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

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Abstract: To stabilize carrier-envelope phase (CEP) in ultrafast laser applications, techniques such as feed-forward control methods are used to reduce CEP shift. This work applies an acousto-optic frequency shifter to stabilize CEP in Er:Yb:glass systems.

INTRODUCTION

This paper discusses the stabilization of the carrier-envelope phase (CEP) of a laser output, which refers to the offset between the phase of the laser wave envelope and the carrier wave within the envelope. As laser beams were refined in the time domain to ultrafast pulses, the once-marginal difference between pulses of different CEP became significant enough to warrant scientific attention. This is because as the wave envelope is refined to a smaller timeframe, any phase difference of the carrier wave begins to noticeably alter the intensity of the wave within the envelope, as variances in CEP can alter the field intensity at the start of the pulse, which can itself alter the interaction the pulse has with a target.

Some variations in CEP can be attributed to timing jitter, which are variations in the time-domain profile of the laser. If there exist deviations in the profile or temporal behavior of the envelope of a laser output, the phase difference between the envelope and the carrier waves will also exhibit deviations. Timing jitter is therefore detrimental to stabilizing the CEP and can obfuscate the true incident intensity of the laser on a target.

Precise intensity profiles and therefore CEP is essential in some fields, such as optical frequency metrology, which depends on ultrafast frequency combs on the femtosecond level. These precise pulses are used to measure extremely short durations in time[1]. Methods to control and stabilize CEP are hence applicable to optical frequency metrology and other photonic applications where precise control over the intensity profile of ultrafast pulses is desired, as any uncontrolled deviation from ideal would alter the observed photonic system properties.

METHODS

The laser used in this paper was OneFive ORIGAMI-15, a semiconductor saturable absorber mirror mode-locked Er:Yb:glass laser emitting a soliton and tuned by a feed-forward method[2]. This laser was split into two lines, the first leading to an in-loop conditioning pathway which feeds into an acousto-optic frequency shifter (AOFS) which can tune the phase of the laser frequency spectrum of the second beamline[2]. This second beamline was sent to an out-of-loop pathway and is the beam to be measured and characterized for further analysis.

The AOFS operates by accepting as laser beam, which in this work is filtered and mixed to arrive at a beat frequency of 80 MHz, which is susceptible to drifting away from ideal operation due to a natural, slow drift due to changing laser properties of the input laser beam[3]. This beat frequency is responsible for inducing an acoustic wave within the AOFS medium, which changes the internal index of refraction and thereby adjusts the transmitted laser properties. By filtering the input signal, the AOFS adjusts the other beamline and allows for the stabilization of the CEP of the out-of-loop pathway. The beamline adjustment is equal to the input frequency, meaning that the input frequency should be equivalent to the carrier-envelope offset frequency f_{CEO}, which is why investigators chose to implement the in-loop beamline for the pump frequency of the AOFS. The f_{CEO} of the in-loop beamline was isolated and redirected into the AOFS, resulting in application of the proper pumping frequency for this system.

RESULTS AND INTERPRETATION

This work determined that the laser CEP can be stabilized through the application of feed-forward methods. This is due to the reduction in a parameter known as integrated phase noise (IPN), which is the adjusted integration of spectral density of phase fluctuation across the frequency domain. This accounts for the phase noise across the spectrum. The integration over the frequency domain is then multiplied by two, then its square root is taken to yield the IPN. This value was found to be 3.5 mrad between the frequencies of 1 Hz and 3 MHz.

Flicker noise significantly impacted these results below 1 Hz, leading investigators to report both the results above the 1 Hz cutoff. Because flicker noise arises from quantum properties, they are not mitigable through refining the frequency of the emitted laser pulses, but instead require an electronic chopper or zero-drift amplifier to be installed for flicker noise to be reduced[4]. Therefore, the presented results reflect a truncated reality to better reflect the improvements made by this system design rather than lead with the "complete" results including lower frequencies.

One possible avenue for improvement in future results collection would be the application of electronic signal processing techniques in the laser design to mitigate flicker noise. However, because signal choppers and zero-drift amplifiers currently exist to process electronic signals, they may not be directly applicable to photonic devices, though future creative developments may make this a feasible approach to further signal refinement[4]. This may include creating an optical chopper, which would have to physically block and unblock light at a very high frequency or developing a zero-drift amplification system in the laser source.

Additionally, variance was tested across the duration of the experiment. The rms phase jitter was found to be 2.9 attoseconds following data truncation. Authors additionally found a 0.16 Hz rms variance over the eight-hour period tested.

This work claims that these values represent significant advancements in CEP stabilization from the figures attained by previous work. This suggests that the method used in this review is an effective technique in Er:Yb:glass laser systems.

CONCLUSIONS

This paper concluded with the identification of the improvements made to contemporary knowledge of the limits of achievable CEP stability and demonstrated the effectiveness of feed-forward methods to this end. By extending application of this approach to the telecom wavelengths, perhaps application of this advancement may be found not only in optical frequency metrology, but also in the development of ultra-high data rate transmission systems, as refined pulses and control over CEP is necessary for high-fidelity data transfer.

However, this paper only provided results for the output of the system with the caveat that the pump power to the AOFS had to be manually adjusted by an operator every 30 minutes, which authors identified as a source of "large amounts of phase noise"[2]. This suggests that a further improvement to the apparatus could be made by the addition of an autonomous PID controller to adjust the pump power without human intervention. This would allow for continuous operation of the laser system beyond the eight hours attempted in this work and reduce the phase noise introduced by operator intervention.

In fact, this approach was applied in a subsequent paper authored by many of the same authors the year after. In Hirschman *et. al*, experimenters introduced a PID controller to apply a hybrid technique, implementing both a feed-forward conditioning as seen in this work and a feedback-receptive component, specifically a PID controller which adjusted the pump power to the system as necessary to support the steady operation of the system[5]. This system was tested for a period of 75 hours, significantly longer than the eight hours of this work, suggesting the feasibility of this hybrid approach in future work and experimentation[5].

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