Title

Review of “Carrier-envelope phase stabilization of an Er:Yb:glass laser via a feed-forward technique”

Author
McGovern, Daniel

Publication Date
2023-07-31

Review of “Carrier-envelope phase stabilization of an Er:Yb:glass laser via a feed-forward technique”

Daniel McGovern,[1] and Sergio Carbajo[1]

[1] *Electrical & Computer Engineering Department, University of California Los Angeles, Los Angeles, CA 90045*
danieljmcgovern@ucla.edu

Abstract:
A feed-forward technique is presented for stabilizing the carrier-envelope phase (CEP) of an Er:Yb:glass laser. The technique achieves high levels of stability and is simple to implement.

INTRODUCTION

Lasers operating in the femtosecond and attosecond regime are significant because they can be used to study and manipulate matter on the atomic and molecular level. Femtosecond lasers have a pulse duration of 10^{-15} seconds, which is about the same time it takes for an electron to orbit an atom. This makes them ideal for studying ultrafast processes, such as the motion of electrons and the formation of chemical bonds. Attosecond lasers have a pulse duration of 10^{-18} seconds, which is about the time it takes for an electron to absorb or emit a photon. This makes them ideal for studying the dynamics of electrons in atoms and molecules. At present, the world’s shortest laser pulse is 43 attoseconds[1]. Such short pulses require precise control of “the offset of the underlying electric field with respect to the pulse, known as carrier envelope offset phase (CEP).”[2] Control of the CEP for long timescales is critical for real-world applications

METHODS

Applications such as high-resolution spectroscopy and fiber timing networks require stability in frequency and precision in time and may make use of few-cycle pulsed lasers operating at single-digit attosecond stabilization at telecom wavelengths. Such lasers require control and stabilization of the carrier-envelope phase (CEP). The CEP is “relative shift of envelope with respect to the peak of the electric field[3]”.

Arising from intracavity environmental conditions, in a single shot of the laser there is a difference in the phase velocity and group velocity, i.e., the CEP. From shot-to-shot, the CEP will vary, leading to a frequency shift in the mode-locked comb; this frequency difference is the carrier-envelope offset (CEO) frequency. The method of detection for f_{CEO} is via the f-2f interferometer, a heterodyne detection method which uses a frequency doubled signal from the laser itself as the local oscillator. This signal, f_{CEO}, may be used for control of CEP variation.

There are two main modes of control of CEP. Feedback control modifies pump power or cavity length to change intracavity velocities or path length respectively. The primary downside of this approach is the use of specialized electronics to maintain a lock between f_{CEO} and the changes made by the feedback control. Feedforward techniques operate on the pulses at the output rather than on the internals of the cavity. Here the f_{CEO} signal is used to directly drive an acousto-optic frequency shifter (AOFS) which allows for phase-modulation of the laser frequency spectrum. What’s novel in this investigation is the use primarily of a feed-forward approach.

The experimental setup uses a SESAM soliton mode-locked Er:Yb:glass 1.55 µm laser delivering 140 mW power in 175 fs pulses; this laser already exhibits very low timing jitter. Light output from this laser is split, one path to the in-loop feedback, the other through the AOFS to the out-of-loop feed-forward. One of the novelties represented in this approach is the use of amplification of these signals before they are measured; this increases SNR and leads to an improvement in measurement of f_{CEO} and an increase in control performance. As well this allows the use of a monolithic design, in which more of the components are integrated on a single chip for a less complex design. The pulses are then spectrally broadened with the use of a highly nonlinear fiber (HNLF). The anomalous dispersion of the HNLF allows a broader range of frequencies to arrive simultaneously in the time domain, i.e., for a shorter pulse. These pulses propagate in free space to an avalanche photodiode (APD) from which the desired control signal f_{CEO} can be obtained. This signal, now in the MHz range, is conditioned and mixed with a local oscillator before being sent to the AOFS. Here is the primary difference for the OOL FF technique: the CEP is not measured and then compensated for, but rather directly controlled. The AOFS controls CEP by modulating the laser frequency spectrum. This is done by passing the laser light through a material that has a frequency-dependent refractive index. When an acoustic wave is applied to the material, it creates a periodic variation in the refractive index. This causes the laser light to be diffracted, which results in a change in the frequency spectrum.

RESULTS AND INTERPRETATION

The main result of this study is the reporting of long term stabilization over a duration of 8 hours of a Er:Yb:glass laser at 1.55 µm with measured timing jitter of 2.9 as (1-3 MHz). This improvement was accomplished with the use of a feed-forward OOL control technique.

The f-2f interferometer warrants further discussion. The introduction of optical gain into the f-2f represents a significant step forward for attosecond pulses. Previously, CEP beat notes often barely surpassed minimum SNR required for stable phase lock[4], in which the beat notes consisted of around only 10 photons per pulse. In the newer approach, before undergoing frequency doubling, the signal is amplified. The original signal at f and the doubled signal at 2f are then recombined and fed into an interferometer (such as a Mach-Zehnder interferometer), the interference of these two signals creates a beat note. The beat note contains information from which the CEP can be inferred, as well the beat note exists at frequencies amenable to electronic analysis, such as in the AOFS used in this setup. Amplification of the signal prior to entering the f-2f arm of the OOL control can boost signal strength by as much as 20dB.

Another advantage of this approach is that introducing amplification prior to the f-2f step allows for a simpler design as the amplification is accomplished with Er:fiber amplifiers which can be integrated with the f-2f interferometer. Such a monolithic design helps increase widespread adoptability, lowers cost, and promises a more sustainable design.

CONCLUSIONS

To our knowledge, the long term stabilization over a duration of 8 hours of a Er:Yb:glass laser at 1.55 µm with measured timing jitter of 2.9 as (1-3 MHz) represents the state of the art for such a laser. Applications such as communications and high precision timekeeping do not use such a laser for a few hours and then turn it off. Such applications require nearly continuous use of these devices. The very long term stabilization of attosecond pulsed lasers would open up numerous applications for high speed, long distance communication, as well as allow for highly precise time keeping for scientific and engineering applications that require very high precision. This paper represents a significant step towards long term stabilized attosecond pulse laser.

It should be noted that feedback systems remain important as in this setup there was a slow drift from the beat signal that required adjustments to pump power on the order of every half hour. In this investigation these adjustments were made manually, which was a source of phase noise. In future work, the use of a slow feedback PID controller may eliminate this labor and source of noise, which are both necessary for this FF method to achieve wider adoption.

REFERENCES

1. Gaumnitz, T. *et al.* Streaking of 43-attosecond soft-X-ray pulses generated by a passively CEP-stable mid-infrared driver. *Opt. Express* **25**, 27506–27518 (2017).
2. Hirschman, J., Lemons, R., Chansky, E., Steinmeyer, G. & Carbajo, S. Long-term hybrid stabilization of the carrier-envelope phase. *Opt. Express* **28**, 34093–34103 (2020).
3. Lemons, R. *et al.* Carrier-envelope phase stabilization of an Er:Yb:glass laser via a feed-forward technique. *Opt. Lett.* **44**, 5610–5613 (2019).

4. Liao, R. *et al.* Active f-to-2f interferometer for record-low jitter carrier-envelope phase locking. *Opt. Lett.* **44**, 1060–1063 (2019).