Multichannel optogalvanic frequency stabilization of diode lasers using an audio interface

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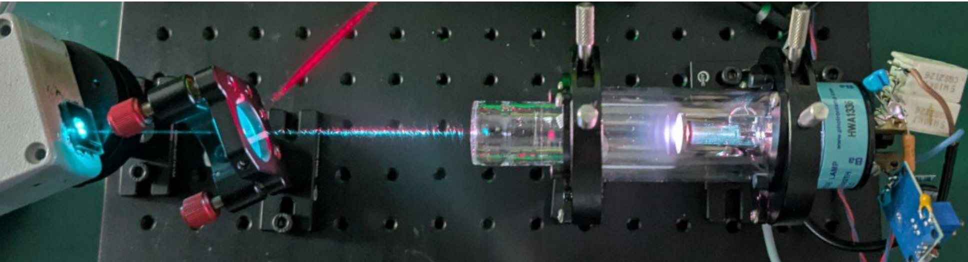

Why Johnny can't laser-cool

"You need this \$30,000 argon-ion laser that takes 15kW of three-phase power, and use it to pump this \$20,000 dye jet laser filled with toxic dye, then..."

"You need two ECDLs at \$35,000 each, with a \$40,000 driver, and buy a license for the locking feature. Don't forget optical isolators at \$3,000 each, they'll make your life easier. Then, ..."

"You can make the ECDLs yourself if you are on a budget. You just need to buy this rare laser diode that shows up once every five years at around \$4,000 from specialty resellers. Don't kill it with ESD or optical feedback!"

"We offset-lock it from a \$2,500 tellurium vapor cell held at 550C..."

"Use this \$50,000 Fizeau-Snyder wavemeter to determine which resonance of this \$20,000 optical cavity made of export-controlled and patented ULE® glass you are on, then use a \$5,000 AOM with driver for fine adjustment of the optical frequency..."

What if there was another way?

- Unlike "research-grade" hardware, telecommunication hardware has to perform.
- $200 buys you a single-frequency laser diode, tunable by at least 2nm, with 10MHz linewidth.
- $800 says your linewidth is down to 100kHz.
- All in small and rugged "butterfly" packages with fiber output.
- Cooling and repumping transitions of typical ions have natural (quantum-limited) linewidths around 5-25MHz.

Is it really that hard?

Oh, the wavelength!

- Telecom lasers are in the 1270-1600nm region only.[1]
  No interesting transitions ☹
- Frequency conversion is difficult and/or expensive.[2]
- Visible Fabry-Perot diodes without EC – how bad are they?

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[1] Because the industry doesn't care, or because DFB diodes are hard at visible wavelengths? Laser diode experts please enlighten me.

[2] Cheap DPSS pointers can be hacked for SFG, but this will be for another talk. See the PoC on 193THz.com if you're curious.

FP diode pathologies

- Multimode: ”single mode” in FP diode datasheets really means ”single spatial mode”. ☹ ☹
- SSM diode resonances are separated by many dozens GHz: ☺
  - Large FSR + homogeneous broadening = many diodes single-frequency just above threshold
  - Ion typically transparent to any additional frequencies
  - Beware of mode hops
  - Beware of mode partition noise
  - Beware of hysteresis
  - Easy to see and can be kept in check by diffracting collimated beam on holographic grating
- Linewidth (one mode): dozens of MHz. Not great, not terrible.

To EC or not to EC?

- EC adds complexity, cost, and vibration sensitivity. ☹ ☹ ☹
- EC reduces linewidth. ☺
- EC increases optical power available in a single frequency. ☺
- Some diodes behave well with EC.
- Some diodes behave well without EC.
- Testing a diode takes longer with EC. ☹
- Many experiments done by holographers, see `http://hololaser.kwaoo.me`.

Optogalvanic stabilization

- Main problem: keeping laser optical frequency at a setpoint within spectral line of interest.
- Using the ionized species as reference:[3] hollow cathode discharges produce large numbers of ions with "brute forcing" of all quantum states. $50 off Taobao.
- Hollow cathode lamp (HCL) spectral lines are sufficiently far apart that inexpensive grating spectrometer can resolve them. NIST ASD gives you the exact wavelengths.
- Optogalvanic effect: when the laser drives a transition in the HCL plasma, the plasma impedance varies by a small amount.
- No need to use expensive "see-through" lamp.
- But plasma discharge is noisy.

