RedWave Labs

APPLICATION NOTE

Laser Frequency Stabilisation for Compact Quantum Systems

System architecture, stability and cold-atom demonstration

Abstract
This application note introduces RedWave Labs' laser-frequency stabilisation platform for compact quantum systems. It explains the line-lock and offset-lock architecture, shows an integrated implementation with performance characterisation, and presents its application to cold-atom generation on a compact gMOT platform.

Document number	AN-001
Revision	0.1
Date	15 July 2026
Author	J. Waller
Keywords	Laser Stabilisation, Line-lock, Offset-lock, Rubidium, Quantum Technology, Cold Atoms

www.redwavelabs.com

Contents

1 Introduction

Cold-atom experiments depend on laser systems that are not only tunable, but stable over the timescales required for trapping, cooling and interrogation. In compact or deployable platforms, that requirement has to be met without relying on fragile laboratory infrastructure or frequent manual adjustment.

RedWave Labs supports this need in two complementary ways. For customers building their own systems, we supply individual subsystems, including laser drivers, temperature controllers and control electronics, together with the Quantum Control & Integration Platform for OEM integration. For customers who want a more complete solution, we also offer a fully integrated laser stabilisation instrument incorporating the laser drivers, control PC, lasers and optics required to implement the locking architecture as a ready-to-deploy platform.

This application note focuses on how that stabilisation platform is used to lock lasers to atomic references and how the resulting stability supports cold-atom generation and downstream measurements.

1.1 Scope

This document covers the following:

- the role of line-lock and offset-lock architectures in a cold-atom laser system;
- how the technology can be adopted either as an integrated stabilisation instrument or as OEM subsystems;
- the practical operating principle of the stabilisation loop and its system interfaces;
- representative wavemeter-based measurements of line-lock and offset-lock performance;
- an integrated instrument implementation and its use for cold-atom generation on a compact gMOT platform.

2 System architecture

The laser stabilisation system comprises two coupled functions: a line-lock that locks a reference laser to an atomic feature, and an offset-lock that transfers that stability to additional lasers at programmable detunings. In a cold-atom system, this architecture allows a single absolute reference to generate stable cooling and repump frequencies. The overall architecture of one such implementation is shown in figure 1.

2.1 Line-lock configuration

The line-lock holds the laser on an atomic transition, providing an absolute frequency reference and reducing sensitivity to environmental perturbations.

The operating principle of the line-lock is illustrated in figure 2. The laser frequency is modulated about the chosen spectral feature, producing a corresponding modulation in the detected optical signal. Demodulation at the same frequency generates a dispersive error signal with an approximately linear region around the target frequency. The sign of that signal indicates which side of the resonance the laser is on, while its magnitude sets the correction applied by the controller. Fast and slow actuator paths are used to reduce short-term disturbances and maintain long-term stability. The C230 line-lock controller implements these functions in a compact package.

