). The resulting octave-spanning spectrum is sent to a fiber-coupled periodically-poled potassium titanyl phosphate (PPKTP) waveguide which acts as an in-line *f-to-2f* interferometer [26]. The output of the PPKTP is filtered to a few nanometers wide band around 980 nm that contains the $f_{\mathrm{ceo},}$ detected on a 350 MHz bandwidth photodiode, and low pass filtered at 50 MHz. In order to stabilize an optical comb tooth, comb light from a 5% oscillator tap is filtered and heterodyned against a 1565 nm cavity-stabilized CW laser.

### 2.2. Loop filter design for CEO control

The $f_{\mathrm{ceo}}$ is stabilized via simultaneous feedback to the optical gain, through the 980-nm pump diode, and OOM, through the 1064 nm OOM light source. A schematic of this hybrid feedback loop in shown in Fig. 2. To reduce latency in the OOM loop, this portion of the feedback uses an analog loop filter as opposed to the digital system used for the pump laser [11]. This hybrid approach combines the large phase capture range and configurability of digital locking techniques with the higher feedback bandwidths allowed by analog techniques. The $f_{\mathrm{ceo}}$ RF signal is split after detection and filtering. One signal is digitized by an analog-to-digital converter (ADC) and sent to a field-programmable gate array (FPGA), in-phase/quadrature (I/Q)-demodulated and sent to a digital phase-locked loop which feeds back to the setpoint for our 980-nm oscillator pump diode driver. The other CEO signal is sent to a frequency discriminator (FD) circuit. The FD circuit requires dual-stage amplification and filtering to achieve the 7 dBm power level required to drive a double-balanced mixer. After this stage, the FD circuit splits the CEO beat, introduces a differential delay of 10 ns (using a 90 MHz lowpass filter) between the two split electrical paths and then re-combines the signals on a mixer. For $f_{\mathrm{ceo}} = 25$ MHz, this small delay causes the mixer to output a signal proportional to the instantaneous frequency error of the CEO beat. A FD circuit allows for high bandwidth error signal generation without introducing a separate phase zero-point from the one determined by the digital phase-locked loop. The FD signal is low pass filtered at 5 MHz and fed into an analog loop filter box, which is used to drive the 1064 nm EO-MZM. The response of the FD circuit is approximately linear over input CEO frequencies ranging from 20 MHz to 30 MHz.

The hybrid servo loop is stable with both proportional and differential gain turned on for the analog portion and the lowest noise was achieved with only proportional feedback for the OOM loop combined with proportional, integral and derivative (PID) feedback to the 980-nm pump laser. This lowest noise operation occurs when proportional gain for the optical gain control loop was increased compared to the settings without the additional OOM feedback. Consequently,

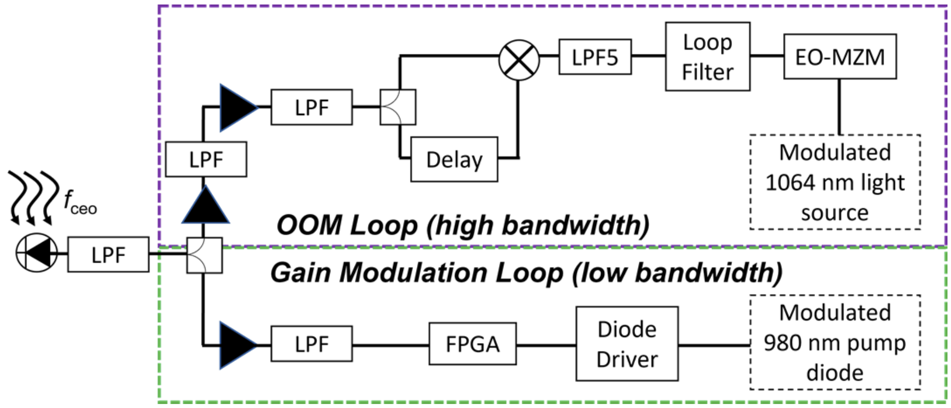


**Fig. 2.** Hybrid analog/digital CEO control loop. Green box surrounds traditional optical gain modulation loop and purple box surrounds the novel high-bandwidth analog OOM loop. RF amplifiers shown as black triangles. LPF: low pass filter for 25 MHz CEO signal, LPF5: 5 MHz low pass filter for frequency discrimination signal.

if the OOM is turned off suddenly while the system is an optimal phase-noise state, the gain modulation loop becomes unstable. Otherwise, the hybrid modulation is very insensitive to perturbations.

