Title

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Role of Upper-State Lifetime in Carrier-Envelope Phase Control of Er:Yb:glass Lasers

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Abstract: We critically review carrier-envelope phase stabilization of Er:Yb:glass mode-locked lasers, reproducing attosecond-level jitter and illustrating that millisecond-level upper-state lifetime limits bandwidth, forcing a hybrid feed-forward/feedback architecture and motivating fast intracavity actuation.

INTRODUCTION

Carrier-envelope phase (CEP) stabilization must increasingly deliver attosecond precision and indefinite duration at once, yet the two pull against each other: feed-forward control supplies the precision [7,8]; feedback supplies the longevity [5,6]. Demonstrations on Er:Yb:glass reconcile them in a hybrid feed-forward/feedback architecture [9,10], buying 75 hours of stabilization at a roughly fourfold short-term noise penalty (per integrated phase noise). We argue that penalty is largely required, simply because the millisecond upper-state lifetime common to rare-earth gain media sets a ceiling on feedback bandwidth, limiting feedback to correcting slow drift while fast phase noise must be externally corrected. By verifying the reported jitter and modeling the gain dynamics, we show that the FF/FB split is dictated by the gain medium rather than chosen; we then identify fast intracavity actuation as the route most likely to escape the trade-off, with implications for any ultrafast laser built on a long-lifetime gain medium, from optical clocks and timing networks to attosecond beamlines [1–4].

METHODS

We evaluate each paper by verifying reported stability metrics and then modeling the gain dynamics that bound them, all done in Python. The single-sideband phase-noise density $\mathcal{L}(f)$, in dBc, integrates to an integrated phase noise, then is converted to an rms timing jitter:

$$\Delta t = \frac{\mathrm{IPN}}{2\pi}\frac{\lambda}{c} \tag{1}$$

The feed-forward limitation follows from the AOFS group delay τ. A constant drive frequency produces a constant phase shift; a drifting offset Δf instead accumulates a CEP error:

$$\Delta\phi = 2\pi\,\Delta f\,\tau \tag{2}$$

The feedback limitation follows from the gain medium. Linearizing the class-B rate equations about steady state, the small-signal response of the output to pump modulation is a damped second-order (RLC-like) system:

$$H(s) = \frac{\omega_{\mathrm{RO}}^2}{s^2 + 2\gamma s + \omega_{\mathrm{RO}}^2}, \quad \omega_{\mathrm{RO}} = \sqrt{\frac{r-1}{\tau_2\tau_p}}, \quad \gamma = \frac{r}{2\tau_2} \tag{3}$$

where r is the pump ratio above threshold, τ_p is the photon lifetime, and τ_2 is the upper-state lifetime.

RESULTS AND INTERPRETATION

Converting the published integrated phase noise to timing jitter through Eq. (1) reproduces the quoted values to within rounding: 3.5 mrad maps to 2.9 as and 13.72 mrad to 11.3 as at 1.55 µm.

The feed-forward lock, however, is intrinsically transient. Evaluating Eq. (2) with the AOFS group delay $\tau \approx 2$ µs, a CEO drift of only ~80 kHz already accumulates a full radian of CEP error, and the hundreds of kHz of drift seen in free-running operation [9,10] corresponds to several radians. Because this one-radian threshold lies well within the AOFS ±2.5 MHz operating band, the beam remains apparently functional even as its phase information is lost; feed-forward is, thus, not sufficient on its own.

The natural remedy—slow feedback on the pump—is bounded by the gain dynamics of Eq. (3). For Er:Yb:glass (Fig. 1), the response is flat only up to a relaxation-oscillation resonance at 50–160 kHz, and that resonance is sharply underdamped ($Q \approx 500$–1600), forcing any stable loop to cross over far below it. The settling time $1/\gamma \approx 1$–10 ms confirms this: pump feedback tracks millisecond-level drift but not the kHz–MHz noise that feed-forward suppresses. The two controls are thus separated by three to four decades of bandwidth.

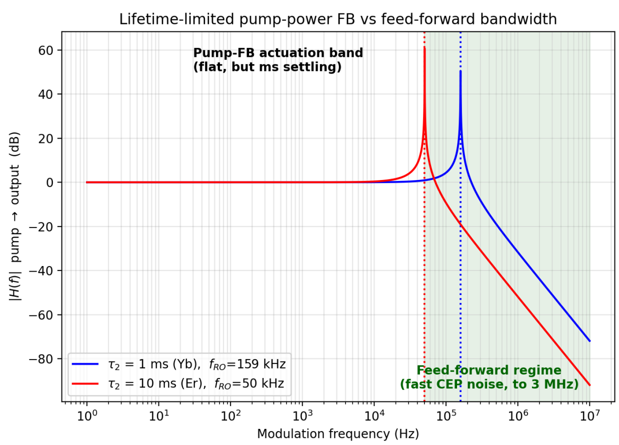

Fig. 1. Pump-to-output transfer function H(s) [Eq. (3)] for Yb-like and Er-like lifetimes. The flat response ends at the underdamped relaxation-oscillation resonance. Shading marks the kHz–MHz band left to feed-forward.

This division is not free. Closing the pump loop to hold the AOFS on band injects pump-power noise back into the cavity, and the short-term integrated phase noise rises fourfold, from 3.13 to 13.72 mrad (2.6 to 11.3 as) [10].

CONCLUSIONS

The hybrid architecture is therefore imposed by the gain medium rather than chosen, and its short-term penalty is intrinsic to the pump actuator. Because the bottleneck is the millisecond upper-state lifetime, feeding back to a fast intracavity element—a SESAM opto-optical modulator[11,12]—whose response is set by carrier dynamics could lift the feedback bandwidth into the feed-forward band, breaking the trade-off without the short-term cost.

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