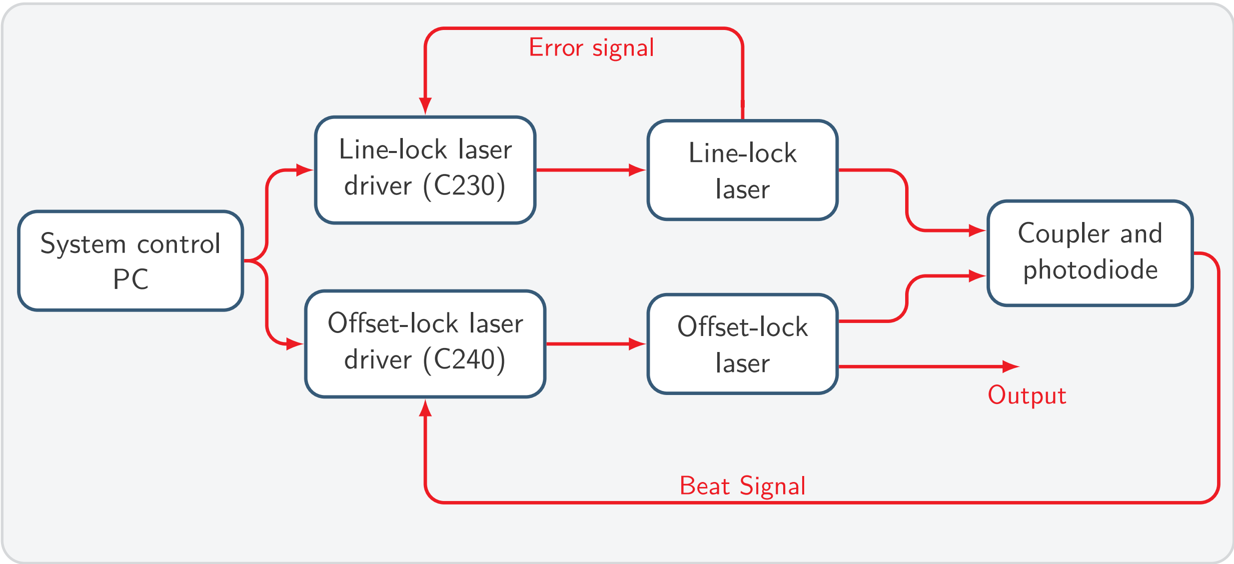


Figure 1: High-level architecture of the combined line-lock and offset-lock system used to generate stable cooling and repump lasers from a common reference. For simplicity only one offset-lock is shown.

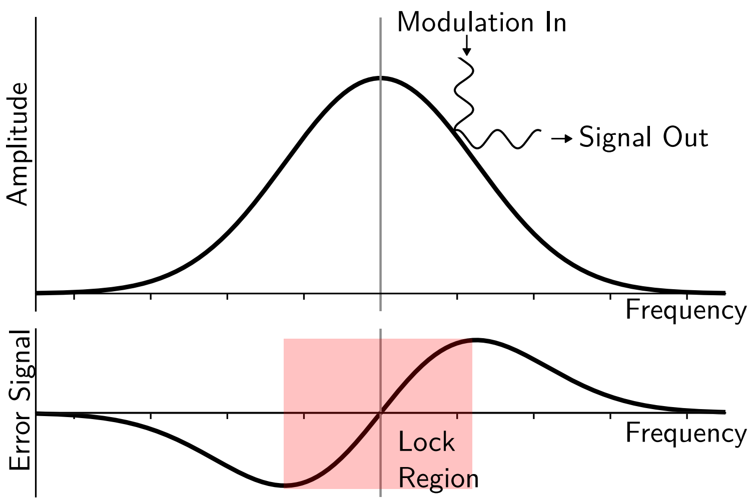


Figure 2: Measured line-lock response. The spectroscopy feature is converted into a dispersive error signal whose zero crossing defines the lock point.

2.2 Offset-lock configuration

The offset-lock transfers the stability of the line-locked laser to an arbitrary frequency offset. This enables the generation of cooling and repump lasers at suitable frequencies for cold-atom experiments.

In operation, a small fraction of light from the offset laser is combined with light from the reference laser on a fast photodiode to produce an optical beat note. That beat note is divided to a suitable frequency range and compared against the desired offset within a phase-locked loop. The resulting error signal drives the offset laser's current actuator, forcing the beat frequency, and therefore the optical detuning, to remain locked to the programmed value.