## 3. Results

### 3.1. Open-loop transfer functions

Figure 3 shows the measured open-loop magnitude and phase transfer functions for gain modulation (via the 980-nm optical gain pump laser) and OOM (via the 1064-nm OOM light source) of the CEO frequency. The magnitude of the transfer functions has been normalized to unity at 10 Hz. As the phase response of the gain modulation and OOM was characterized using an FPGA, the open-loop phase transfer functions in Fig. 3 have been corrected by removing the phase slope due to the estimated digital latency in the FPGA which is ~680 ns [11].

The gain modulation phase transfer function has a 90° roll-off at ~9 kHz with a corresponding 3 dB magnitude roll-off at ~9 kHz. The low frequency gain modulation magnitude response is $\sim 1.6 \times 10^{10}$ Hz/V, which corresponds to approximately 50 MHz/mW [16]. Adding a differential term to the FPGA-based feedback loop (see Fig. 2) gives a bandwidth (servo bump) of 150 kHz, as shown in Fig. 4. which is near the reported performance of similar laser cavities [4,6,11,22]. Based on the relative modulation of the CEO frequency and the optical beat signal with the CW laser at 1565 nm, the fixed point for gain modulation is within a few THz from the CW laser frequency, as expected [3].

Due to the existence of a zero in the generalized loss modulation transfer function, the OOM transfer function differs quite considerably from the gain modulation transfer function with the effects of a high frequency first-order pole made apparent in the loss modulation magnitude response [5]. The effect of this pole is to push the 3 dB magnitude roll-off for SESAM OOM to ~3 MHz. The measured improvement in phase response is also large with the 90° roll-off increased to ~2.2 MHz. Assuming no loss in the fiber cavity at the OOM wavelength (1064 nm) leads to a lower limit for the peak OOM magnitude response (see Fig. 3) of 1 MHz/mW. The fixed-point for the opto-optical modulation of the SESAM is close to 1565 nm as the $f_{\text{ceo}}$ response is two orders of magnitude stronger than the $f_{\text{opt}}$ response to OOM. The difference between this OOM transfer function and the ones described in previous loss modulation results

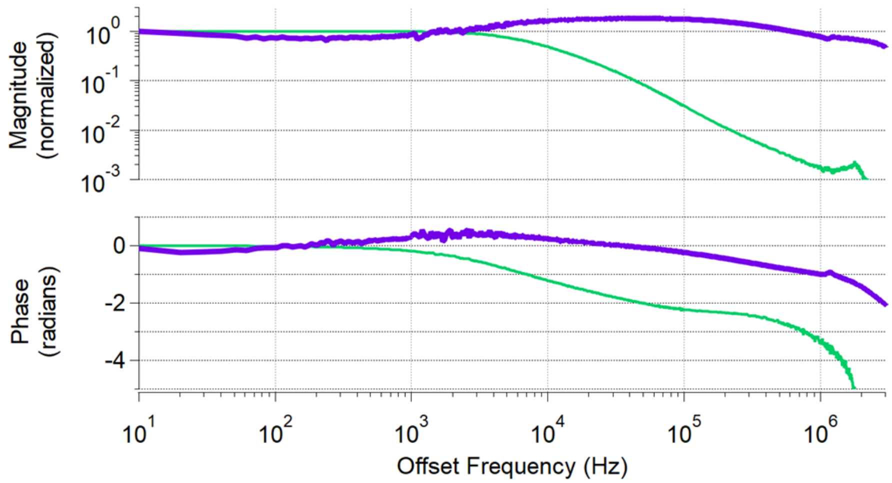


**Fig. 3.** Open-loop transfer functions for $f_{ceo}$ modulation. Thin green line: optical gain modulation; Thick purple line: OOM. Note: magnitude transfer functions are normalized to the response at 10 Hz. Note: frequency axis refers to offset from 25 MHz carrier.

