Robust Dynamic Laser Cleaning for Microwave-to-Optical Transduction via State-Aware Control and Hardware-Software Co-Design

Opening: Enabling Repeatable Lock–Unlock Operation in Multi-Cavity Filter Systems

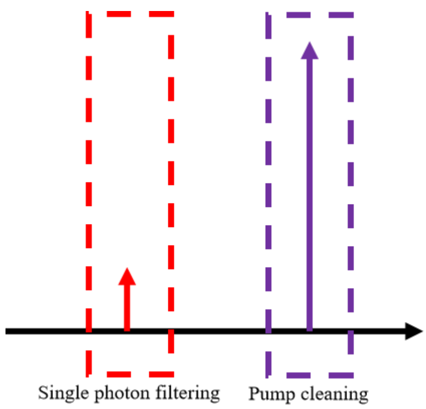
Reliable microwave-to-optical transduction measurement at the single-photon level requires stable suppression of the optical pump. This demands not only robust laser-cavity locking, but also **repeatable, low-noise transitions between locked and unlocked states** to enable background-free signal acquisition without sacrificing long-term stability.

On commercial locking platforms, however, such dynamic operation is often treated as an auxiliary feature. In **thin-linewidth, high-extinction cavity systems**, this assumption fails: during repeated lock–unlock cycles, millivolt-level offsets errors and broadband noise in **high-voltage actuation paths** convert into large effective detuning, causing loss of lock on cavity PZTs. These failures come not from inadequate feedback gain or poor PID tuning, but from the interplay between control timing, electronic noise, and the physical response of piezo-actuated cavities.

To address this, I treat the laser-cleaning stage as a **state-dependent control system**. Rather than optimizing feedback parameters in isolation, I adopt a hardware–software co-design approach that jointly considers actuation precision, noise filtering, and timing-aware control logic. This enables robust multi-cavity laser cleaning under repeated dynamic operation and achieved a **208.68uV noise RMS within 100KHz** in the lock/unlock feedback loop.

Objective:

Pump Filtering across Locking-Measurement Cycles



Before the detection of the signal photons, the pump should be fully filtered out.

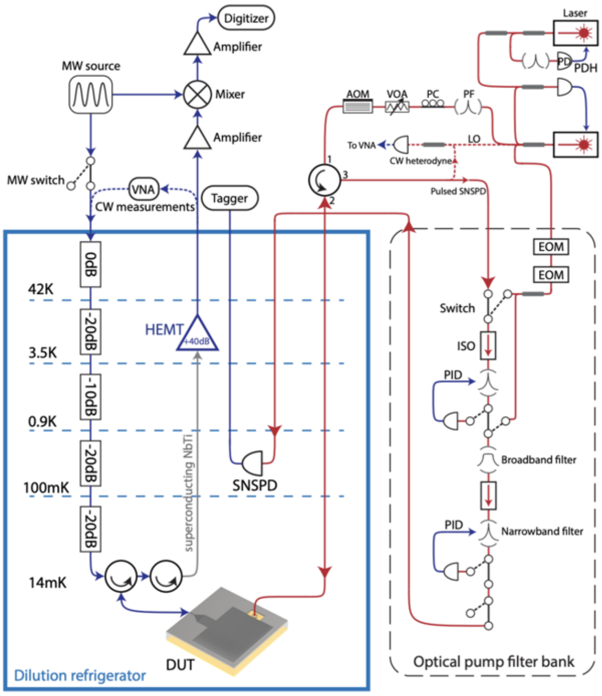
Main challenge:

