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Abstract: Investigation into the emergence of carrier-envelope phase in mode-locked lasers and methods to achieve stabilization of this parameter.

INTRODUCTION

In "Carrier-envelope phase stabilization of an Er:Yb:glass laser via a feed-forward technique" by Lemons, Randy, et al, the authors outline two different methods plausible for stabilizing the carrier-envelope phase, or CEP, of a mode-locked laser [1]. This review provides background into the problem of carrier-envelope phase and examines the feedforward method utilized in the paper to address that issue.

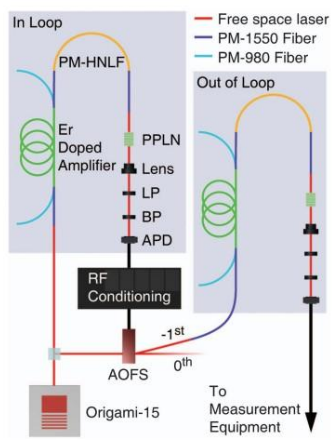

Figure 1. Experimental Setup Utilized in "Carrier-envelope phase stabilization of an Er:Yb:glass laser via a feed-forward technique"

It is crucial to establish an understanding of what exactly the researchers are attempting to stabilize: the carrier-envelope phase. Practical laser systems do not perfectly amplify at a single wavelength [2]. Rather the gain media of lasers often feature optical gain curves with a mixture of Lorentzian lineshapes from homogeneous broadening and Gaussian lineshapes from inhomogeneous broadening [2,3]. Since laser cavities act as interferometers, a subsection of those wavelengths with gain greater than loss actually get amplified because the other wavelengths get lost to destructive interference [2]. Those wavelengths that do get amplified are called the longitudinal modes, which are spaced evenly apart by the free spectral range (FSR), a value determined by the geometry of the cavity given here in terms of the frequency difference as $\Delta\nu = \frac{c}{2nL}$, where c is the speed of light in a vacuum, n is the index of refraction inside the cavity, and L is the length between the cavity's mirrors [2]. In the paper by Lemons, et al, the term f_{REP} is used, described as "the repetition rate of the laser," which is equivalent to the frequency spacing between wavelengths defined by FSR, or simply the inverse of round-trip time, $f_{REP} = \frac{1}{\tau_R} = \frac{c}{2nl}$ [1].

Since the output of the laser in the frequency domain is the product of these longitudinal modes multiplied by some amount of amplification by the optic gain curve of the gain medium, one can plot the electric field of the laser in the frequency domain as:

$$E(f) = A(f - f_C) * \sum_{m=-\infty}^{\infty} \delta(f - mf_{REP})\ [4]$$

This equation is the optic gain curve centered at frequency f_c multiplied by the resonant modes spaced apart by f_{REP}, but it makes the assumption that no carrier-envelope phase exists, which in the frequency domain is represented by the carrier-envelope offset frequency f_{CEO} [4]. This factor's emergence is only briefly alluded to in the paper, but to include this frequency offset, a term needs to be added to the Dirac delta comb relation: $\sum_{m=-\infty}^{\infty} \delta(f - mf_{REP} - f_{CEO})$ [4]. With regards to how f_{CEO} emerges, the paper states that "intracavity environmental conditions and optical power fluctuations" cause a difference in the group velocity and the phase velocity, two quantities that can more easily be understood by using Fourier analysis to look at the above equation in the time domain:

$$E(t) = A(t)exp(i\omega_c t + i\phi(t)) \otimes \sum_{m=-\infty}^{\infty} \delta(t - mT_R)\ [4]$$

where ω_c is the carrier frequency and $\phi(t)$ is a phase shift [4]. The graph that emerges from this equation is a train of pulses in the time-domain where each pulse is a complex sinusoidal with frequency ω_c fitted into intensity "envelopes" characterized by the optic gain curve [5]. Physically, the carrier-envelope phase is the phase difference between the maximum intensity of the envelope and the maximum intensity of the complex sinusoid [5]. If the phase velocity, how fast an individual point on the sinusoid moves, is equal to the group velocity, how fast the pulse intensity envelope moves, then $\phi(t)$ is a constant in time and the carrier-envelope phase is stabilized [4,6]. Phase and group velocity differ, however, due to changes in refractive index in the laser cavity, with this difference given by $\frac{1}{v_g} = \frac{1}{v_p} + \frac{dn(\omega)}{d\omega}\frac{\omega}{c}$ [4]. Therefore, with L as the length of the cavity, the CEP in the time-domain is obtained:

$$\Delta\phi = \left[-\ \omega\int_0^L (\frac{1}{v_g} - \frac{1}{v_p})dx\right] mod\ 2\pi = \left[\int_0^L (\frac{\omega^2}{c}\frac{dn(\omega,x)}{d\omega})dx\right] mod\ 2\pi$$

