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Carrier-envelope phase stabilization: a review of a feed-forward technique in a Er:Yb:glass laser

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Abstract: In their 2019 Optics Letter, Lemons et al. demonstrate a novel feed-forward technique for achieving CEP stabilization in a SESAM mode-locked Er:Yb:glass laser, using a in-loop/out-of-loop system design and a NKS photonics OneFive ORIGAMI-15 oscillator. In this review article, feedback and feed-forward CEP stabilization methods are introduced. The low IPND results from *Lemons et al.* (2019) are then compared to the state-of-the-art. Recommendations for future work are presented.

INTRODUCTION: FEEDBACK AND FEED-FORWARD CEP STABILIZATION

In the field of CEP stabilization, there are two main methods to lower integrated phase noise (IPN) for a laser system. In the literature these methods are referred to as *feedback* and *feed-forward* techniques. Both methods involve measuring the carrier-envelope offset (CEO) frequency of a laser system, typically with a $f - 2f$ interferometer, and then adjusting parameters to achieve higher pulse train stability accordingly.

Feedback CEP stabilization techniques involve tuning laser system parameters on the input side. Commonly, adjustments are made to the laser cavity length and pump power—where the cavity length determines the period wherein pulse elements will diverge, and pump power modulations regulate the amplification of nonlinear effects in the cavity to tune the phase and group velocities of a pulse.

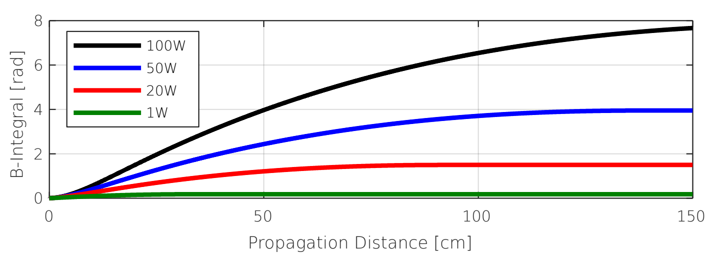

Fig. 1. Phase change simulation for a laser pulse as a function of pump power and propagation.

The simulation above (Fig. 1) demonstrates the theory behind adjusting laser input parameters for CEP stabilization. Here, the nonlinear effects on a 500 ps pulse in a Er:Yb:glass fiber were simulated as a function of propagation distance at different four pump powers. These results show that as the pump power and propagation distance increase, so does the B-integral term—i.e. the phase change due to the nonlinear effect—illustrating how pulse phase can be tuned using these parameters.

Alternatively, CEP stabilization can be achieved by modulating the output of a pulsed laser system. This is the feed-forward technique. Typically feed-forward techniques rely on laser oscillators and acousto-optic frequency shifters (AOFS), which read-in CEO frequency values to stabilize the pulse train output independent of cavity optics.

REVIEW: METHODS, RESULTS, AND CONCLUSIONS

In their 2019 Optics Letter, Lemons et al. use a feed-forward technique to improve CEP stabilization in their mode-locked, pulsed laser system, achieving notably low integrated phase noise density (IPND) results [1]. The group partly attributed low IPND results to the intrinsically low timing jitter of Er:Yb:glass lasers. They also attribute low phase noise to high SNR in their in-loop *f—2f* interferometer. A comparison with similar CEP stabilization techniques is provided in the table below.

Table 1. Survey of several feed-forward CEP stabilization techniques

Group/Company	Laser oscillator	Frequency range	Time (hours)	Stabilization
Lemons et al. (2019)	OneFive ORIGAMI-15	100 mHz – 3 MHz 1 Hz – 3 MHz	8 hours	25 mrad 3.5 mrad (IPND)
Lucking et al. (2012) [2]	FEMTOSOURCE rainbow, Femtolasers GmbH	50 mHz – 500 kHz	10 hours	<50 mrad (RMS phase error)
Koke et al. (2010) [3]	FEMTOSOURCE synergy, Femtolasers GmbH	20 mHz – 2.5 MHz	5 seconds	45 mrad (IPN)
MKS/Spectra-Physics	Element 2 CEP4	50 mHz – 500 kHz	12 hours	<60 mrad rms (CEP stability)

Different than other groups, Lemons et al. report two IPND values in their 2019 work. The first refers to the IPND of the stabilized OOL signal from 100 mHz to 3 MHz. The second refers to the IPND of the same signal, ignoring any contributions from frequencies below 1 Hz. This latter value is reported to help distinguish their CEP stabilization results from 1/f spurious noise due to quantum noise in the laser cavity [4]. As can be seen in Table 1, the IPND results from *Lemons et al.* are low compared to similar CEP stabilization efforts.

For future work, it is recommended that Lemons et al. further investigate the sources of drift noise in their system below 1 Hz. There are examples of thermal-noise-limited optical stabilities that can be found in the literature, where ultralow drift conditions are found by cooling cavities in cryogenic thermal damping systems [5]. Adopting this type of apparatus could help Lemons et al. validate their assumptions regarding the source of this low-frequency noise and continue to minimize their IPND over long periods of time.

REFERENCES

1. Randy Lemons, Wei Liu, Irene Fernandez de Fuentes, Stefan Droste, Günter Steinmeyer, Charles G. Durfee, and Sergio Carbajo, "Carrier-envelope phase stabilization of an Er:Yb:glass laser via a feed-forward technique," Opt. Lett. 44, 5610-5613 (2019)
2. Fabian Lücking, Andreas Assion, Alexander Apolonski, Ferenc Krausz, and Günter Steinmeyer, "Long-term carrier-envelope-phase-stable few-cycle pulses by use of the feed-forward method," Opt. Lett. 37, 2076-2078 (2012)

3. Koke, S., Grebing, C., Frei, H. *et al.* Direct frequency comb synthesis with arbitrary offset and shot-noise-limited phase noise. *Nature Photon* 4, 462–465 (2010). https://doi.org/10.1038/nphoton.2010.91
4. Y. Song, F. Lucking, B. Borchers, and G. Steinmeyer, Opt. Lett. 39, 6989 (2014).
5. John M. Robinson, Eric Oelker, William R. Milner, Wei Zhang, Thomas Legero, Dan G. Matei, Fritz Riehle, Uwe Sterr, and Jun Ye, "Crystalline optical cavity at 4 K with thermal-noise-limited instability and ultralow drift," Optica 6, 240-243 (2019)