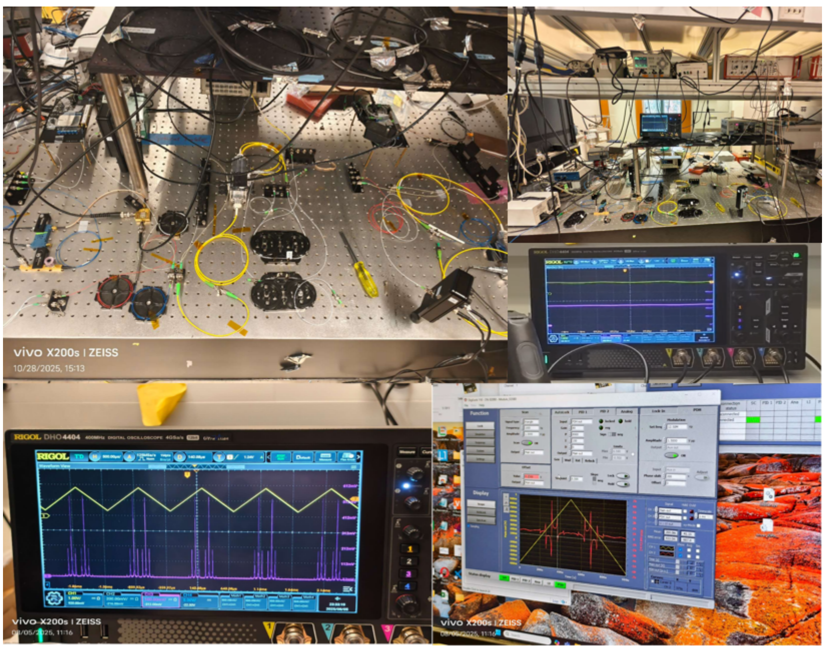
We need to **stabilize transmission in a free-running state, rather than a locked state**. Because during the free-running measurement window, feedback will contaminate the signal.

Multi-cavity pump filter bank

Pound–Drever–Hall (PDH) Locking

I implement laser–cavity stabilization using the **Pound-Drever-Hall (PDH)** technique. I apply phase modulation via an electro-optic modulator (**EOM**) and demodulate the reflected signal to generate a dispersive error signal. I feed this signal back to a piezoelectric transducer (**PZT**) controlling the cavity length, enabling robust locking with constant feedback polarity. Compared to transmission-based locking, PDH is resilient to cavity drift and well suited for the dynamic lock–unlock cycles required in laser cleaning.



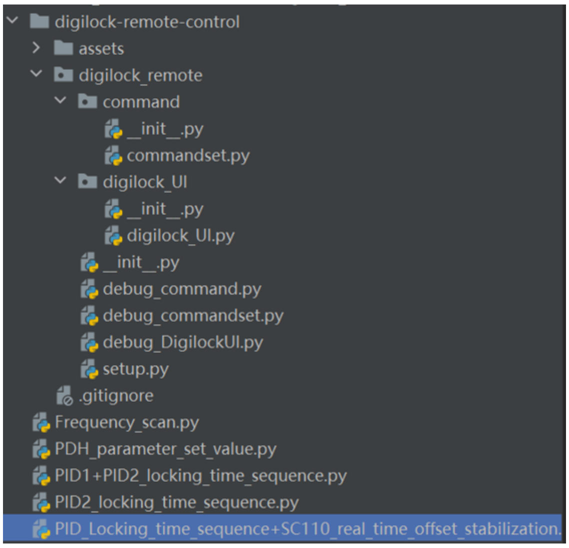


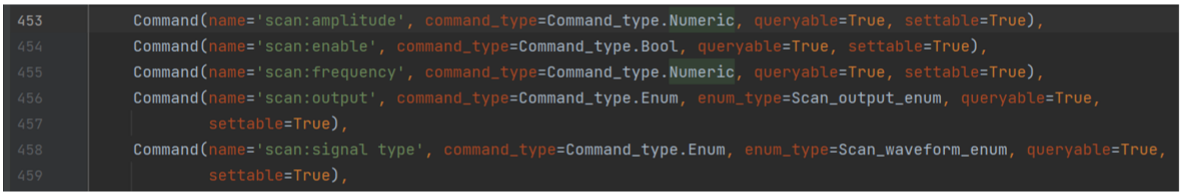
1. Control Strategy: State-Aware Locking Software Development

- Commercial controllers assume static lock
- Dynamic operation violates implicit assumptions

Using Python' s telnetlib, I developed a DigiLock 110 Control Interface:

- Established 310+ full-featured DigiLock commands ()
- Unified command parser with consistent syntax