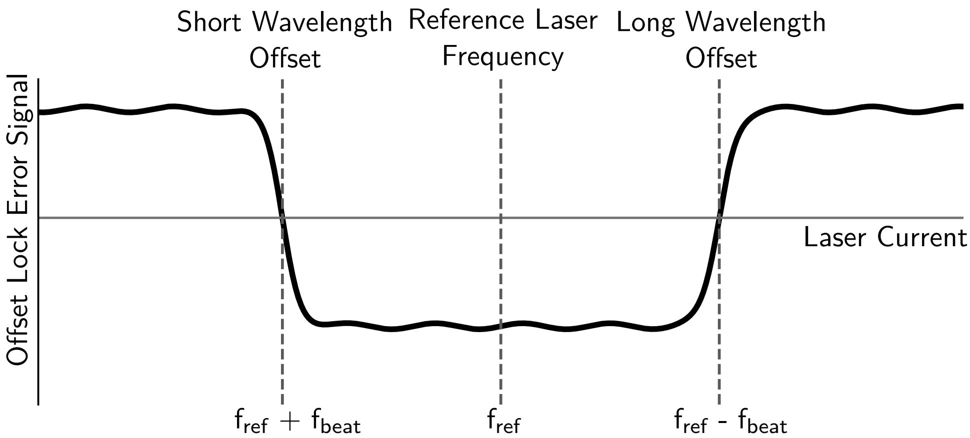
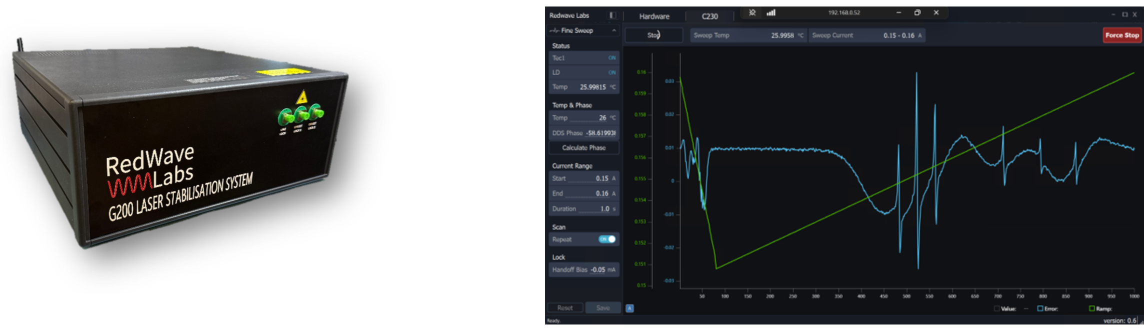


Figure 3: Measured offset-lock response. The PLL forces the beat note to the target value, allowing stable operation above or below the reference frequency.

As shown in figure 3, the zero crossing defines the desired frequency offset. By selecting loop polarity, the system can support lock points above or below the reference laser frequency. The C240 offset-lock controller includes the same general fast-correction and offload strategy used in the line-lock path, helping the loop remain within actuator range over long timescales.

2.3 Standalone and integrated operation

The line-lock and offset-lock drivers are available either as standalone USB-controlled modules or as part of an integrated laser stabilisation system that combines lasers, optics and control electronics. The integrated system also includes a Python application for system control and monitoring, allowing the user to create, control and monitor locked lasers for experimental use. An example of the integrated hardware and software is shown in figure 4.



(a) Integrated laser stabilisation instrument.

(b) Control and monitoring software interface.

Figure 4: Example integrated implementation of the laser stabilisation platform, combining instrument hardware with a dedicated user interface for setup, lock control and monitoring.

2.4 Typical instrument configuration

Parameter	Value
Operating wavelength	780 nm (795 nm available on request)
Configuration	1x Line-lock, 2x Offset-lock
Reference medium	Rubidium vapour cell
Offset-lock Detuning Range	± 6.8 GHz
Output power	10 mW per channel
Output interface	Polarization-maintaining optical fibre

3 System implementation, stability and cold-atom demonstration

This section presents an integrated implementation of the laser stabilisation platform, wavemeter-based stability measurements, and its initial use for cold-atom generation.

3.1 Instrument Architecture

A more detailed diagram of the line-lock module within the laser stabilisation instrument is shown in figure 5.

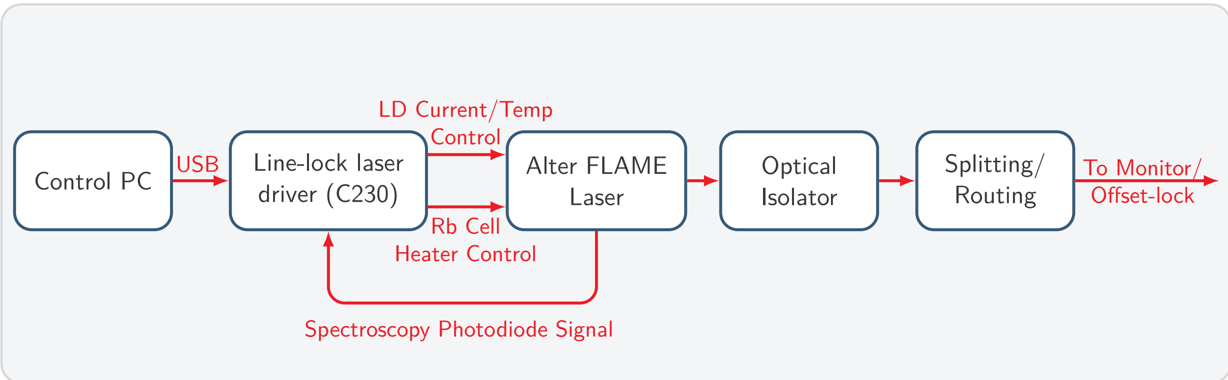


Figure 5: High-level architecture of the experimental line-lock instrument, showing the control interface, integrated laser module and downstream optical routing.