To stabilize the carrier-envelope phase, the researchers use a common control technique: a feedforward method (FF) [1]. Feedforward refers to a method whereby a "disturbance" is detected, which in the case of the paper is a deviation in the value of f_{CEO}, and a correction is made to fix that error while not actually adjusting the dynamic system that produced the fluctuation [1,7]. This contrasts to a feedback method like used in "Few-optical-cycle light pulses with passive carrier-envelope phase stabilization" by Cerullo, et al, where the deviations in f_{CEO} were used to vary the pump power of the laser, a means of acting directly on the system producing the undesired behavior [7,8]. In terms of the paper by Lemons, et al, the feedforward method is implemented with an acousto-optic frequency shifter (AOFS) acting on a beamline exiting the OneFive ORIGAMI-15 mode-locked laser according to deviations in f_{CEO} determined by f-2f interferometry performed in the in loop as seen in Figure 1[1].

Optical frequency can easily be shifted using an AOFS, whereby an acoustic wave in the radio frequency (RF) range between 20kHz and 300GHz strains a crystal or glass and introduces a grating in the index of refraction [2,3,9]. This grating means that light incident on the AOFS will be diffracted, with the diffracted beam experiencing a desired phase shift equal to $\omega \pm \Omega$, where ω is the frequency of the optical wave incident on the AOFS and Ω is the frequency of the acoustic wave [3]. From Figure 1, it can be seen that the paper by Lemons, et al, used the -1st mode, in which the diffracted beam experiences a phase shift $\omega - \Omega$ [1]. This phase shift zeroes out the carrier envelope phase since the frequency of the incident laser is $\omega = nf_{REP} + f_{CEO}$, an expression derived above inside the Dirac delta comb of the electric field of the laser in the frequency domain, and $\Omega = f_{CEO} + f_{LO}$, where f_{LO} is just a term added to ensure Ω equals the operational frequency of 80 ± 2.5 MHz of the AOFS, such that $\omega - \Omega = nf_{REP} + f_{CEO} - f_{CEO} - f_{LO} = f_{REP} - f_{LO}$ [1].

REFERENCES

1. Lemons R, Liu W, de Fuentes IF, Droste S, Steinmeyer G, Durfee CG, et al. Carrier-envelope phase stabilization of an Er:Yb:glass laser via a feed-forward technique. Opt Lett. 2019;44: 5610–5613.

2. Csele M. Fundamentals of Light Sources and Lasers. John Wiley & Sons; 2011.

3. Liu J-M. Principles of Photonics. Cambridge University Press; 2016.

4. Helbing FW, Steinmeyer G, Keller U. Carrier-envelope offset phase-locking with attosecond timing jitter. IEEE J Sel Top Quantum Electron. 2003;9: 1030–1040.

5. Jones DJ, Diddams SA, Ranka JK, Stentz A, Windeler RS, Hall JL, et al. Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis. Science. 2000;288: 635–640.

6. Reichert J, Holzwarth R, Udem T, Hänsch TW. Measuring the frequency of light with mode-locked lasers. Opt Commun. 1999;172: 59–68.

7. Liu L, Tian S, Xue D, Zhang T, Chen Y. Industrial feedforward control technology: a review. J Intell Manuf. 2019;30: 2819–2833.

8. Cerullo G, Baltuška A, Mücke OD, Vozzi C. Few-optical-cycle light pulses with passive carrier-envelope phase stabilization. Laser Photon Rev. 2011;5: 323–351.

9. Ghirardi AA. Radio physics course : an elementary radio text book on electricity and radio. cir.nii.ac.jp; 1932.