Functional Modules for laser cleaning system

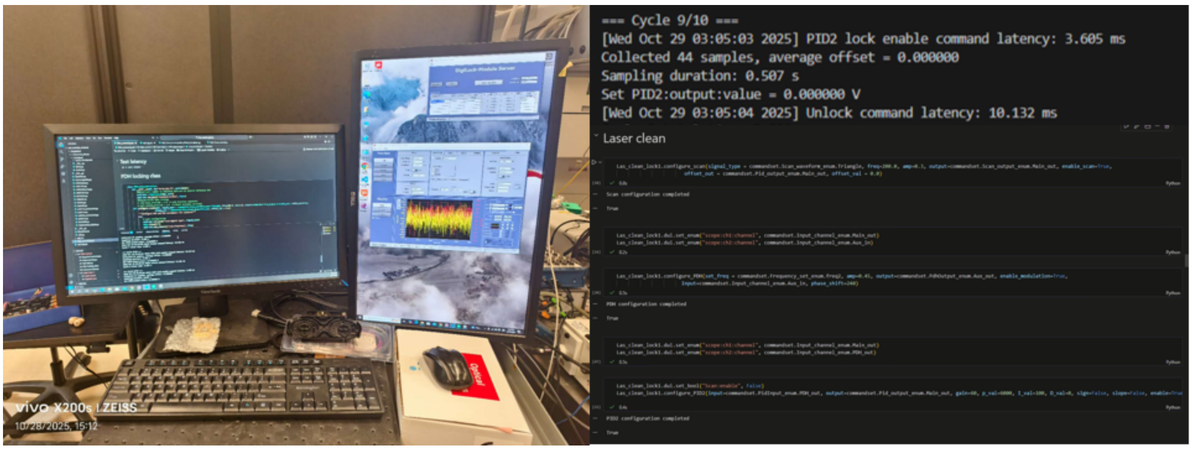
- PID1 + PID2 dynamic locking sequence
- PID locking time sequence with SC110 real-time offset stablization
- Developed a **sample-to-hold algorithm**.

```
# logic for dynamic lock-unlock control with offset holdback
enable_lock()
wait(t_lock - t_sample)

offset_avg = mean(read_offset(t_sample))
set_hold_value(offset_avg)

disable_lock()
wait(t_unlock)
```

These strategies significantly improved the lock/unlock stability.

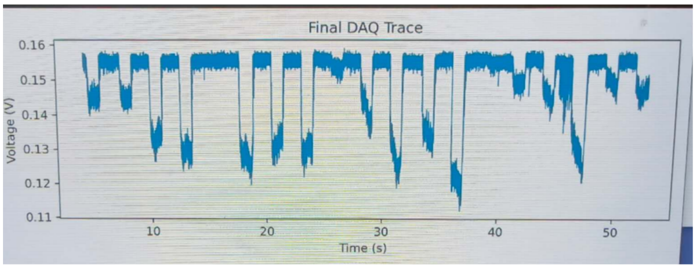


- This strategy prevents abrupt voltage jumps that would otherwise detune the cavity. My interface runs on the lab computer with **10 ms latency**, enabling fully automated laser cleaning. As a result, I reduce the total cleaning time from **~30 minutes to under one minute**.

2. Limitation of Commercial High-Voltage Outputs Hardware

1. A ~3 mV random error
2. Substantial output noise

The sample-to-hold routine computes the correct offset, but the SC110 outputs an incorrect voltage to the cavity PZTs, causing the cavity to **immediately fall out of lock** during the unlock phase.



(3s / 2s lock / free-running cycle)

Purchasing a More Expensive Controller Is Not a Solution

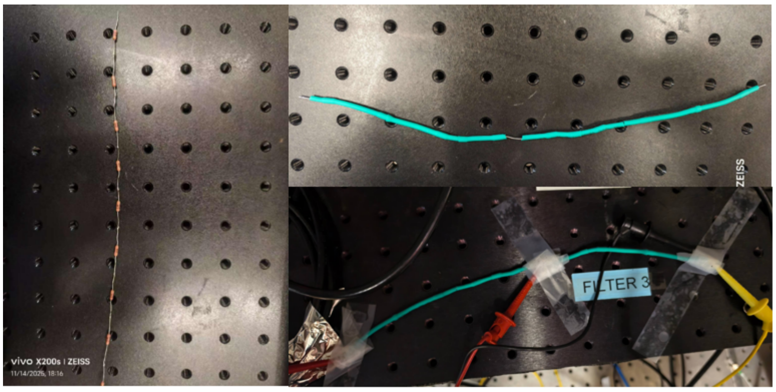
The instability originates from control-path mismatch and output noise, not from insufficient controller performance. Replacing the controller with a higher-end unit would not resolve the system-level failure mode and would obscure, rather than fix, the underlying dynamics.