In this implementation, an Alter FLAME laser provides the source for the line-lock module and integrates a Doppler-free spectroscopy setup with a rubidium reference cell inside the laser package [1]. This allows tight integration with the C230 line-lock laser driver.

To support the high-power, detuned cooling and repump lasers required in cold-atom experiments, two offset-lock channels are integrated into the instrument, each having the architecture shown in figure 6.

The optical system used to combine and route the lasers is entirely fiberised, reducing sensitivity to ambient effects and minimising the risk of alignment drift over time.

The laser drivers are mounted on a quantum system universal platform, which contains an embedded control PC running the laser lock application. The platform also incorporates fast ADCs and DACs for experimental control and data logging.

The whole electronic and optical system is enclosed in a 19-inch, 3U rack enclosure.

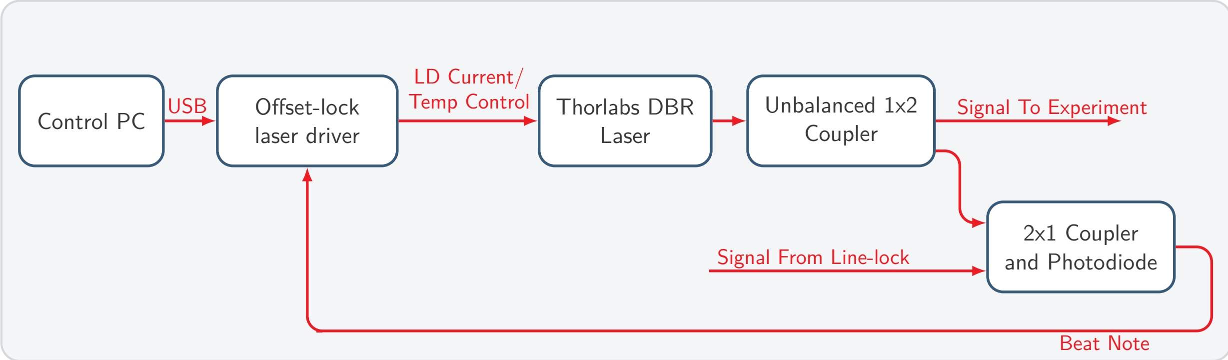


Figure 6: High-level architecture of the experimental offset-lock instrument, showing the laser channel, optical tap and beat-note detection path.

3.2 Performance of the laser stabilisation system

3.2.1 Spectroscopy Data

The spectroscopy data were acquired by sweeping the laser current in open-loop mode and recording the resulting error signal. Figure 7 shows the spectroscopy around the $^{87}\mathrm{Rb}$ D_2 transitions originating from the $F = 2$ ground-state manifold, with the lines annotated using a simple linear current-to-frequency fit.

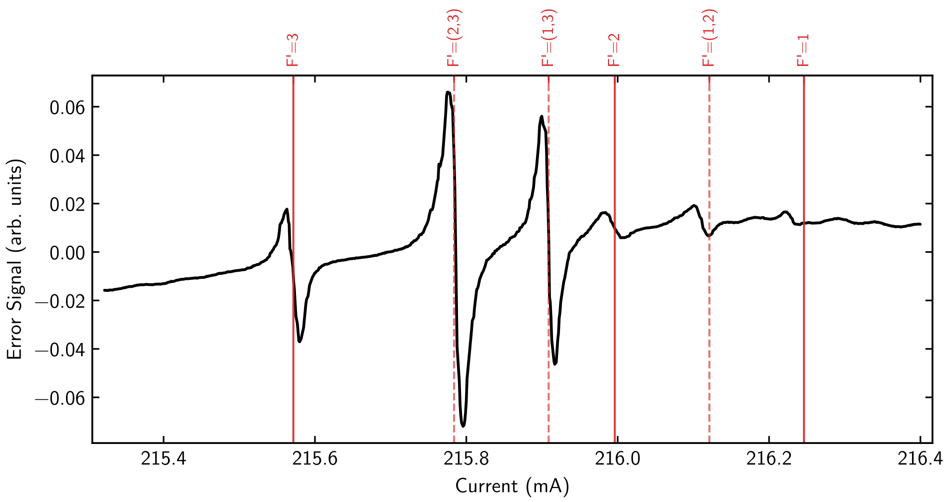


Figure 7: Line-lock spectroscopy around the $^{87}\mathrm{Rb}$ D_2 transitions from the $F = 2$ ground-state manifold, showing Doppler-free transitions. Direct transitions are shown as solid lines and crossovers as dashed.