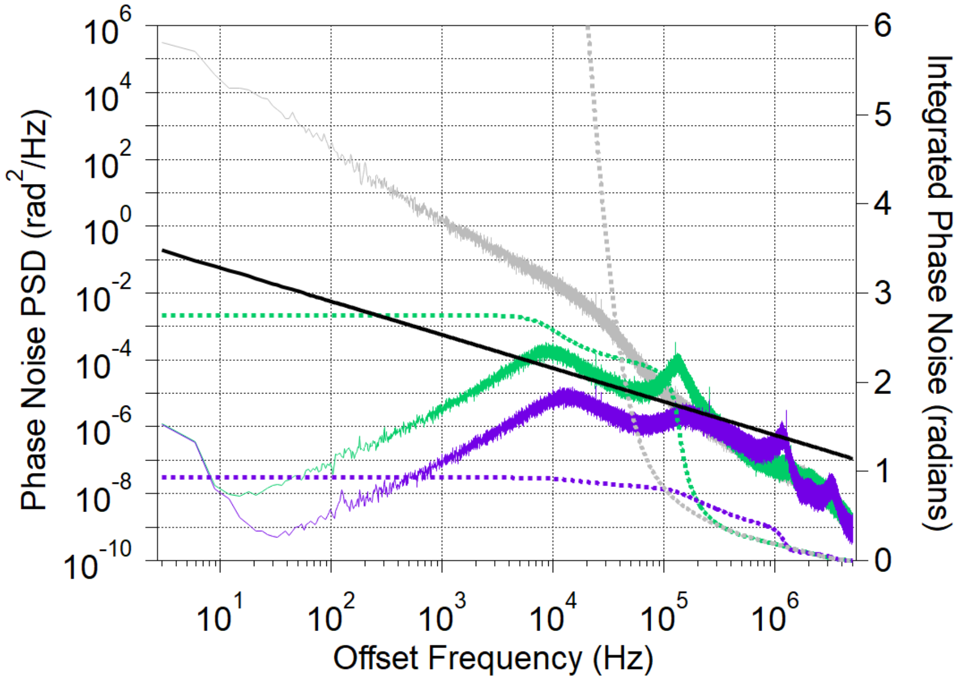


**Fig. 4.** Residual CEO phase noise for the locked system. Solid lines are phase noise power spectral densities (PSDs). Dotted lines are the phase noise integrated from 5 MHz to 3 Hz. Gray lines correspond to a loosely locked system, the green lines correspond to a gain modulated system and the purple lines show the hybrid system (OOM/gain modulation). The black line indicates the β-separation line. Note: frequency axis refers to offset from 25 MHz carrier.

Optics EXPRESS

[5–7] is driven by differences in the properties of the laser cavities (*e.g.* gain relaxation time, gain saturation energy, round-trip gain, round-trip time) that are included in a relatively simple model of cavity loss modulation described in Ref. [5].

### *3.2. CEO phase noise and beat note measurements*

CEO phase noise results are shown in Fig. 4 and Table 1. With only gain modulation and without OOM, the optimized system achieves 2.75 radians of integrated phase noise (3 Hz to 5 MHz) (see green trace in Fig. 4). The CEO phase noise power spectral density (PSD) is significantly reduced with 3 dB of rejection out to ~70 kHz and a servo bump just under 150 kHz. When the OOM feedback is also engaged via the hybrid feedback and after optimization, the carrier-envelope phase noise PSD (see purple trace in Fig. 4) is further reduced by over an order of magnitude from 50 Hz to 150 kHz. Servo bumps appear at 180 kHz and 1.15 MHz, attributable to gain modulation and OOM respectively. The actual 3 dB noise rejection bandwidth of the hybrid loop is approximately 150 kHz (compared against free-running or loosely locked comb), about twice the 70-kHz rejection bandwidth using gain modulation alone. When integrated from 3 Hz to 5 MHz, the integrated phase noise in the optimal hybrid OOM/gain modulation state is 0.92 radians, a 66% improvement compared to gain modulation only. The results displayed in Fig. 4 are for lock conditions that result in the lowest integrated phase noise. We can also optimize our hybrid lock conditions based on rejection bandwidth by reducing the electrical gain on the optical gain feedback loop. In this state, we achieve a rejection bandwidth of nearly 500 kHz, enabling reduction of white frequency noise in this region, although in this lock state the integrated phase noise rises to nearly 2 radians.