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[3] Neutrals in MOTs need hundreds of mW of single-frequency laser power, which cannot be done with free-running FP diodes. This is why we focus on ions.

Lock-in amplifier to the rescue

- Most noise is at DC (1/f).
- Solution: Modulate the laser then look for an optogalvanic signal in a narrow band around the modulation.
- Since modulation is known, bandwidth and noise can be reduced indefinitely,[4] at the expense of response time.

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[4] In a perfectly linear (ideal) system.

The DSP lock-in amplifier

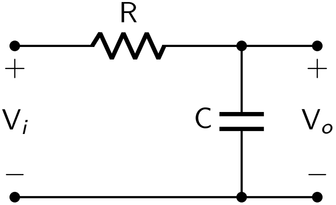
$i(t)$: (real) input signal, $\mathscr{L}()$: low-pass filter, $\omega_i \approx \omega_m$

$$
\begin{aligned}
&\mathscr{L}(i(t) \cdot e^{-i\omega_m t}) \\
&= \mathscr{L}(A_i cos(\omega_i t + \phi_i) \cdot e^{-i\omega_m t}) \\
&= \mathscr{L}(A_i \frac{e^{i(\omega_i t+\phi_i)} + e^{-i(\omega_i t+\phi_i)}}{2} \cdot e^{-i\omega_m t}) \\
&= \frac{A_i}{2}\mathscr{L}(e^{i((\omega_i-\omega_m)t+\phi_i)} + e^{-i((\omega_i+\omega_m)t+\phi_i)}) \\
&\approx \frac{A_i}{2} e^{i((\omega_i-\omega_m)t+\phi_i)} \\
&\approx \frac{A_i}{2} e^{i\phi_i}
\end{aligned}
$$

Both magnitude A_i and phase ϕ_i of the carrier are extracted from the noise.

A simple DSP low-pass filter

First-order analog RC low-pass filter with bandwidth $\frac{1}{2\pi RC}$:



Its time-domain behavior is determined by the differential equation:

$$\frac{dV_o(t)}{dt} = \frac{1}{RC}(V_i(t) - V_o(t))$$

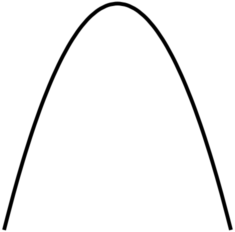
Similar behavior is easy to implement in a DSP:

$$V_o(n+1) = V_o(n) + k(V_i(n) - V_o(n))$$

Just cascade the equation for a higher-order filter (steeper rolloff).

Lock-in optogalvanic spectroscopy

- Many experiments use chopper wheel as modulator.
- But with a diode laser, one can do better!
- Use optical frequency dependence on current ("chirp").
- Spectral line converts FM to AM.
- Phase tells you which side of the line you are.
- Allows locking the laser to the top of the line.

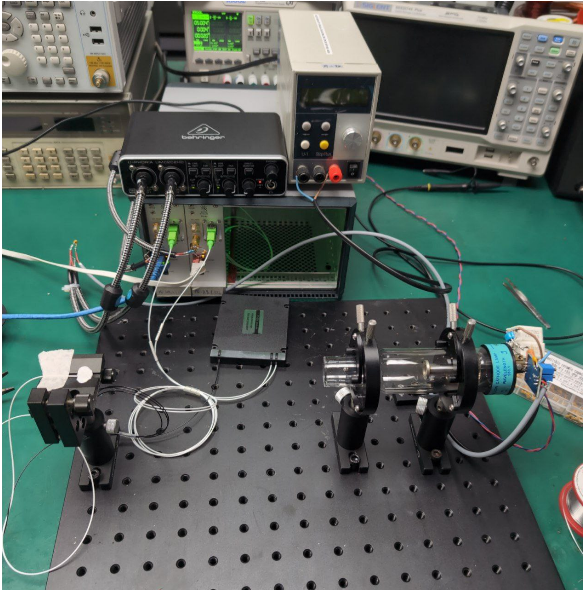


Soundlocker

- Cheap DAC/ADC: USB audio interface (Behringer UMC202HD, 2x192kHz 24-bit) with USB isolator.
- Lesser soundcards might work, motherboard audio quality varies greatly (but always inferior to UMC202HD in my tests).
- Software written in C++ with ImGui and OpenBSD sndio.
- DDS to modulate laser, DSP lock-in as above, GUI for setup and testing, control loop.
- Open source – `https://git.m-labs.hk/sb10q/sndlock`

Lanthanum III test

Transitions aligned to CWDM grid (1390nm/1410nm), hyperfine structure.