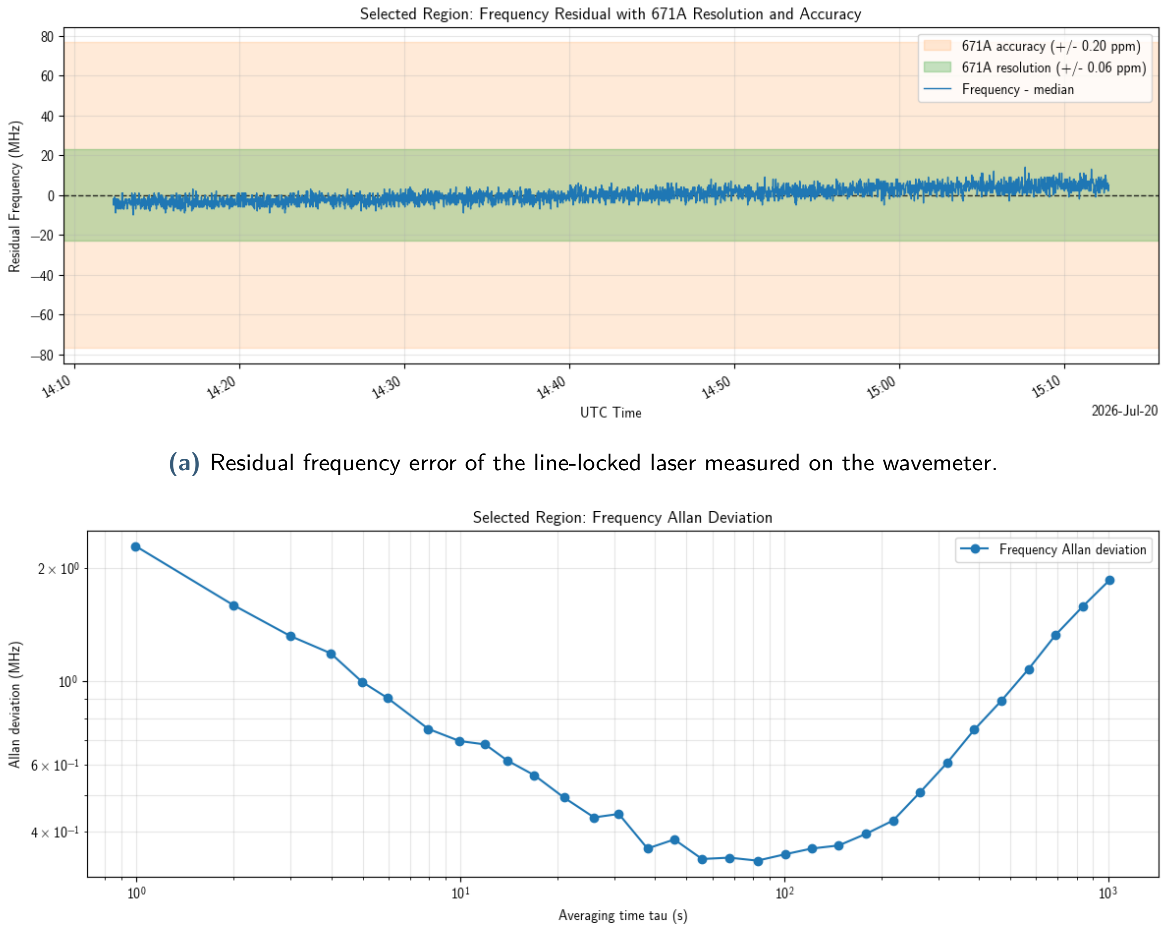
3.2.2 Line-lock Performance

Once the spectroscopy had been acquired, the system was locked to the $^{87}\mathrm{Rb}$ D_2 $F = 2 \rightarrow F' = 3$ transition, and the laser frequency was recorded using a Bristol 671A wavemeter.