**Table 1. Comparison summary of $f_{ceo}$ phase noise**

| Feedback | Integrated Phase Noise (3 Hz to 5 MHz) | Phase Noise PSD at 100 kHz | Servo Bump Location |
|---|---|---|---|
| Gain Modulation alone | 2.75 radians | $3.0 \times 10^{-5}$ rad$^2$/Hz | 150 kHz |
| Hybrid (Gain Modulation/OOM) | 0.92 radians | $1.5 \times 10^{-6}$ rad$^2$/Hz | 1.15 MHz |

The improvement from SESAM OOM is clear when we examine the $f_{ceo}$ beat signal, as shown in Fig. 5. The free running Lorentzian line-width of the $f_{ceo}$ beat is ~250 kHz due to the relatively large anomalous cavity dispersion and intracavity loss. Figure 5 shows the RF spectrum of the $f_{ceo}$ beat as stabilized using gain modulation alone and hybrid OOM/gain modulation. The servo bumps from Fig. 4 are also clearly visible in Fig. 5. Importantly, hybrid modulation drastically increases the power in the central coherent peak by 30 dB (for 5 Hz resolution bandwidth). This large increase of coherent carrier power is consistent with the observation that the phase noise PSD for hybrid OOM/gain modulation (see Fig. 4) falls nearly completely below the β-separation line whereas the gain modulation trace rises above the β-separation line at 5 kHz [27].

As previously mentioned, the OOM modulation has a fixed point within a 4 THz band centered at 1565 nm (191.6 THz), which leads us to assume that locking against the stable CW reference would not disturb the OOM and vice versa. This prediction was confirmed by locking a comb tooth to a stable CW laser using slow and fast piezo-electric transducers (PZTs) with a servo bandwidth of ~90 kHz. The integrated phase noise on this optical lock was 50 milliradians (3 Hz to 5 MHz) and did not change when either gain modulation or hybrid modulation was applied. Finally, stable locking of both the CEO and optical beat signals was achieved for multiple days.

At the low injected power levels of the OOM light (10 mW), the presence of the OOM light has very little effect on most laser parameters other than the CEO phase. A full on/off step change in the OOM light does not increase either the free-running relative intensity noise (RIN) measured from 100 Hz to 1 MHz or the free-running CEO phase noise of our comb. Furthermore, the optical bandwidth remains unchanged, and the mode-locking stability is unaffected. We do see a

Optics EXPRESS

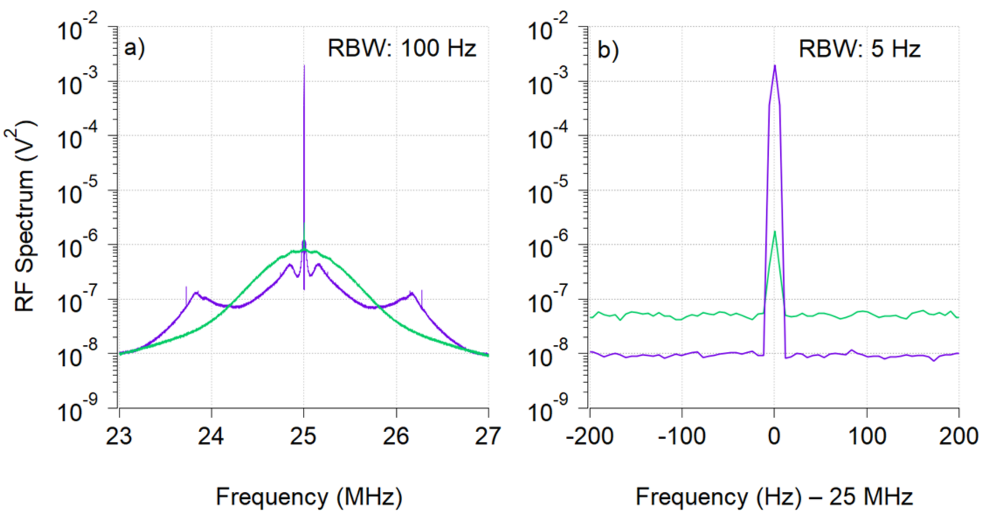


**Fig. 5.** RF spectrum of optimal $f_{\text{ceo}}$ beat during gain modulation (green) and hybrid OOM/gain modulation (purple). a) RF spectrum with 100 Hz resolution bandwidth (RBW). b) Same beat notes measured with 5 Hz resolution bandwidth. Note: 25 MHz carrier frequency has been subtracted from the x-axis.

small, slow drift of the CEO frequency that we attribute to cavity heating from absorption [12]. This drift does not affect our ability to reliably maintain the CEO lock.

