Linewidth measurement of a home-built external cavity diode laser via self-heterodyne interferometry

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Precise characterization of laser linewidth, frequency noise and stability is essential for quantum technologies such as optical atomic clocks and precision spectroscopy, where linewidth limits coherent control and gate fidelity. The delayed self-heterodyne interferometer (DSHI) [1] splits the laser output, delays one arm beyond the coherence time and recombines the two, giving a Lorentzian beat note whose width is the intrinsic linewidth. For narrow lasers this requires fiber spools tens of kilometres long, and $1/f$ frequency noise broadens the spectrum and biases the result [2, 3]. The short-delay coherent-envelope method avoids this limitation [4, 5].

For a Lorentzian laser of linewidth $\Delta\nu$ and a fiber delay τ_d, the beat-note power spectral density is $S(\nu) = S_1 S_2 + S_3$, where S_1 is a Lorentzian of width $\Delta\nu$, S_3 is a delta function at the carrier, and

$$S_2 = 1 - e^{-2\pi\tau_d\Delta\nu}\left[\cos(2\pi\tau_d\tilde{\nu}) + \Delta\nu\,\frac{\sin(2\pi\tau_d\tilde{\nu})}{\tilde{\nu}}\right], \tag{1}$$

with $\tilde{\nu} = \nu - \nu_0$. For $\tau_d\Delta\nu \gg 1$, $S_2 \to 1$ and the conventional Lorentzian is recovered. For a short fiber, S_2 oscillates and $S(\nu)$ develops a coherence envelope whose extrema lie at offsets $\Delta\nu_m = (m+2)c/2nL$, fixed only by the fiber length L and index n. The power-independent amplitude difference between the first minimum and maximum, $\Delta S = 10\log_{10}(S_H/S_L)$, is

$$\Delta S^* = 10\log_{10}\frac{\left[\Delta\nu^2 + (\frac{c}{nL})^2\right]\left[1 + e^{-2\pi\frac{nL}{c}\Delta\nu}\right]}{\left[\Delta\nu^2 + (\frac{3c}{2nL})^2\right]\left[1 - e^{-2\pi\frac{nL}{c}\Delta\nu}\right]}, \tag{2}$$

a monotonic function of $\Delta\nu$ that is solved numerically from the measured ΔS [5].

The setup is an unbalanced Mach–Zehnder DSHI. The ECDL output (780 nm, 50 mW) is split at a 50:50 beam splitter; one arm passes through a 110 MHz acousto-optic modulator, which moves the beat note away from low-frequency environmental noise, and the other through 30 m of single-mode fiber ($n \approx 1.468$). The recombined beams are detected on a 380 MHz photodiode and the beat note is recorded on an electrical spectrum analyzer (40 MHz span, 40 kHz RBW) in real-time mode. Figure 1 shows the measured spectrum with the theoretical envelope fit; from ΔS at the extrema nearest the carrier we obtain a free-running linewidth of 487 kHz.

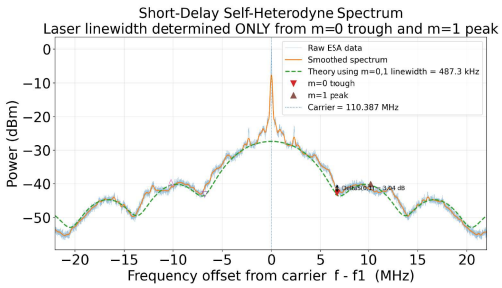

Figure 1. Measured self-heterodyne beat-note spectrum (30 m delay) with the coherence-envelope fit, giving a free-running linewidth of 487 kHz.

This short-delay method offers a simple, robust route to narrow-linewidth laser characterization for quantum technologies.

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References

[1] Okoshi T, Kikuchi K and Nakayama A 1980 *Electron. Lett.* **16** 630
[2] Richter L E, Mandelberg H I, Kruger M S and McGrath P A 1986 *IEEE J. Quantum Electron.* **22** 2070
[3] Mercer L B 1991 *J. Lightwave Technol.* **9** 485
[4] Huang S *et al.* 2016 *IEEE Photon. Technol. Lett.* **28** 759
[5] Zhao Z *et al.* 2022 *Opt. Express* **30** 30600

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