Lanthanum III test

▼ Demodulation

Channel 0

multiplier: ● f ○ 2f ○ 3f

8.210 LPF BW

0.554 principal angle

plot: ☑ hold ● magnitude ○ phase ○ principal

Channel 1

multiplier: ● f ○ 2f ○ 3f

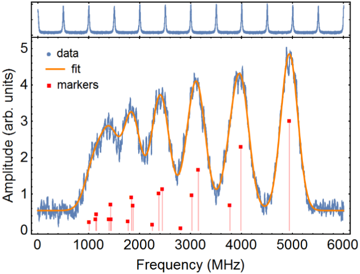
8.742 LPF BW

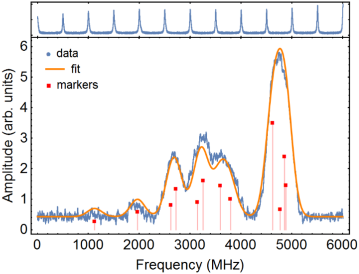
2.356 principal angle

plot: ☑ hold ● magnitude ○ phase ○ principal

Soundlocker on $100 UMC202HD, 2x$200 telecom diodes
9mW laser power, single pass.

Lanthanum III test





Olmschenk (2018):

traditional lock-in ($6,500 SRS?), $$$$$ ECDL+BOA

60/50mW laser power, 5/10 passes.

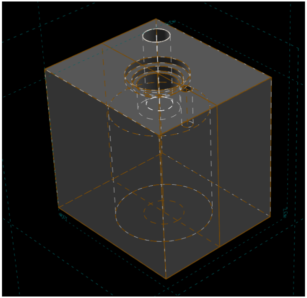
(Shape is different due to AM with chopper vs. FM and magnitude plot)

Why not a lanthanum ion trap?

- Narrow natural linewidths (kHz): low photon scattering rate.
- 1400nm is completely invisible.
- 1400nm cameras are very expensive and generally awful.
- Complicated hyperfine structure requiring many lasers.
- Barium looks better: no hfs, lots of scattering, near peak eye sensitivity, well-studied.

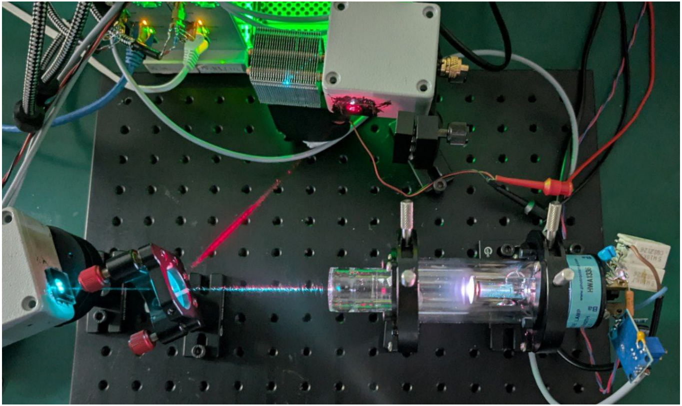
Building simple tunable diode lasers

- SHARP wavelength-selected diode for 493nm, DVD writer diode for 650nm.
- Machined copper mount (PCBWay), diode soldered with indium/tin, collimator, venting hole, TEC, thermistor.
- Into IP68 die-cast box, sealed with Apiezon Wax W.
- Two ways to avoid condensation on cold diode:
  - silica gel, DHT22 sensor for monitoring.
  - vacuum (from air conditioning service gear), open light bulb as Pirani gauge: better thermal insulation, but less forgiving.



Locking to Barium II

- 493nm and 650nm beams combined on dichroic mirror.
- Orthogonal modulation frequencies from stereo channels ☺
- RAM and photoelectric effect at 493nm adds constant signal, simply subtracted.
- Both lasers locked to single lamp with TEC feedback!



What comes next

- Using harmonics to improve SNR and lock accuracy.
- Building the world's cheapest laser-cooled ion trap!