### *3.3. Efficiency of collinear opto-optical modulation*

There are two related aspects in which our collinear OOM method improves the efficiency of OOM over previous non-collinear designs: the magnitude of the CEO response per mW of power applied and the required steady-state power of the OOM light source. These advantages are derived from the much smaller beam diameter of the OOM light source at the cavity SESAM (20 µm) in our experiment versus previously reported beam diameters in OOM experiments (on the order of 100 µm to 1 mm [7,12]). This difference leads to at least a 25 times increase in fluence achievable per mW of OOM light source power applied. As mentioned previously, the peak OOM response for our cavity is approximately 1 MHz/mW. This response is two orders of magnitude stronger than previous OOM demonstrations, which have had responses between 1 kHz/mW to 10 kHz/mW [7,12]. In addition to increased CEO response, collinear OOM also reduces the steady-state power requirements for the OOM light source. Here, 10 mW of 1064 nm light is injected collinearly into the laser cavity in order to achieve optimal locking whereas previous experiments have required between 80 mW and 200 mW of injected light to achieve optimal locking performance [12]. An attractive added benefit of the collinear technique is that the OOM light will always be perfectly overlapped with the intra-cavity pulse spot even in the presence of significant vibrations.

## 4. Discussion and conclusion

We have shown collinear opto-optical modulation to be a simple and robust method for improving the CEO phase noise performance of well-tested all-PM erbium fiber frequency comb technology. A simple femtosecond laser design with a 250 kHz CEO free-running linewidth had its phase noise reduced to the single radian level with servo response above 1 MHz. Future collinear OOM designs would replace the EO-MZM with a low-power laser diode near 1064 nm and high bandwidth diode driver electronics. Using a current-modulated laser diode as the OOM

Optics EXPRESS

light source would improve the dynamic range of future collinear OOM stabilization and would possibly enable full CEO stabilization using OOM alone. Considering that no cavity component was added and the required power levels for modulation were small, we consider collinear OOM a viable path towards reliable, inexpensive sub-radian fiber frequency combs built entirely from commercial parts. Such a tool would enable further advancement of frequency comb field applications such as high-resolution atmospheric spectroscopy, long-distance time and frequency transfer, ultra-precise ranging and low-noise microwave generation.

The demonstrated improvement from 2.75 radians of integrated CEO phase noise to 0.92 radian enables a wide coherence bandwidth of about 380 THz for an optically locked comb. This level of coherence reduces the complexity of the phase-correction algorithm needed for dual-comb spectroscopy in the 3.0 µm to 5.0 µm region, a useful spectral band for atmospheric remote sensing experiments [20]. With the improvements discussed above, this hybrid approach could yield CEO phase noise well below a radian in an extremely simple, inexpensive platform. Such CEO phase noise performance would increase the coherence bandwidth to the >400 THz level simplifying the phase correction procedure for DCS from the THz to the UV. The fast CEO phase response of OOM may also improve agile frequency comb technology for timing applications [18]. Another interesting strength of OOM is its application to high repetition rate oscillators where even faster CEO feedback is possible [17]. It should be possible to use collinear OOM to stabilize high repetition rate fiber lasers [28] and other future compact chip-scale laser designs [29].

OOM could also be applied to an intrinsically quieter laser source if ultra-low noise combs were required. Although the fractional noise improvement demonstrated in this work is on par with previous results [12], dispersion management could be performed to reduce the CEO linewidth by up to two orders of magnitude [6,30] allowing one to apply the same feedback bandwidth to a quieter source. Also, the free-running CEO phase noise PSD shows signs of significant pump-induced noise below 100 kHz. In the future, experiments with lower RIN pump sources and/or RIN reducing servos will likely contribute to improved phase noise suppression for SESAM lasers [31].

It is also worthwhile to consider design changes to the SESAM. In this experiment, the SESAM used has 6% non-saturable loss which is high compared to SESAMs used in low noise diode-pumped solid-state laser combs [32,33]. A SESAM should be designed to minimize this non-saturable loss and simultaneously minimize absorption in non-MQW layers to the best degree possible. It has been speculated that such spurious absorption could cause slower modulations of the CEO frequency which might limit locking performance [12]. It should be possible to design a SESAM with multiple reflection bands at zero angle incidence which could include both the gain pump and OOM light source wavelengths while minimizing non-saturable loss at the laser wavelength as well [12]. It is also unknown which OOM wavelength generates the optimal magnitude/phase response of $f_{\text{ceo}}$ to OOM for any given SESAM. By tuning the OOM wavelength across the various erbium transparency bands, one may find resonances in MQW structures where OOM response is markedly increased.