3. Custom Summing and Filtering Architecture

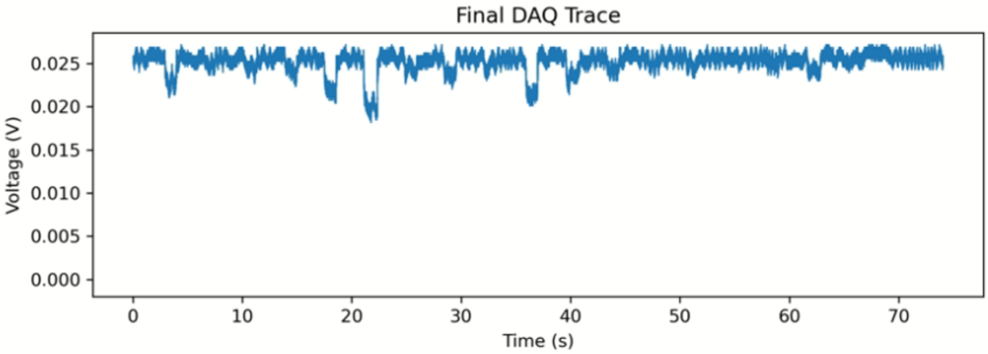
SC 110 Output Error - Solution 1: Voltage Divider+Noise Filtering

The SC 110 output range is 150 V, while PZT control requires only 65 V

- Soldered a voltage divider using 50-kΩ resistors
- **Impedance matching**
- This not only proportionally reduced the voltage error to **1.2 mV**, but also acted as a low pass filter, which further reduced the sharp peaks of transmission, as shown in the pictures.



Voltage Divider and Filtering Result



SC 110 Output Error - Solution 2: Inverting Summing Amplifier

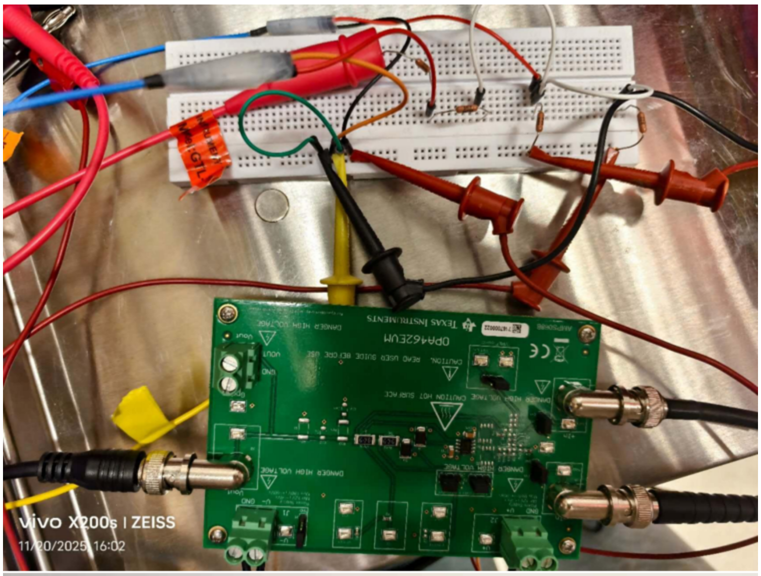
I notice that the Digilock **Main Out** port does not suffer from the same DC offset error as the SC110. To exploit this, I build an **inverting summing amplifier** that combines:

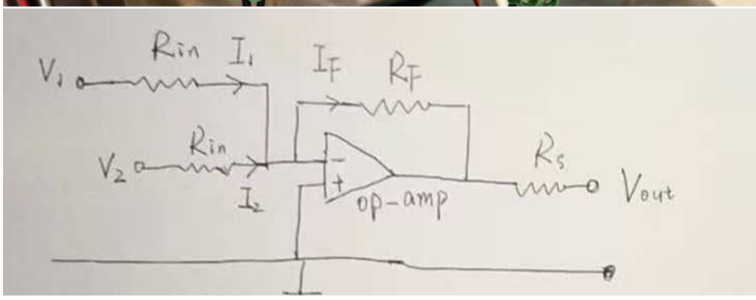
Using a summing amplifier to add SC110 output with Main out, SC110 provide offset and Main out provides feedback to the cavity PZTs.