The median measured frequency of this transition was found to be 384 228 119.000 MHz. This is consistent, within wavemeter uncertainty, with the tabulated transition frequency reported by Steck [2]. The residual over a one-hour period is shown in figure 8a.

As shown in figure 8a, the measured residuals are significantly below the stated accuracy of the Bristol 671A wavemeter [3], so the measurement is likely limited by the wavemeter rather than the lock itself. The long-term drift in the measured frequency is likely due to ambient drift in the wavemeter, and requires further investigation.

The Allan deviation of the data collected is shown in figure 8b. This indicates that any instability is white-noise-dominated up to averaging times of approximately 100 s, after which drift begins to dominate.



(a) Residual frequency error of the line-locked laser measured on the wavemeter.

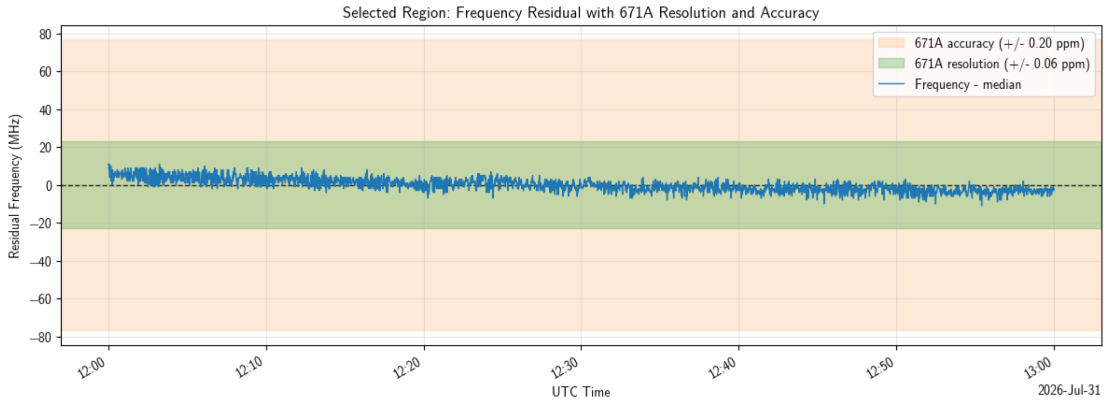
(b) Allan deviation of the line-lock frequency.

Figure 8: Wavemeter-based line-lock performance.

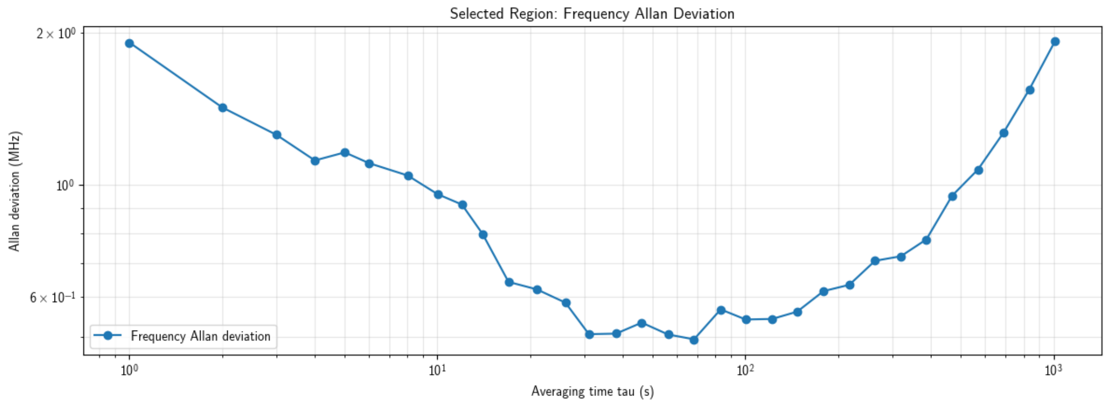
3.2.3 Offset-lock Performance

The same measurement was then repeated for the offset-lock channel. For this test, the line-lock laser was locked to the $^{87}\mathrm{Rb}$ D$_2$ $F = 2 \to F' = (2, 3)$ crossover feature, and the offset-lock frequency was set to +123.326 MHz. This corresponds to a detuning of 10 MHz from the main cooling transition, matching the cooling-laser operating point used for Doppler cooling of $^{87}\mathrm{Rb}$.