**Funding.** National Institute of Standards and Technology.

**Acknowledgments.** We recognize Gabriel Colacion for constructing the PPKTP *f-to-2f* interferometer. We thank Fabrizio Giorgetta, Brian Washburn, Bill Swann, Laura Sinclair, Tara Fortier and Scott Diddams for useful technical discussions. We thank Esther Baumann, Curtis Rau and Melissa Midzor for helpful manuscript comments.

**Disclosures.** The authors declare no conflicts of interest.

**Data availability.** Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

Optics EXPRESS

## References


1. S. T. Cundiff and J. Ye, "Colloquium: Femtosecond optical frequency combs," Rev. Mod. Phys. **75**(1), 325–342 (2003).
2. B. R. Washburn, S. A. Diddams, N. R. Newbury, J. W. Nicholson, M. F. Yan, and C. G. Jorgensen, "Phase-locked, erbium-fiber-laser-based frequency comb in the near infrared," Opt. Lett. **29**(3), 250–252 (2004).
3. 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).
4. 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).
5. 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).
6. 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).
7. M. Hoffmann, S. Schilt, and T. Südmeyer, "CEO stabilization of a femtosecond laser using a SESAM as fast opto-optical modulator," Opt. Express **21**(24), 30054–30064 (2013).
8. K. Gürel, S. Schilt, and T. Südmeyer, "Carrier-Envelope Offset Frequency Stabilization of a Fiber Laser by Cross Gain Modulation," IEEE Photonics J. **10**(2), 1–6 (2018).
9. S. Salman, Y. Ma, K. Gürel, S. Schilt, C. Li, P. Pfäfflein, C. Mahnke, J. Fellinger, S. Droste, A. S. Mayer, O. H. Heckl, T. Südmeyer, C. M. Heyl, and I. Hartl, "Comparison of two low-noise CEO frequency stabilization methods for an all-PM Yb:fiber NALM oscillator," OSA Continuum **4**(6), 1889–1896 (2021).
10. W. Hänsel, M. Giunta, M. Lezius, M. Fischer, and R. Holzwarth, "Electro-optic modulator for rapid control of the carrier-envelope offset frequency," in *Conference on Lasers and Electro-Optics (2017)*, Paper SF1C.5 (Optical Society of America, 2017), p. SF1C.5.
11. L. C. Sinclair, J.-D. Deschênes, L. Sonderhouse, W. C. Swann, I. H. Khader, E. Baumann, N. R. Newbury, and I. Coddington, "Invited Article: A compact optically coherent fiber frequency comb," Rev. Sci. Instrum. **86**(8), 081301 (2015).
12. K. Gürel, S. Hakobyan, V. J. Wittwer, S. Schilt, and T. Südmeyer, "Frequency Comb Stabilization of Ultrafast Lasers by Opto-Optical Modulation of Semiconductors," IEEE J. Sel. Top. Quantum Electron. **24**(5), 1–9 (2018).
13. J. Kim and Y. Song, "Ultralow-noise mode-locked fiber lasers and frequency combs: principles, status, and applications," Adv. Opt. Photonics **8**(3), 465–540 (2016).
14. S. Coburn, C. B. Alden, R. Wright, K. Cossel, E. Baumann, G.-W. Truong, F. Giorgetta, C. Sweeney, N. R. Newbury, K. Prasad, I. Coddington, and G. B. Rieker, "Regional trace-gas source attribution using a field-deployed dual frequency comb spectrometer," Optica **5**(4), 320–327 (2018).
15. D. I. Herman, C. Weerasekara, L. C. Hutcherson, F. R. Giorgetta, K. C. Cossel, E. M. Waxman, G. M. Colacion, N. R. Newbury, S. M. Welch, B. D. DePaola, I. Coddington, E. A. Santos, and B. R. Washburn, "Precise multispecies agricultural gas flux determined using broadband open-path dual-comb spectroscopy," Sci. Adv. **7**(14), eabe9765 (2021).
16. 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).
17. J.-D. Deschênes, L. C. Sinclair, F. R. Giorgetta, W. C. Swann, E. Baumann, H. Bergeron, M. Cermak, I. Coddington, and N. R. Newbury, "Synchronization of Distant Optical Clocks at the Femtosecond Level," Phys. Rev. X **6**(2), 021016 (2016).
18. E. D. Caldwell, L. C. Sinclair, N. R. Newbury, and J.-D. Deschenes, "The Time Programmable Frequency Comb: Generation and Application to Quantum-Limited Dual-Comb Ranging," *ArXiv220501147 Phys.* (2022).
19. G.-W. Truong, E. M. Waxman, K. C. Cossel, E. Baumann, A. Klose, F. R. Giorgetta, W. C. Swann, N. R. Newbury, and I. Coddington, "Accurate frequency referencing for fieldable dual-comb spectroscopy," Opt. Express **24**(26), 30495–30504 (2016).
20. G. Ycas, F. R. Giorgetta, E. Baumann, I. Coddington, D. Herman, S. A. Diddams, and N. R. Newbury, "High-coherence mid-infrared dual-comb spectroscopy spanning 2.6 to 5.2 µm," Nat. Photonics **12**(4), 202–208 (2018).
21. 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).
22. S. M. Schweyer, B. Eder, P. Putzer, M. Mayerbacher, N. Lemke, K. U. Schreiber, U. Hugentobler, and R. Kienberger, "All-in-fiber SESAM based comb oscillator with an intra-cavity electro-optic modulator for coherent high bandwidth stabilization," Opt. Express **26**(18), 23798–23807 (2018).
23. J. L. Hall, M. S. Taubman, and J. Ye, "Laser Stabilization," in *Handbook of Optics*, *Volume IV*, M. Bass, ed. (McGraw-Hill, 2000).
24. R. G. Smart, J. L. Zyskind, and D. J. DiGiovanni, "Experimental comparison of 980 nm and 1480 nm-pumped saturated in-line erbium-doped fiber amplifiers suitable for long-haul soliton transmission systems," IEEE Photonics Technol. Lett. **5**(7), 770–773 (1993).