High-Voltage Inverting Summing Amplifier (OPA462) + Voltage Divider

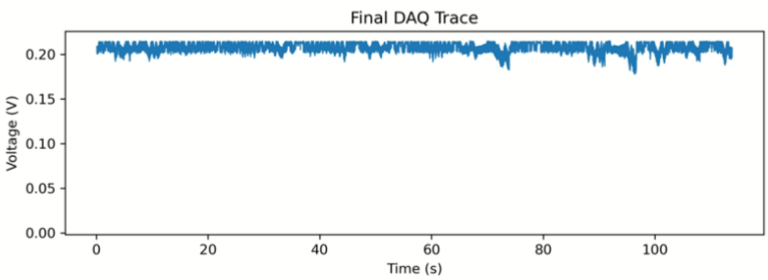
$$R_F = R_{\text{in}} = 47.5k\Omega, \qquad R_s = 49.9k\Omega \qquad\qquad I_1 = \frac{V_1}{R_{\text{in}}}, \qquad I_2 = \frac{V_2}{R_{\text{in}}}.$$

$$V_{\text{out}} = -R_F\left(\frac{V_1}{R_{\text{in}}} + \frac{V_2}{R_{\text{in}}}\right) \qquad\qquad V_{\text{out}} = -(V_1 + V_2)$$





Results:



Quantified the resulting RMS noise.

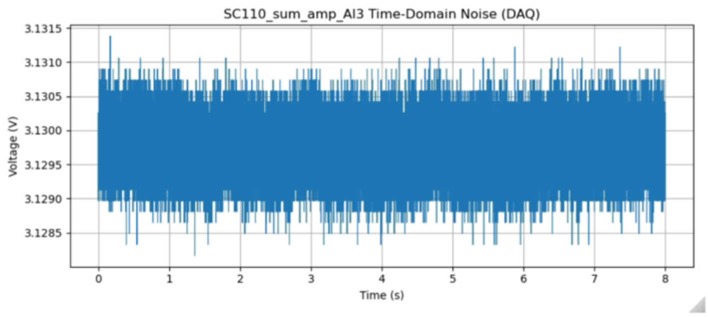
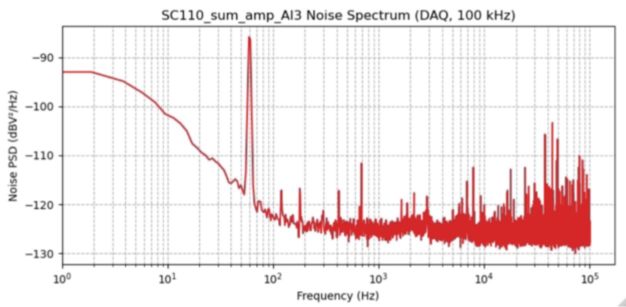


Figure 32



- **Noise RMS within 100KHz is 208.68uV**.
- Stable transmission during **lock 1s+free running 4mins cycles**
- Reliable cycling between **1-second lock and 4-minute unlock phases**.

Conclusion and Implications

I demonstrate that robust dynamic laser cleaning for microwave-to-optical transduction cannot be achieved through feedback tuning alone. Instead, it requires co-design of **control logic, actuation precision, and hardware interfaces**.

By reframing laser cleaning as a **state-dependent control problem**, I identify that lock failure originates from high-voltage output noise and control-path mismatch, not PID limitations. I then develop a timing-aware software framework and integrate custom analog filtering to enable repeatable lock-unlock cycles with stable free-running transmission.

The resulting system supports **fully automated laser cleaning** with millivolt-level actuation stability, reducing experimental overhead from tens of minutes to under one minute. More broadly, this work shows that **dynamic stability in quantum photonic systems emerges from integrated hardware-software design**, not from black-box controllers. In such experiments, the control system must be treated as an intrinsic part of the physical system.