The resulting residual frequency error and Allan deviation are shown in figures 9a and 9b. Together, these results show that the offset-lock channel transfers the stability of the line-lock reference to a second laser at the required programmed offset. As with the line-lock measurement, the observed performance is limited by the resolution and long-term stability of the wavemeter.



(a) Residual frequency error of the offset-locked laser measured on the wavemeter.



(b) Allan deviation of the offset-lock frequency.

Figure 9: Wavemeter-based offset-lock performance.

3.3 Generation of cold atoms

The laser stabilisation system was then connected to a CPI gMOT platform as a first system-level demonstration of cold-atom generation [4]. The experimental arrangement is shown in figure 10. The cooling and repump beams were combined using a 2x1 PM fibre coupler before delivery to the gMOT.

In this configuration, the line-lock channel was locked to the chosen rubidium reference transition and used as the optical reference for the offset-lock channels that generated the cooling and repump frequencies required by the gMOT sequence. The initial objective was to demonstrate reliable trap loading using the integrated stabilisation instrument before moving on to more detailed sequence-driven measurements.

The cooling laser was set to 201.7 MHz relative to the $^{87}\mathrm{Rb}$ $\mathrm{D_2}$ $F = 2 \rightarrow F' = (1,3)$ crossover transition, corresponding to a detuning of 10 MHz from the target cooling transition. This operating point was chosen to remain within the minimum offset-lock frequency while still providing a strong line-lock reference signal. The repump laser was set to 6.701 GHz relative to the same transition. Trap fluorescence was imaged using an Arducam camera module fitted with a 780 nm bandpass filter to reject ambient light. The resulting image of the trap is shown in figure 10.

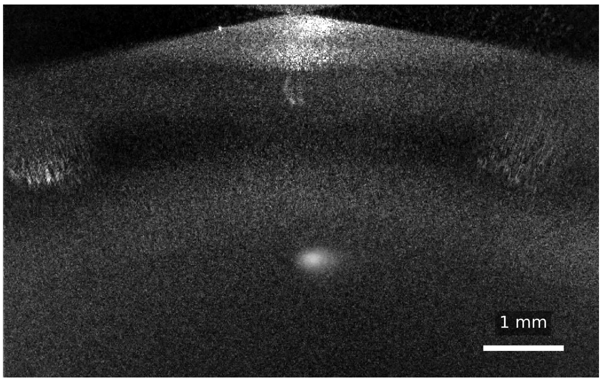


Figure 10: Representative image of the trapped atom cloud in the cold-atom demonstration platform.

4 Conclusion

RedWave Labs' laser stabilisation platform provides a practical route from an atomic frequency reference to the cooling and repump frequencies required for cold-atom experiments. The line-lock and offset-lock architecture can be deployed as a complete instrument, combining lasers, optics, control electronics and software, or as individual OEM subsystems for integration into a customer-designed platform.

Transfer of stability to arbitrary frequency offsets has been demonstrated, enabling doppler cooling experiments.

The cold-atom demonstration shows how the integrated system can be applied to a compact gMOT experiment.

Further information

For product information, related manuals and technical support, contact RedWave Labs.

https://www.redwavelabs.com

References

[1] Alter Technology TÜV Nord S.A.U. Flame frequency-stabilised laser, 2026. Product datasheet accessed 21 July 2026. Available at https://packaging.altertechnology.com/downloads/datasheets/flame-frequency-stabilised-laser/.

[2] Daniel A. Steck. *Rubidium 87 D Line Data*. University of Oregon, 2025. Revision 2.3.4, 8 August 2025. Available at https://steck.us/alkalidata/.

[3] Bristol Instruments, Inc. 671 series laser wavelength meter, 2026. Product page accessed 21 July 2026. Available at https://www.bristol-inst.com/bristol-instruments-products/wavelength-meters-scientific/671-series-cw-lasers/.

[4] CPI Electron Device Business. gmot – grating magneto-optical trap, 2026. Product page accessed 21 July 2026. Available at https://www.cpi-edb.com/products/quantum-technology/gmot-3/.

Revision history

Revision	Date	Description	Author
0.1	15 July 2026	Initial application-note draft with template setup.	J. Waller