Optics EXPRESS


25. U. Keller, K. J. Weingarten, F. X. Kartner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Honninger, N. Matuschek, and J. Aus der Au, "Semiconductor saturable absorber mirrors (SESAM's) for femtosecond to nanosecond pulse generation in solid-state lasers," IEEE J. Sel. Top. Quantum Electron. **2**(3), 435–453 (1996).
26. P. Manurkar, E. F. Perez, D. D. Hickstein, D. R. Carlson, J. Chiles, D. A. Westly, E. Baumann, S. A. Diddams, N. R. Newbury, K. Srinivasan, S. B. Papp, and I. Coddington, "Fully self-referenced frequency comb consuming 5 watts of electrical power," OSA Continuum **1**(1), 274–282 (2018).
27. 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).
28. H. Byun, M. Y. Sander, A. Motamedi, H. Shen, G. S. Petrich, L. A. Kolodziejski, E. P. Ippen, and F. X. Kärtner, "Compact, stable 1 GHz femtosecond Er-doped fiber lasers," Appl. Opt. **49**(29), 5577–5582 (2010).
29. S. Cuyvers, B. Haq, C. Op de Beeck, S. Poelman, A. Hermans, Z. Wang, A. Gocalinska, E. Pelucchi, B. Corbett, G. Roelkens, K. Van Gasse, and B. Kuyken, "Low Noise Heterogeneous III-V-on-Silicon-Nitride Mode-Locked Comb Laser," Laser Photonics Rev. **15**(8), 2000485 (2021).
30. 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).
31. 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).
32. S. Schilt, N. Bucalovic, V. Dolgovskiy, C. Schori, M. C. Stumpf, G. D. Domenico, S. Pekarek, A. E. H. Oehler, T. Südmeyer, U. Keller, and P. Thomann, "Fully stabilized optical frequency comb with sub-radian CEO phase noise from a SESAM-modelocked 1.5-μm solid-state laser," Opt. Express **19**(24), 24171–24181 (2011).
33. T. D. Shoji, W. Xie, K. L. Silverman, A. Feldman, T. Harvey, R. P. Mirin, and T. R. Schibli, "Ultra-low-noise monolithic mode-locked solid-state laser," Optica **3**(9), 995–998 (2016).