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Review of "Hybrid Feed-Forward and Feedback Long-term CEP Stabilization of All-Solid-State Laser"

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Abstract: In this work, the authors are able to combine a feed-forward (FF) and feedback (FB) technique in order to maintain a carrier envelope phase (CEP) stable for 75 hours of an Er:Yb:glass mode-locked laser. The system has integrated phase noise of 14mrad which corresponds to about 11as of envelope jitter.

INTRODUCTION

The carrier envelope offset phase (CEP) is used to describe the breakdown of pulsed a puled laser's envelope; the CEP is important for any optical application where the instantaneous electric field has nonlinear dependence (i.e. arbitrary waveform generation and quantum control). However, measuring and maintaining a stable CEP remains difficult. In order to lock CEP, research has proposed FB and FF approaches. In the former, the laser cavity and and pump power are varied in order to make changes to phase and group velocities as well as the path length; these are usually implemented through PID controls. In the latter, an acousto-optic frequency shifter (AOFS) naturally modulates the phase pulse once they are coupled out of the mode-locked laser.

METHODS

The motivation for this work comes from previous implementations [2] that relied individually on FB and FF schemes. Additionally, by using manual adjustments, stabilization was reached for 75 hours but with the cost of introducing 150mrad of phase noise [3]. However, these works are done with Ti:sapphire laser fiber. Stabilization of all-solid-state-lasers such as Er:Yb:glass is more difficult; for the purposes of the paper, the system can be represented as a RLC circuit abstraction: the energy stored in the gain medium is C, the intracavity pulse energy translates into magnetic energy is L, and resistance is represented as R_{SA} and R_{OC} for the saturable absorber and output coupler respectively.

For short term stabilization FF techniques are used. The AOFS's first order diffracted beam is used by the laser's frequency comb in order to alter the CEO frequency. This, however, only works for short time scales because of the need to analyze the signal path from the laser. That is, the drifts change the CEO frequency causing the RF drive frequency to deviate from the center frequency of the AOFS. For longer term stabilization FB techniques are used. An error signal is generated from the AOFS frequency which is then fed into a PID controller. The AOFS frequency is the sum of the CEO frequency and local oscillator frequency; any deviation from their fixed sum is considered error. The error is converted to a voltage which in turn affects the center wavelength of the beam.

The system consists of seven blocks: the laser, the in-loop (IL) interferometer, the IL radio frequency (RF) conditioning, the FF AOFS system, the AOFS-based feed-forward system, the PID-based FB system, the out-of-loop (OOL) interferometer, and the OOL RF diagnostics.

RESULTS AND INTERPRETATION

The study is able to stabilize a Er:Yb:glass laser for 75 hours. Normally, FF approaches introduce low phase noise, however due to the integration of FB the phase noise jumps to 13.72 mrad. This is an insignificant increase for short term noise because it does not affect short term phase noise. Also, without FB's integration the system would not be able to maintain stabilization for over 30 minutes. The FB is responsible for constraining the AOFS frequency to less than tens of kHz (which is within the bandwidth of the AOFS). Now, in the long term, the drifts in the AOFS frequency are primarily dominated by the CEO frequency. This is mainly because the local oscillator frequency is fixed to a lower value (because of its role in FF stabilization). Thanks to FB, however, the drifts in CEO frequency are contained and have low rms jitter of 0.27kHz.

Besides the effect of 1/f noise, the results also consider the impacts of environmental factors such as temperature, humidity, and pressure. In fact, it was found that the time period of the largest shift in environmental factors also corresponds to the largest drifts in the frequency of the AOFS.

Mode-locked lasers present many parameters that exist for optimization. Changing the cavity length of the gain medium or the saturable absorber's reflectance are two good starting points of optimization. To this regard, this work incorporates a systematic way of varying these parameters. Recent work has also offered Deep-reinforcement-learning-based approaches [6]. They take a Yb-doped fiber laser system and apply the proposed Deep-Q algorithm which through iterative learning. The agent had four possible actions: ±0.1nm for width and ±0.1nm for central length, where width and length are for the fiber and wavelength respectively. The optimization space included two spectral filters and five output radiation characteristics: power and width of spectrum, noise, and duration at half maximum of autocorrelation function, amplitude of pulses. The DDQN algorithm [7] is applied to evaluate the agents' interaction with the environment and estimate an appropriate Q-function value- the optimal policy for maintaining a stable beam. The reward function for the agent is a ration between the average output power to the power of the noise. Training is done through multiple sessions where the agent performs multiple actions each time. Their results indicate that the agent was consistently able to find conditions for mode-locking (in each session). However, the system they used was greatly simplified to allow for easy training. The hybrid approach presented by Prof. Carbajo and his group is more robust to the outside environment and has increased complexity making it more applicable to real-world applications.

CONCLUSIONS

The control of CEP is crucial to the application of pulsed lasers to real-world applications. The FB and FF techniques used throughout past work can by combined into a hybrid workflow where they each independently help each other out. The FF portion is a short-term AOFS that modulates the beam downstream, and the FB portion adjusts the deviation from the AOFS frequency by using a PID controller. The FF technique is responsible for the CEO frequency; it can be maintained until the drift from the local oscillator plus CEO frequency is so large that the FB must take over. The FB then maintains the frequency of the AOFS through the control electronics. The FF system is thus always able to remained locked. Other potential drift sources were found in the environment; they potentially played a significant role in drifts in the frequency of the AOFS that were measured. The stabilization lasted for 75 hours and only included 13.72 mrad of phase noise.

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